

# EMERGING TRAJECTORIES

Advances in Cyber-Physical Systems, Biorobotics and  
Cyber-Human Integration



## **EDITORS:**

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Gabriel Martínez Soltero



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*Emerging Trajectories. Advances in Cyber-Physical Systems, Biorobotics and Cyber-Human Integration.* **Editors:** Alma Y. Alanis, Jorge Galvez, Omar Avalos, Eduardo Méndez-Palos, Jorge D. Rios, Adriana Peña Perez-Negron & Gabriel Martínez Soltero— *Guadalajara, México. 2025.*

578 P. 23 cm.

*First Edition*

ISBN: **979-13-87837-54-9**

DOI: <https://doi.org/10.61728/AE20254735>



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This work was reviewed under a double-blind system and has been endorsed by academic peers in the field of social sciences in Mexico.

Layout by **Astra ediciones**



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HECHO EN MÉXICO | MADE IN MEXICO

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## Prologue

For many years, humans have tried to understand the world by finding patterns and rules hidden within the systems around us. This pursuit encountered two significant challenges: the scarcity of recorded data and limited computational capabilities. Now, the landscape has been transformed. Real-world applications now generate massive amounts of data and computational power has been expanded. However, this originates new challenges. We need better ways for experts from different backgrounds to work together and combine their experiences. Effective collaboration across disciplines requires new methodologies that enable specialists from diverse fields to share insights and integrate their expertise. This book embodies this spirit of integration, bringing together diverse research topics that collectively drive progress in science and technology. This volume represents more than a collection of papers—it embodies a vision for collaborative research that transcends traditional academic boundaries. By connecting experts from computational intelligence, technological management, bioengineering, robotics, and cyber-physical systems, we build strong conditions for new innovations that address complex challenges of our time.

The contributions within these pages showcase cutting-edge methodologies and novel applications that extend the limits of research and practice. From intelligent algorithms that enhance decision-making processes to adaptive robotic systems that revolutionize manufacturing, and from biomedical designs that transform healthcare to cyber-physical systems that optimize infrastructure, each trajectory demonstrates how interdisciplinary approaches yield exponential rather than incremental progress.

We extend our sincere gratitude to all contributors whose dedication and expertise have made this publication possible. Their willingness to share insights across disciplinary lines exemplifies the collaborative spirit essential for meaningful innovation. We also acknowledge the reviewers whose rigorous evaluation has ensured the quality and relevance of the included works.

As we navigate an increasingly complex technological landscape, this book serves not only as a repository of current knowledge but also as a compass pointing toward promising directions for future exploration. We invite readers to engage deeply in these contributions, question assumptions, forge new connections, and ultimately chart their own innovative trajectories that will shape the next generation of scientific and technological advancement.

The Editorial Committee May 2025



# Conformal Net and Evolutionary Computing for Object Detection in Point Clouds

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**Abstract.** In this paper, we introduce a method for detecting objects in point clouds by creating a hybrid approach that combines a Conformal Neural Network (CNet) with a bio-inspired algorithm called Germinal Center Optimization (GCO). This innovative approach addresses the challenge of detecting objects within 3D point clouds. Our hybrid model demonstrates competitive results, delivering a higher accuracy in object delineation along with a reduced runtime compared to other optimization algorithms such as Particle Swarm Optimization (PSO), Differential Evolution (DE), and Firefly Algorithm (FA). The improved efficiency of our model highlights its potential for applications that require fast and precise object detection in complex 3D environments.

**Keywords:** Object Detection, Neural Network, Evolutionary Computing

## 1 Introduction

In recent years, object detection has become a key topic in navigation, both for robotics and autonomous driving. Most object detection systems rely heavily on cameras; however, these present limitations, as they capture images in a 2D plane, which leads to a loss of information about depth and the spatial relationships between multiple objects. Point clouds provide a geometric 3D representation that is useful for different robotics operations like path planning or object avoidance.

The use of light detection and ranging (LiDAR) technology for object detection was not initially widespread, because of its capability but rather due to its high cost. However, as LiDAR has become more affordable, it has gained traction as a viable method for study and application, especially for more common equipment and robotic applications.

This paper is organized as follow: First in Section ??, we introduce the Conformal Net, used to estimate the probability of seeing each object. In Section 3, we present the Germinal Center Optimization (GCO) Algorithm. In Section 4, we present the proposed method for object detection. In Section 5, we present our results and comparison with other state-of-the-art algorithms. Finally in section 6 we offer a conclusion.

<https://doi.org/10.61728/AE20254902>



## 2 Conformal Net

In this section we explain in general terms the CNet architecture [1]. The kernel trick is a classic machine learning technique used to solve non-linear problems. It is a core concept in Support Vector Machines, Gaussian processes, and kernel machines [2, 3]. A real-valued kernel function has the form  $K : \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}$  and it represents a proper inner product in high dimensional space ( $m > n$ ), as shown in Eq. (1), where  $x_1, x_2 \in \mathbb{R}^n$  and  $\phi : \mathbb{R}^n \rightarrow \mathbb{R}^m$ .

$$K(x_1, x_2) = \langle \phi(x_1), \phi(x_2) \rangle \quad (1)$$

The proposed method uses a Geometric Algebra conformal mapping as a kernel. Geometric Algebra (GA), also known as Clifford Algebra, is a powerful mathematical framework with numerous applications in physics, robotics, and computer science [4, 5, 7].

The architecture for neural Conformal Net show in Figure 1.

Let us define  $n$  as the number of points in a point cloud that represent one object. For experimentation, we set  $n = 1024$ . The input to the classification network is  $(n, 3)$ . We implement two layers for preprocessing the point cloud; these layers center and normalize the point cloud.

After that, we map the normalized points to  $G_{4,1}$  using the conformal kernel map.  $G_{4,1}$  has 32 subspaces, resulting in a  $(n, 32)$  tensor. We extract the six subspaces from the conformal maps corresponding to  $\{e_1, e_2, e_3, e_+, e_-, e_{123+-}\}$  (where  $e_{123+-}$  is the pseudoscalar element).

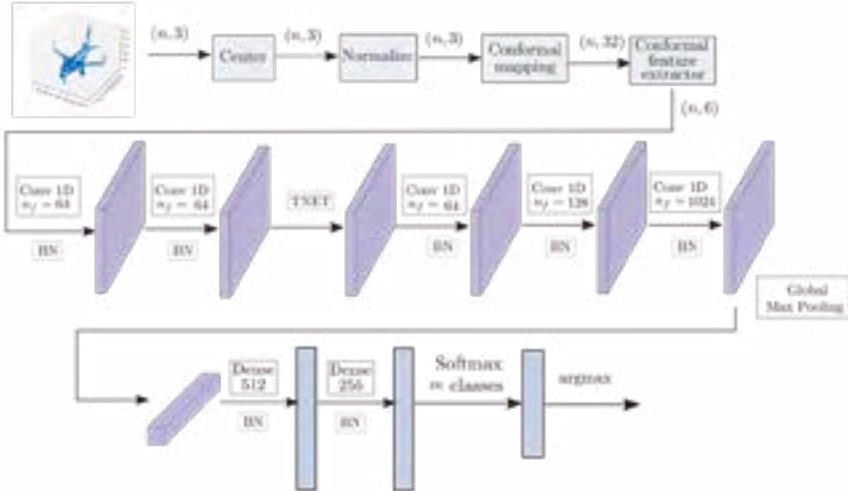


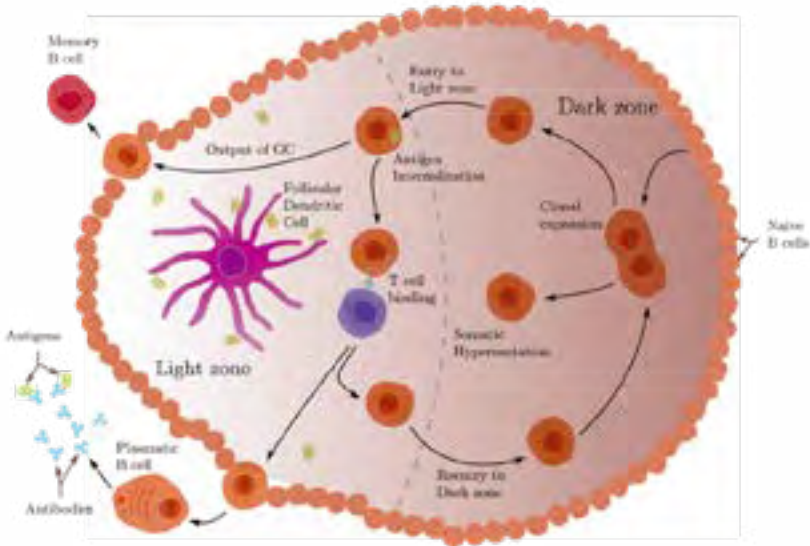
Fig. 1. Architecture CNet



### 3 Germinal Center Optimization

In this section, we provide an overview of the GCO algorithm, which is bio-inspired by the immunology system.

Germinal Centers (GCs) are histologically distinguishable aggregates of B-cells and other immune cells. GCs are formed in the secondary lymphatic nodes when an infection persists for more than seven to ten days [6]. In GCs, the B-cells undergo a competitive process to generate Antibodies (Ab) with high affinity for a specific antigen (Ag). We present the GC process in Figure 2.



**Fig. 2.** Germinal Center Reaction

In [8], we presented an algorithm inspired by the GC process, and we have called it Germinal Center Optimization (GCO). We have found applications of GCO in automatic control [9–11], time series forecasting [12], and medical applications [13].

The GCs have two distinct areas: the Dark and Light zones. B-cells cycle through generations between these two zones. This process is mimicked in the Algorithm 1.

**Algorithm 1: GCO algorithm**


---

```

1 Initialize B-cells ( $B_i$ )
2 foreach  $k \in \{1, \dots, \text{Iterations}\}$  do
3   | Dark zone process (Algorithm 2)
4   | Light zone process (Algorithm ??)
5 end

```

---

**Algorithm 2: Dark Zone process**


---

```

1 foreach  $i \in \{1, \dots, N\}$  do
2   | if  $r_i \sim U[0, 100] < L_i$  of  $B_i$  then
3   |   | Add one to  $B_i$  cells counter
4   | else
5   |   | if Cells in  $B_i > 1$  then
6   |   |   | Rest one to  $B_i$  cells counter
7   |   | end
8   | end
9   | Mutate  $B_i$  (Algorithm 3)
10 end

```

---

In the Dark Zone, the B-cells  $B_i$  proliferate through clonal expansion. We replicate this process in Algorithm 2, where B-cells with high life signal  $L_i$  can proliferate more while others will die.

Some B-cells mutate with a process called somatic hyper-mutation. We imitate this with the mutation Algorithm 3. Notice that the mutation algorithm is close to the differential evolution mutation.

## 4 Object detection with CNet and GCO

In this section explain who was working hybridization which the CNet and GCO for Object detection.

Object detection is the problem of classifying and finding the bounding box of an object; typically, this is a problem formulated for computer vision [14]. In recent years, LiDAR (Light Detection and Ranging) technology has become more affordable and the challenges that its use represents have attracted the attention of the scientific community. We can find new algorithms for object detection in point clouds [15] and others based in neural networks like Localization Network (LocNet) [16]. However, many of these algorithms have high requirements for parallel computing.

We present a hybrid algorithm that uses the CNet and the GCO algorithm to find objects at a point cloud. The B-cells in GCO will represent the parameter of a bounding box, as we show in Eq. (2).

$$B_i = [x_{min}, y_{min}, z_{min}, x_{max}, y_{max}, z_{max}]^T \quad (2)$$

**Algorithm 3:** Mutation algorithm

---

```

1 Calculate distribution  $C$ 
2 Calculate  $r_1, r_2, r_3 \sim C$ 
3 foreach  $j \in \{1, \dots, d\}$  do
4   if  $r \sim U[0, 1] < CR$  then
5      $M(j) \leftarrow B_{r_1}(j) + F * (B_{r_2}(j) - B_{r_3}(j))$ 
6   else
7      $M(j) \leftarrow B_i(j)$ 
8   end
9 end
10 Calculate  $f(M)$ 
11 if  $f(M) < f(B_i)$  then
12    $B_i \leftarrow M$ 
13   Add 10 to  $L$  of  $B_i$ 
14   if  $f(M) < best$  then
15      $best \leftarrow f(M)$ 
16      $best\_index \leftarrow i$ 
17   end
18 end

```

---

We create random environments consisting of  $k$  objects taken from the ModelNet40 dataset and apply random rigid transformations to each object. For example, Figure 3 shows a randomly generated environment with 15 objects.

We generated 300 of these environments, 250 for retraining the CNet and 50 for testing. In Figure 4, we present the training schedule for the CNet.

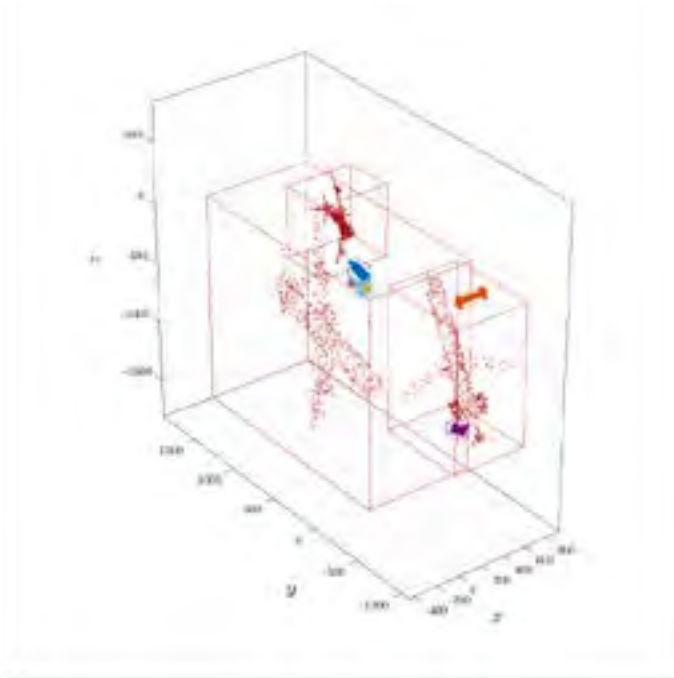
First, we take a randomly generated environment with  $1024o \times 3$  points and generate a random bounding box cut of the point cloud. We will get a  $m \times 3$  point cloud. If  $m < 400$ , we dismiss the sample; if  $400 < m < 1024$ , we sample with replacement until the size reaches 1024. For  $m > 1024$ , we sample uniformly to get 1024. We apply this method because the CNet's input is a tensor of  $1024 \times 3$ .

As the point cloud is labeled, we can calculate the proportion of points belonging to each object, giving us a probability distribution. We retrain the CNet to approach this vector using the categorical cross entropy as cost function.

Once the CNet is trained, it can provide the probability distribution of the classes in the cut. The probability allows the algorithm to search in the space to find a target object. In Figure 5, we show the hybrid system for object detection.

We work with a random, unlabeled environment. The particles of the evolutionary algorithm (it could be GCO or another EC algorithm) have information about the bounding boxes used to cut the original point cloud. If the cut is valid, let  $v = 1$ , and if it is not, let  $v = 0$ . We resample to fill the point cloud and feed the CNet. The CNet estimates a probability distribution of the objects in the cut.

To guide the particles towards the target, we have developed a custom objective function. Consider  $p \sim U[0, 1]^{40}$  as the probability vector output by the



**Fig. 3.** Example of a randomly generated environment

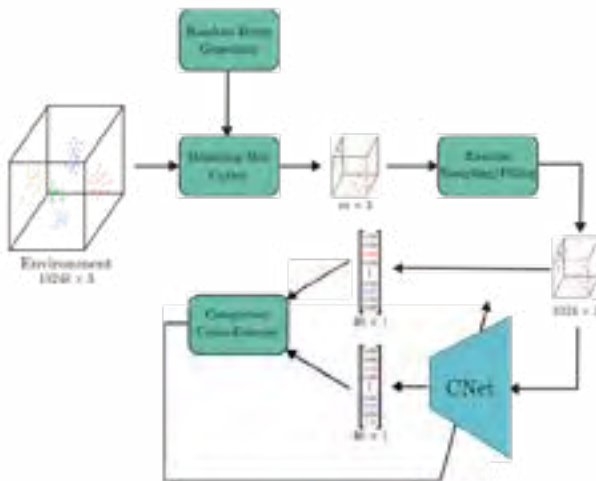


Fig. 4. Training schedule for the CNet for object detection

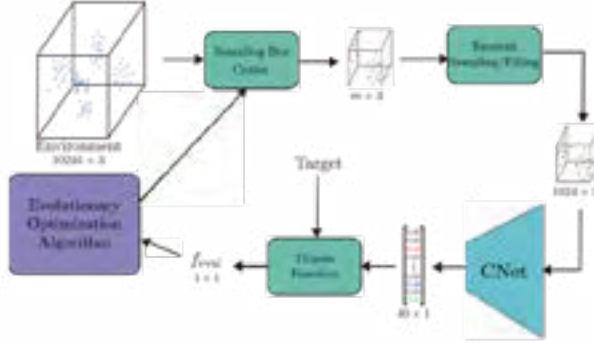


Fig. 5. Evolutionary-CNet detection Scheme.

CNet, where  $\text{sum}(p) = 1$ . Let  $M$  be a signed mask that depends on the target object  $t$ , and it is defined by

$$M(t)_i = \begin{cases} -1 & \text{if } i = t \\ 1 & \text{if otherwise} \end{cases} \quad (3)$$

where  $i \in \{1, 2, \dots, 40\}$ . To mitigate growing bounding boxes, let us define the range of the environment:

$$E = [ex_{min}, ey_{min}, ez_{min}, ex_{max}, ey_{max}, ez_{max}]^T \quad (4)$$

We can calculate the volumetric ratio between a bounding box and the environment with

$$V = \frac{(x_{max} - x_{min})(y_{max} - y_{min})(z_{max} - z_{min})}{(ex_{max} - ex_{min})(ey_{max} - ey_{min})(ez_{max} - ez_{min})} \quad (5)$$

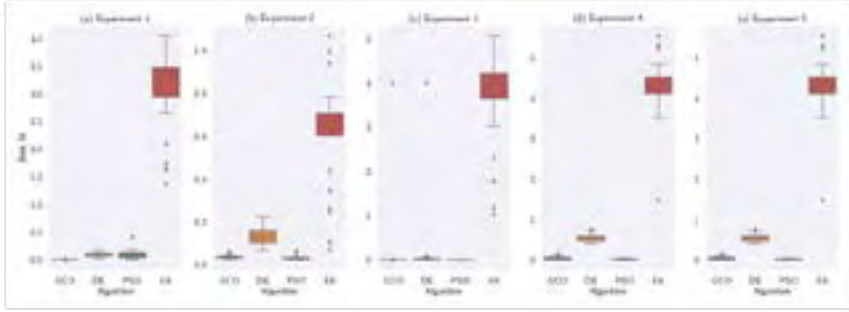
Then, we can define the fitness function for this problem by

$$f(t, p, v) = \begin{cases} [M^T p + 1 + \eta V]^2 & \text{if } v = 1 \\ \infty & \text{if } v = 0 \end{cases} \quad (6)$$

Notice that  $V \in [0, 1]$  and  $M^T p$  as a minimum of  $-1$  (when  $p$  is one in the target position); we compensate this by adding one. Consequently, the minimum of  $f$  is 0. We have set  $\eta = 0.1$  heuristically.

## 5 Results and Comparisons

We have compared the GCO algorithm with three classical algorithms: Differential Evolution (DE), Particle Swarm Optimization (PSO), and Firefly Algorithm (FA). We have tested these algorithms with five randomly selected cases and conducted 30 tests for each algorithm.



**Fig. 6.** Results of the detection over the five experiments

**Table 2.** Time results in seconds of the different Evolutionary Algorithms. For Each experiment, we show the mean and standard deviation; mean  $\pm$  std. **Bold values** indicate the best result.

| Experiment | GCO                                   | DE                  | PSO                 | FA                   |
|------------|---------------------------------------|---------------------|---------------------|----------------------|
| 1          | <b>0.9565 <math>\pm</math> 0.0268</b> | 8.1013 $\pm$ 0.2709 | 1.3396 $\pm$ 0.0640 | 40.0578 $\pm$ 0.8207 |
| 2          | <b>0.9704 <math>\pm</math> 0.0162</b> | 7.7933 $\pm$ 0.2146 | 1.8114 $\pm$ 0.0458 | 39.9203 $\pm$ 1.0637 |
| 3          | <b>0.8864 <math>\pm</math> 0.0381</b> | 7.2119 $\pm$ 0.4800 | 1.2662 $\pm$ 0.0426 | 38.1189 $\pm$ 0.5941 |
| 4          | <b>0.9950 <math>\pm</math> 0.0178</b> | 7.9625 $\pm$ 0.1634 | 1.4072 $\pm$ 0.0600 | 38.1494 $\pm$ 0.4109 |
| 5          | <b>0.9107 <math>\pm</math> 0.0596</b> | 8.0411 $\pm$ 0.4220 | 1.3784 $\pm$ 0.2459 | 36.1937 $\pm$ 0.4255 |



For each algorithm, we used 20 particles and 100 iterations. For GCO and DE, we use the  $F=1.25$  and  $CR=0.7$  parameters. DE is set in its variant DE/rand/1. For PSO, we used an inertial weight of  $W=0.8$  and  $c1=c2=2$ . Finally, we use  $\alpha = 1.0$ ,  $\beta = 1$ , and  $\gamma = 0.01$  for the FA. All test software was programmed in Python 3 with an RTX3060 GPU for the neural network programmed in Tensorflow/Keras.

Table 1 shows the results of the experiments as the and standard deviation of the best value in the fitness function. Notice that GCO wins one of the experiments, and PSO wins the other 4. However, the results are very close. DE is close to GCO and PSO, but FA yielded the lowest performance.

**Table 1.** Results of the different Evolutionary Algorithms. For Each experiment, we show the and standard deviation of best fit:  $\pm$  std. **Bold values indicate the best result.**

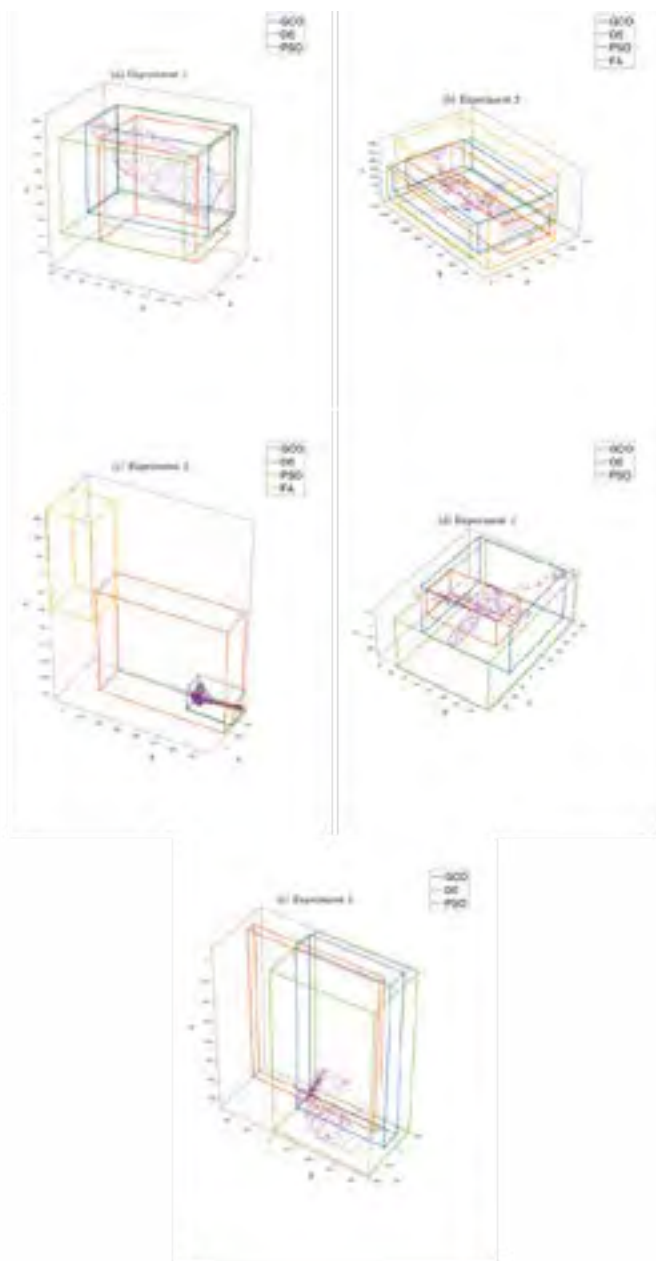
| Experiment | GCO                                   | DE                  | PSO                                   | FA                  |
|------------|---------------------------------------|---------------------|---------------------------------------|---------------------|
| 1          | <b>0.0005 <math>\pm</math> 0.0017</b> | 0.0870 $\pm$ 0.0305 | 0.0953 $\pm$ 0.0822                   | 3.1449 $\pm$ 0.7241 |
| 2          | 0.0358 $\pm$ 0.0080                   | 0.1356 $\pm$ 0.0423 | <b>0.0307 <math>\pm</math> 0.0090</b> | 0.6031 $\pm$ 0.2230 |
| 3          | 0.1333 $\pm$ 0.7180                   | 0.2823 $\pm$ 0.9337 | <b>0.0000 <math>\pm</math> 0.0000</b> | 3.6550 $\pm$ 0.9925 |
| 4          | 0.0365 $\pm$ 0.0361                   | 0.5409 $\pm$ 0.0850 | <b>0.0127 <math>\pm</math> 0.0123</b> | 4.2689 $\pm$ 0.6677 |
| 5          | 0.4173 $\pm$ 1.1948                   | 0.0887 $\pm$ 0.0848 | <b>0.1095 <math>\pm</math> 0.5827</b> | 2.8874 $\pm$ 0.2008 |

In Figure 6, we present the boxplots of the experimental results. Notice that FA has the worst results with high variability. GCO and PSO have similar performances, very close to 0, with small variability, and DE is always slightly behind.

On the other hand, we also present the table that summarizes the fastest running times in seconds for the same experiments. Notice that GCO always achieves the best time, followed by PSO. In third place, we have DE and FA as the last one. These differences in time depend highly on the number of invalid bounding boxes that each algorithm computes.

For visual comparison, in Figure 7, we have selected the first run of each experiment and drawn the target object in the point cloud. We have drawn the best bounding box found by every algorithm in different colors.

Note that we have not drawn the FA bounding box in some cases because it was very far from the others. DE tends to make smaller bounding boxes (except for experiment 3). Qualitative GCO makes better bounding boxes than PSO (except in experiment 5), but they are very close in results.



**Fig. 7.** Comparison of the best solution of the Evolutionary Algorithms for the target object in each experiment, Color scheme: GCO (blue), DE (Orange), PSO (Green), FA (Yellow)



## 6 Conclusions

We presented a hybrid intelligent system that combines the proposed CNet with the GCO algorithm for object detection in the point cloud. We calculated statistics results against classical state-of-the-art EC algorithms. GCO showed good performance in test, achieving very close minimums with respect to the best results obtained by PSO, but with considerable faster running times due to GCO estimates less invalid bounding boxes than PSO, DE and FA.

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# AI-Powered Analysis for Hadronic Particle Detection in ALICE Open Data

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**Abstract.** The integration of Artificial Intelligence (AI) techniques, particularly Machine Learning (ML), is revolutionizing data analysis in high-energy physics experiments. This study presents the development and implementation of an advanced AI-driven analysis environment for hadronic particle detection using open data from the ALICE experiment at CERN. The research focuses on leveraging ML algorithms, including Deep Learning, ensemble methods, anomaly detection, to enhance particle classification and identification. The methodology involves preprocessing and analyzing data from lead-lead (Pb-Pb) collisions, applying supervised and unsupervised ML techniques to optimize particle detection accuracy. The study explores the use of neural networks for particle classification and prediction, aiming to improve the identification of subatomic interactions in extreme conditions. Additionally, real-time inference through Kafka integration enhances data processing efficiency. Results demonstrate that AI-based approaches significantly improve particle classification performance compared to traditional methods. The findings highlight the potential of ML to refine experimental analysis, reduce uncertainties, and provide new insights into fundamental interactions in particle physics. This research underscores the transformative role of AI in modern high-energy physics, paving the way for future advancements in data-driven scientific discovery.

**Keywords:** Artificial Intelligence, Machine Learning, Hadronic Particle Detection, ALICE Experiment, Particle Classification, Deep Learning

## 1 Introduction

### 1.1 Particle physics and the study of exotic particles

Particle physics explores the basic building blocks of matter and their interactions, aiming to uncover the universe's mysteries at its most fundamental level [1]. These exotic particles possess unique properties and behaviors that challenge our current understanding of particle physics. Their study not only expands our knowledge of the subatomic world but also offers insights into the underlying principles governing the cosmos. The detection and characterization of exotic particles, such as those in High Energy Physics (HEP), require sophisticated experimental techniques and analytical methodologies. Traditional approaches often rely on meticulous data analysis and theoretical modeling to identify these elusive entities within the sea of particle interactions. However, recent

<https://doi.org/10.61728/AE20254919>



advancements in technology and computational methods have opened new frontiers in particle physics research [1].

## 1.2 Role of AI in Hadronic Particle Detection

Artificial Intelligence (AI) has emerged as a powerful tool for advancing hadronic particle detection in high-energy physics experiments. Traditional methods rely on rule-based classification and statistical models, which, while effective, often struggle with the complexity and sheer volume of data generated in large-scale experiments like ALICE at CERN [2]. The integration of Machine Learning (ML) techniques, including supervised, unsupervised, and reinforcement learning, offers a more adaptive and scalable approach to particle identification. Deep learning models, particularly neural networks, have demonstrated remarkable accuracy in distinguishing between hadronic particles such as pions, kaons, and protons based on detector signals. Furthermore, AI-driven anomaly detection methods enhance the identification of rare or unexpected particle interactions, improving the reliability of physics analyses [3]. The real-time processing capabilities of AI, combined with streaming frameworks like Kafka, enable rapid data analysis, reducing computational bottlenecks in experimental workflows. By leveraging AI, researchers can refine particle classification, reduce uncertainties, and gain deeper insights into the fundamental interactions governing high-energy collisions. This study explores the application of AI in optimizing hadronic particle detection, demonstrating its potential to applicability data analysis in modern particle physics.

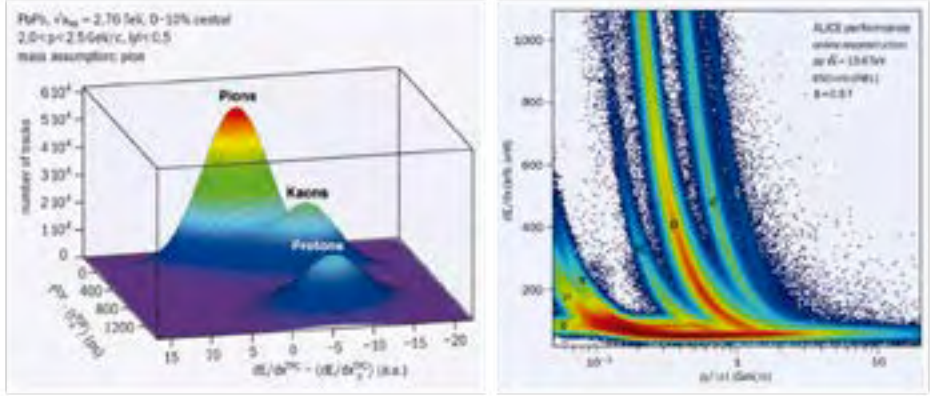
## 2 ALICE Experiment and Open Data

### 2.1 Overview of Alice

The ALICE (A Large Ion Collider Experiment) detector at CERN is a specialized experiment designed to study heavy-ion collisions and investigate the properties of quark-gluon plasma (QGP), a state of matter that existed in the early universe microseconds after the Big Bang [1]. Unlike other LHC experiments, ALICE is optimized for tracking and identifying a wide range of particles emerging from these collisions, providing crucial insights into the behavior of strongly interacting matter under extreme conditions [4]. The experiment utilizes a complex system of detectors, including the Time Projection Chamber (TPC), Inner Tracking System (ITS), and Time-of-Flight (TOF) detectors, which enable precise reconstruction of particle trajectories and identification of hadronic species such as pions, kaons, and protons [3].



One of the primary objectives of ALICE is to analyze Pb-Pb collisions at ultra relativistic speeds, allowing scientists to study deconfined quarks and gluons and their interactions before recombining into hadrons [2]. The experiment's advanced particle identification (PID) techniques, which combine  $dE/dx$  measurements with velocity-based classification, provide a solid foundation for developing artificial intelligence (AI)-driven methodologies for automated particle recognition [3].



**Fig. 1.** Particle Identification (PID) (Left) Composition of Pions, Kaons and Protons (Right) Reconstruction of the data [1].

By integrating AI and machine learning (ML) into the analysis pipeline, researchers aim to enhance detection accuracy, optimize real-time processing, and explore rare and exotic particle states more efficiently [2]. These advancements position ALICE as a key experiment in high-energy physics, bridging traditional particle detection methods with AI-driven approaches to push the frontiers of knowledge in nuclear and particle physics.

## 2.2 Data Characteristics and Challenges

One major challenge in implementing AI-based particle detection within ALICE is the integration of machine learning frameworks into the existing analysis infrastructure. While many machine learning models are developed in Python, ALICE's core analysis framework, O2, primarily operates in C++ and relies heavily on the ROOT library [1]. This language barrier complicates the seamless deployment of AI models, necessitating solutions like Open Neural Network Exchange (ONNX) to bridge Python and C++ environments [5]. ONNX provides a standardized format for storing and deploying machine learning models, ensuring compatibility and efficiency in real-time particle classification (see Figure 2).



Fig. 2. Scheme of the current ML particle identification workflow in O2 in ALICE3 [5].

Another significant issue is handling incomplete data. Since multiple detectors independently measure different particle properties, a single particle may be detected by some subsystems while remaining undetected by others. Factors such as detector malfunctions, low transverse momentum, or signal loss contribute to missing data points, which can degrade the performance of AI models [3]. Standard approaches to missing data handling include case deletion, which discards incomplete samples but reduces dataset diversity, and imputation techniques, which estimate missing values using statistical methods or machine learning predictions [3]. Both methods introduce biases that may affect the accuracy of particle identification.

### Experimental Environment

The processing setup used is constituted by Ubuntu 18.04 Linux system in a Windows computer has a CPU of 2.5 ghz a host memory 34 B and a hard disk capacity of 1TB. The development language uses version 3.5 of Aliroot in Terminal and Pyroot.

## 3 Methodology for Developing Artificial Intelligence

The development of an AI-driven particle detection system for the ALICE 3 experiment followed a structured methodology to ensure efficient data collection, processing, and model evaluation (see Figure 3). The first phase involved collecting Open Access Data from CERN, including Pb-Pb collision records from 2014 to the present, and retrieving LHC Grid Variables relevant to particle interactions. Additionally, historical data was accessed through ROOT tools, allowing for further analysis of lead-ion collisions. Next, a Machine Learning (ML) program was developed to assess the effectiveness of particle identification in high-energy physics (HEP). This step included data preparation, cleaning, and structuring, followed by the implementation of a decision tree and ML algorithms to enhance classification accuracy. Finally, data analytics techniques were used to identify key attributes and clusters in lead-ion collisions, ensuring an optimal feature selection for the AI system. The Monte Carlo methodology was incorporated to improve simulation-based validation, reinforcing the reliability of the proposed approach. This structured plan ensures consistency and precision in AI-assisted particle detection, aligning with CERN's best practices in high-energy physics research.



Fig. 3. Scheme of the current ML particle identification workflow in O2 in ALICE3.

### 3.1 Understanding and Evaluating the Pb-Pb Open Dataset

The development of an AI-based particle detection system relies on a structured approach to handling and analyzing Pb-Pb collision data from the ALICE 3 experiment at CERN. The dataset, obtained through Open Data, consists of 876,363 entries in CSV format, containing historical records of particle interactions. These CSV files were generated using custom macros developed for AliRoot, which enabled the retrieval and extraction of historical data stored in ROOT format. By leveraging these macros, the system efficiently accessed and processed key collision parameters, such as particle trajectories, energy deposits, and timing information, ensuring a structured dataset for AI model training. For enhanced particle classification, the dataset labels were mapped to their respective physical particles, grouping them as follows:

- "π" (pions and antipions)
- "e" (electrons and positrons)
- "K" (kaons and antikaons)
- "p" (protons and antiprotons)
- "d" (deuterium and antideuterium)

This dataset includes crucial attributes for particle identification, such as particle trajectories, energy deposits, and timing information. Key variables include event and particle numbers, multiple energy measurements, collision origin coordinates (X, Y, Z), detector signals (ITS, TPC, TOF), electric charge, and momentum (P). These features are essential for reconstructing collision events and distinguishing between particle types.

## 4 Data Analysis for Particle Identification

### Experimental environment

The processing setup used is constituted by Windows system has a CPU of 3.5 ghz a host memory of 34GB and a hard disk capacity of 500 Gb. The development language uses are Python and MATLAB, Octave for the preprocessing of data.



#### 4.1 Filtering

Ensuring high-quality and structured data is crucial for accurate analysis and machine learning performance. The data filtering process eliminates irrelevant data, normalizes values, and structures datasets for ML compatibility. Additionally, data cleaning addresses outliers, missing values, and input errors, improving dataset integrity and model accuracy. This is particularly important when analyzing TPC detector signals vs. momentum (P) (see Figure 5), where many data points cluster near zero. Understanding the X, Y, Z origin coordinates of each detected particle is essential for accurately reconstructing collision events.

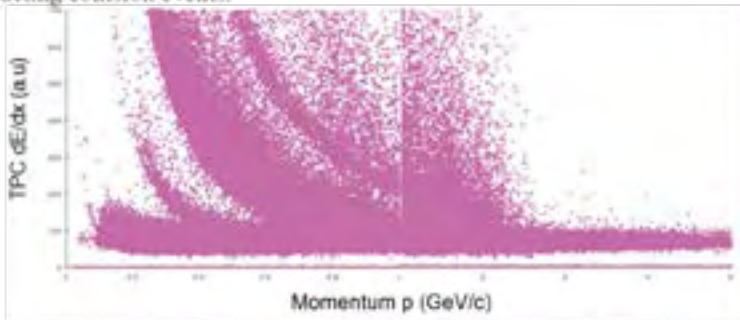


Fig. 5. Total Particles in TPC vs. Momentum for Positive Particles (Unfiltered Data).

During a Pb-Pb collision, protons interact at a specific point near the center of the detector, known as the Primary Collision Vertex [see Figure 6]. The methodology in this study focuses on sub-particles generated at this primary vertex. However, many of these particles scatter and undergo secondary interactions, creating additional sub-particles in what are known as secondary collisions. As particles move through the detector's gas chambers, they leave recorded trajectories, allowing for precise calculation of their point of origin. To accurately reconstruct collision dynamics, each dataset includes three-dimensional origin coordinates (X, Y, Z) of each detected particle, enabling the distinction between primary and secondary collision products.

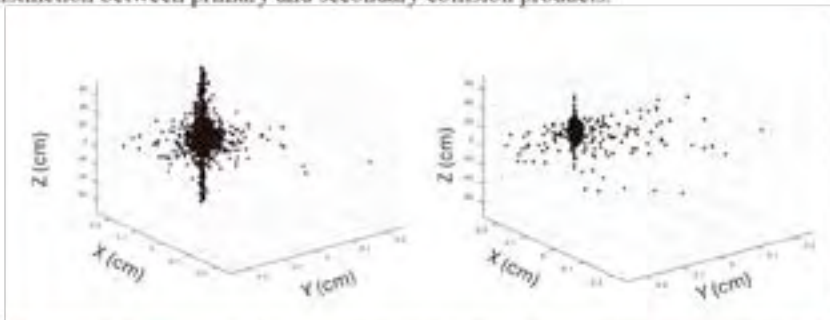


Fig. 5. Collision Vertex Positioning: Detected Particles (Left) and Primary Collisions (Right).



To determine whether a particle originates from the main collision or a secondary interaction, event vertices were extracted from ROOT files and visualized in 3D (see Figure 5). The right side represents main collision vertices, while the left side shows detected particle vertices, revealing a significant presence of secondary collisions. A MATLAB-based filtering algorithm was developed to retain only primary collision particles (see Figure 6). The filtering process calculates the spatial distance between detected particles and the main collision vertex, ensuring data integrity by verifying detector signals. Initial filtering based solely on distance was insufficient, leading to an optimized approach that improved classification accuracy. To enhance data quality, a comprehensive filtering process was applied, reducing the dataset to 147,950 samples across 13 attributes with separate files for negative and positive particles. This refinement increased data clarity and consistency, ensuring that only relevant collision data is used for analysis.

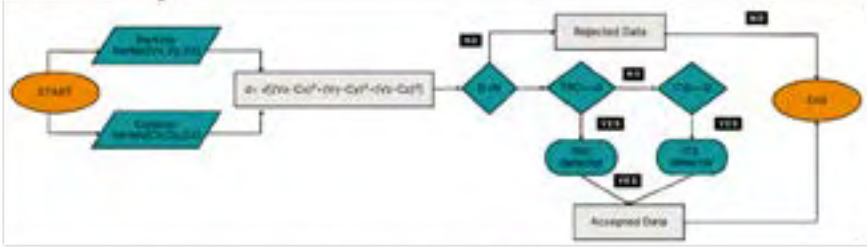


Fig. 6. Decision Tree Algorithm for Primary Data Selection.

## 5 Unsupervised Machine Learning Approaches

The use of clustering algorithms such as K-Means, Gaussian Mixture Models (GMMs), DBSCAN, and Spectral Clustering has improved particle classification by identifying patterns and grouping particles based on shared characteristics. However, applying these methods to large-scale datasets posed challenges due to high dimensionality and complex data distribution, affecting clustering efficiency and classification accuracy. These limitations highlight the need for adaptive or hybrid approaches to enhance large-scale particle classification in high-energy physics.

### 5.1 K-Means

One of the main issues is the limited capability of conventional clustering algorithms, such as KMeans, to capture nonlinear structures or non-convex shapes in the data. These algorithms tend to cluster data into spherical or hyperspherical clusters, which can result in poor segmentation of nonlinear clusters or the under-segmentation of elliptical clusters [8]. As shown in the following result in Figure 7, clustering of 5 groups and 20 groups was achieved, using Momentum and TPC in positive lead-lead particles.

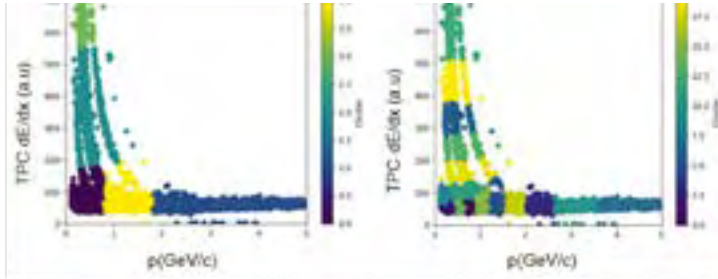


Fig. 7. Clustering graph of positive particles with KMeans left 5 groups and right 20 groups.

It was concluded that the presence of noise or outliers in the data can further hinder the accurate identification of elliptical clusters. Since clustering algorithms can be sensitive to outliers, they negatively affect the quality of the identified clusters.

## 5.2 Gaussian Mixture Models (GMMs)

The Gaussian Mixture Model (GMM) clustering technique was applied in Python to classify positive lead-lead particles, providing valuable insights into the dataset's structure. By assigning 25 labels, the algorithm aimed to assess how well it could capture underlying patterns and distributions within the data. The flexibility of the Gaussian model allowed for a more adaptive representation of nonlinear and multidimensional structures, improving the classification accuracy and robustness of the system. As illustrated in Figure 9, the results highlight clear classification patterns, particularly when analyzing TPC vs. Momentum (P), revealing distinct group formations.

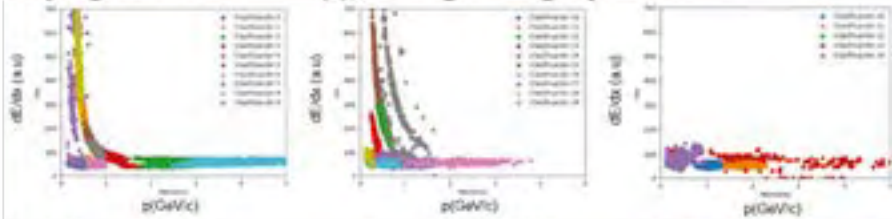


Fig. 8. Clustering graph of positive particles with GMM 25 groups. Divided into Three Visualizations.

To refine the clustering analysis, the classifications were divided into three subsets based on label ranges (0–9, 10–19, and 20–24), which provided a more granular understanding of how the algorithm categorized data, as shown in Figure 8. Additionally, the dataset labels were mapped to their respective physical particles resulting in a more structured and interpretable clustering output. Although Gaussian Clustering produced promising results, manual adjustments were necessary to correctly group positive particles due to noise and irregular data distribution challenges. Since the Gaussian model assumes a normal (spherical) distribution, it struggled to handle complex, high-energy

physics data, making it less effective in cases where non-uniformity and outliers were present.

### 5.3 DBSCAN

DBSCAN (Density-Based Spatial Clustering of Applications with Noise) is effective for irregularly shaped clusters without requiring a predefined number of clusters. However, its success depends on EPS (neighborhood radius) and MinPts (minimum points per cluster), which were optimized using the k-distance method (see Figure 9).

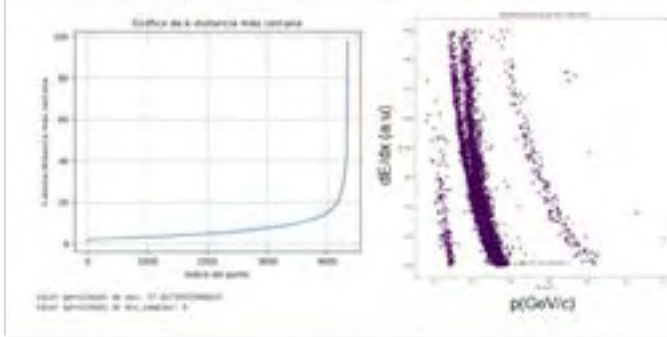


Fig. 9. Nearest Neighbor Distances and Clustering of Positive Particles Using DBSCAN (EPS = 67, Min Samples = 4).

DBSCAN is effective for irregularly shaped clusters but depends on EPS (neighborhood radius) and MinPts (minimum points per cluster) for optimal segmentation. In this study, EPS = 67.01726 and MinPts = 4 improved clustering but significantly increased computational costs. Partitioning the dataset did not improve classification, as DBSCAN misclassified most data as noise due to density similarities. The Nearest Neighbor algorithm was also tested but failed due to outlier sensitivity and high-density regions. DBSCAN's high computational demands and inefficiency in large-scale high-energy physics data make it impractical without further optimizations or alternative clustering techniques. The primary difficulty in implementing DBSCAN lies in its handling of datasets with a vast number of irregular and scattered samples. The method requires substantial computational power and memory, making it impractical for large-scale high-energy physics data analysis without further optimizations or alternative clustering strategies.

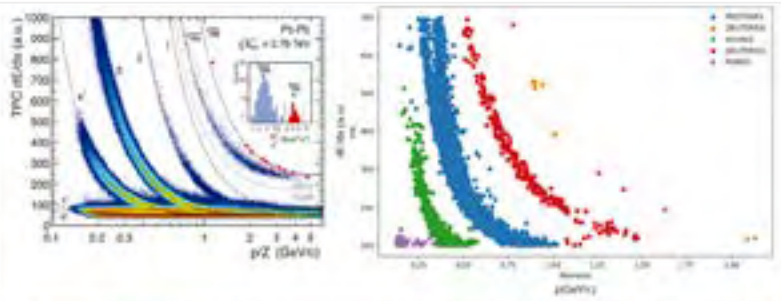
### 5.4 Spectral Clustering

Spectral Clustering is effective for high-dimensional data as it projects information into a lower-dimensional space using spectral decomposition. A key advantage is its ability to customize affinity measures, improving clustering accuracy. Three affinity parameters were tested:



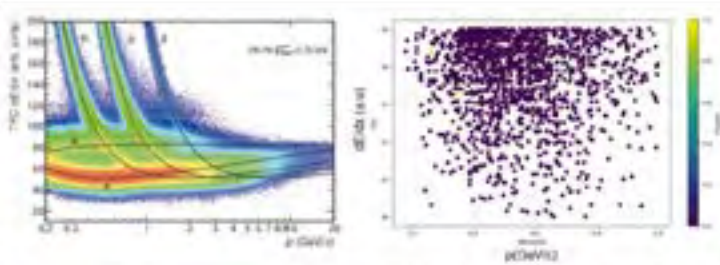
- Nearest Neighbors: Limits calculations, making it suitable for large datasets.
- Radial Basis Function (RBF): Uses a Gaussian kernel to handle nonlinear relationships.
- Precomputed Affinity: Uses a custom similarity matrix for tailored clustering

Each approach was tested to evaluate its effectiveness in detecting clusters within Pb-Pb collision data and the best results were with RBF (see Figure 8).



**Fig. 10.** PID ALICE: TPC vs. Momentum (P) in Pb-Pb Collisions [1] vs. Spectral Clustering Using RBF in the 100–700 TPC Range.

- Nearest Neighbors Approach: Created four clusters in the TPC signal range 200–700, but separations were affected by detector errors and energy loss.
- RBF Kernel & Precomputed Affinity: Improved classification accuracy and reduced computation time, effectively identifying particle interactions in the 100–700 TPC range. However, memory constraints limited analysis of the high-density 0–100 region (see Figure 9).



**Fig. 11.** ALICE TPC vs. Momentum (P) in Pb-Pb Particles (0–200 a.u. in TPC) [1] vs. Spectral Clustering Using RBF (40–45 a.u. in TPC).

Spectral Clustering struggled with high-density data in the 0–100 TPC range, causing memory exhaustion. Irregularities in  $dE/dx$  vs. momentum graphs suggested misclassification or detector effects. Despite effectively identifying particle clusters, its high computational demands limit usability, requiring optimizations or alternative clustering methods for improved efficiency.

## 6 Supervised Classification Using Curve-Based Methods

This methodology leverages advanced machine learning techniques that integrate classification with dynamic curve fitting, allowing for continuous refinement based on data curve analysis.

### *Mathematical Model*

The classification model is based on a curve-fitting equation that describes the relationship between TPC signal and momentum (P). The general formula is:

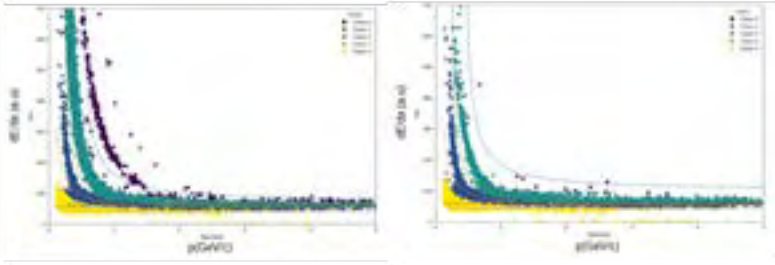
$$\text{curve}(x) = \frac{a}{b(x-h)+c} + d * x + f \quad (1)$$

where:

- **x**: Independent variable (e.g., momentum).
- **a, b, c**: Adjust the shape and position of the fractional term.
- **d**: Scales the linear component.
- **f**: Represents a vertical shift in the curve.
- **h**: An optional parameter that shifts the curve horizontally.

This equation combines a rational function and a linear term, commonly used in particle physics experiments to model nonlinear and asymptotic behaviors in particle trajectories [9]. The fractional term captures complex nonlinear effects, while the linear component adjusts for systematic trends in the data [10]. A Python algorithm was developed to classify hadronic particles in the ALICE experiment, focusing on identifying patterns in TPC signal and momentum. The classification process follows these steps:

- **Data Loading**: The dataset is loaded from a CSV file containing 147,950 rows and 16 columns with separate files for negative and positive particles.
- **Data Filtering**: Only relevant data within a predefined TPC and momentum range are selected to eliminate noise and outliers.
- **Feature Selection**: The most relevant columns ('Momentum', 'TPC') are extracted for analysis.
- **Curve Definition and Parameter Selection**: The predefined equation is used to model five different curves, each corresponding to a specific hadronic particle. Parameters are manually adjusted to represent expected particle patterns.
- **Curve-Based Classification**: The curve equation is applied to the filtered dataset. Each data point is classified based on its proximity to the predefined curves. The closest curve determines the particle type assigned to each data point.
- **Labeling and Data Export**: Class labels are added to the dataset for further analysis. The labeled dataset is exported to CSV, allowing for its use in neural network training and Extended Statistical Data (ESD) validation.
- **Data Visualization**: A scatter plot is generated to visualize classified data and curves. Particles are color-coded by classification, as shown in Figure 12.



**Fig. 12.** Classification of Positive Particles (Left) and Negative Particles (Right) Based on Curves.

The curve-based classifier significantly improved particle identification accuracy, capturing distinct patterns in the TPC signal vs. momentum distribution. However, parameter tuning remains crucial, as some overlap between particle trajectories was observed. Future work will focus on refining the classification model by integrating deep learning techniques and optimizing curve parameters for improved automated hadronic particle detection.

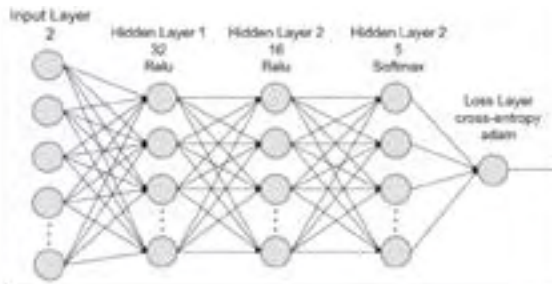
## 7 Deep Learning and Neural Networks

The Deep Learning Particle Classifier is an advanced tool for high-precision particle classification using deep neural networks. Trained on a labeled dataset, it applies normalization and hyperparameter tuning to optimize performance. Once trained, the model can analyze new data, make predictions, and stream real-time results via Kafka, enabling early detection and detailed particle analysis. The process starts with importing essential libraries for data processing, neural network development, and real-time communication. The dataset is then loaded from a CSV file, filtered to select relevant records based on TPC and Momentum ranges, and structured into X (features) and Y (labels). Normalization ensures all feature values have a mean of zero and a standard deviation of one, enhancing model performance and stability for accurate deep learning classification.

### 7.1 Neural Network Construction

The deep learning-based particle classifier applies One-Hot Encoding to transform categorical labels into a binary format, enabling effective multiclass classification. The neural network model is structured as a sequential architecture with multiple dense layers, designed to capture complex relationships in particle physics data (see Figure 13).





**Fig. 13.** Neural Network Particle Classifier Structure.

- **Input Layer:** Processes features such as momentum, energy, and mass in tensor format.
- **Hidden Layers:** Three fully connected layers with ReLU activation, allowing the model to learn nonlinear patterns in the data. Dropout layers are included to prevent overfitting.
- **Output Layer:** Uses Softmax activation to classify positrons, pions, kaons, protons, and deuterons, converting outputs into probability distributions.

The model is compiled using the Adam optimizer and categorical crossentropy as the loss function, with accuracy as the evaluation metric.

## 7.2 Training and Kafka-Based Predictions

The model was trained on 70% of the dataset, using normalized data and encoded labels. Key hyperparameters such as epochs, batch size, and validation split were optimized to enhance predictive performance. The remaining 30% of the data was used for validation and testing. A Kafka producer was implemented to stream particle data to a specific topic to enable real-time integration, allowing seamless deployment in production environments. A function was developed to send new particle data to Kafka, supporting real-time applications. Another function was implemented to predict the class of new samples, applying the same normalization used during training. The frequency of each class in the dataset was calculated to evaluate class distribution. This step ensures that labels remain consistent and accurate for further analysis, particularly when comparing invariant mass values using Event Summary Data (ESD). The dataset was divided into positive and negative particles to enhance classification efficiency. Each classified dataset includes key attributes such as event ID, particle type, momentum components ( $P_x$ ,  $P_y$ ,  $P_z$ ), charge, and class label. These datasets were used to compute invariant mass, a crucial parameter in particle physics, aiding in rare event detection and collisional analysis.

## 7.3 Neural Network Performance in Positive and Negative Particles

The neural network classifier demonstrated outstanding performance, achieving 99% accuracy in test data. Key results include:

- ROC Curves: AUC values of 1.00, indicating perfect classification.
- Confusion Matrix: Minimal misclassifications, mainly between positrons and pions.
- Training Accuracy: Consistent precision across training and validation sets, confirming model robustness.

A comparison of original vs. predicted classifications confirmed strong alignment between the two methods, reinforcing the classifier's reliability in predicting particle identities.

#### 7.4 Comparison with ALICE Experiment Data

The Particle Classifier was validated by comparing its classification percentages with experimental data from ALICE Open Data (see Table 1). The classifier's results closely matched those obtained in Karwowska et al. (2024) [5], demonstrating strong consistency with real-world experiments.

**Table 1.** Percentage of Particles and Antiparticles in Pb-Pb Collisions: ALICE Experiment [5] vs. Open Data.

| Pb-Pb Collision Data from the ALICE Experiment (Karwowska et al., 2024) |           |             |           |               |
|-------------------------------------------------------------------------|-----------|-------------|-----------|---------------|
| Pions                                                                   | Kaons     | Protons     | Positrons | Deuterium     |
| 43.59%                                                                  | 3.415%    | 2.026%      | 0.794%    | 0.323%        |
| Antipions                                                               | Antikaons | Antiprotons | Electrons | Antideuterium |
| 43.66%                                                                  | 3.288%    | 1.819%      | 0.762%    | 0.321%        |
| Particle Classifier                                                     |           |             |           |               |
| Pions                                                                   | Kaons     | Protons     | Positrons | Deuterium     |
| 33.22%                                                                  | 10.14%    | 4.76%       | 3.18%     | 0.089%        |
| Antipions                                                               | Antikaons | Antiprotons | Electrons | Antideuterium |
| 34.06%                                                                  | 10.83%    | 2.29%       | 1.38%     | 0.004%        |

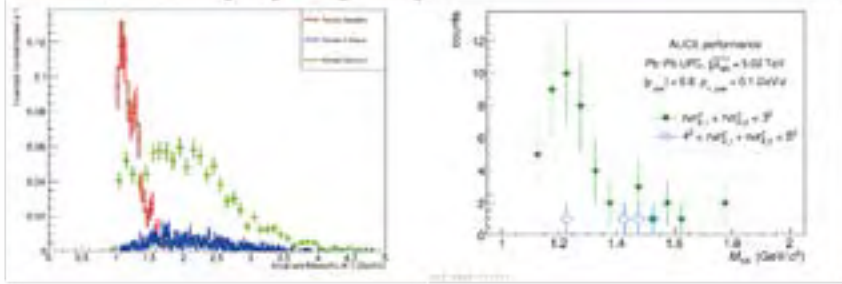
However, Monte Carlo bias corrections were not applied in this study, which may account for slight deviations from ALICE data. Monte Carlo simulations incorporate detector efficiencies, theoretical models, and event reconstruction uncertainties, leading to variations in particle yield predictions. The absence of these corrections in our analysis may introduce minor discrepancies. Despite this, the classifier effectively captured particle distributions, demonstrating its robustness and reliability as a valuable tool for high-energy physics research.

## 8 Invariant Mass Reconstruction of the $\Phi$ (Phi) Meson

One of the most effective methods for identifying particle production in high-energy experiments is analyzing correlations between decay products. The  $\Phi$  (Phi) meson, with a mass of 1.019 GeV/c<sup>2</sup>, predominantly decays into a charged kaon pair (K<sup>+</sup>K<sup>-</sup>), which accounts for 48.9% of all its decays [7]. The Particle Classifier algorithm was evaluated



against two traditional methods (Gaussian and K-means) for reconstructing the invariant mass of this kaon pair [see Figure 14].



**Fig. 14.** Comparison of Invariant Mass Reconstruction Methods for the  $K^+K^-$  Pair in  $\Phi$  Meson Analysis and Validation of the Particle Classifier Algorithm vs. Kim, M ALICE Experiment [8].

- Particle Classifier (Red Curve): Machine Learning-based, showing a sharp peak at 1.019 GeV/c<sup>2</sup>, demonstrating high precision in kaon classification.
- Gaussian Model (Green Curve): Produces a wider peak with lower resolution, indicating less precise reconstruction.
- K-means (Blue Curve): Fails to clearly define the meson peak, making it less effective for accurate particle reconstruction.

The Particle Classifier outperforms traditional approaches, validating its effectiveness in high-energy collision experiments.

## 9 Further Work and Conclusions

This study showcased the effectiveness of AI-based classifiers in hadronic particle detection, surpassing traditional methods. Despite computational challenges, AI techniques proved scalable and adaptable, with real-time implementation via Kafka optimizing experimental workflows. Ongoing AI advancements will further enhance particle classification, leading to faster and more precise physics insights. Future research will focus on refining AI models, improving clustering in dense data regions, integrating real-time AI processing with Kafka, adjusting Monte Carlo bias corrections, and expanding training datasets with simulated and real-time collision data to enhance model accuracy and generalization.

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# A Review on Integrating Photogrammetry and Deep Learning for Semantic Segmentation Applications

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**Abstract.** The monitoring of large areas is essential to assess their conditions and patterns of change and support decision-making from which different ways are look for ways and optimize these problems and techniques such as photogrammetry are used to assess changes in large areas and, in conjunction with semantic segmentation, are important to extract the necessary information and to provide classification analysis at the pixel level for an accurate assessment of irregular shapes. The reference ground sample distance (GSD) method translates pixels into a unit of measurement, facilitating accurate image scale calculations and precise measurements. This method explores these strategies using deep learning, potentially improving accuracy and simplifying segmentation. It also looks at different works that talk about how segmentation and photogrammetry can be used in different areas, including their methods and results, to find the best ways to do things, adapt, and lead to new developments in the field.

**Keywords:** Semantic segmentation, Deep Learning, Photogrammetry, Ground Sample Distance.

## 1 Introduction.

Analyzing the conditions of large areas of buildings, forests, and vegetation is one of the most significant challenges due to the stress they suffer from the consequences of climate change [1]. Therefore, it is essential to constantly record the measurements of the areas to understand their situation and patterns of change and support decision-making regarding their care [2].

Obtain accurate measurements of objects, plants, and cities when looking at large, hard-to-reach areas, especially when government-protected areas and regulatory requirements are involved. Different techniques are used, from traditional methods to modern remote sensing tools. For example, aerial photogrammetry and satellite remote sensing are used to measure changes over large areas. Landsat and Sentinel are two tools that collect data on large areas of vegetation. Light Detection and Ranging (LIDAR)

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technology is one of the most accurate tools for estimating biomass and forest density [3]. Geographic Information Systems (GIS) allow the integration of geospatial data obtained from different sources, facilitating the delineation and analysis of large land areas using software[4].

There are many works proposed using semantic segmentation and photogrammetry in different areas that talk about the improvement of mapping in segmentation, using UAV photogrammetry data (RGB, DSM, VDVI) focused on building and propose the combination of these methods to obtain very accurate results [5], methods that focus on improving the extraction of geometric information [6]; and these studies demonstrate the effectiveness of integrating semantic segmentation with photogrammetry for various applications, including building care, image analysis of historic building facades, and applied in architecture. [7] In addition, different applications of photogrammetry for environmental investigations and the impact that can be obtained by combining LiDAR photogrammetry and improved spatial resolution and accuracy and the possible investigations for understanding ecological processes and hazard prevention [8]. However, some of these techniques have disadvantages, such as their cost due to sensors and cameras [9].

The main objective is to understand how these techniques can be used in conjunction with deep learning and other methods, focusing on the advantages of their use, the methodology used, and proposals, as well as how it has improved computational cost and accuracy [10]. But first, we will analyze why to apply these semantic segmentation and photogrammetry techniques.

## **2 Semantic segmentation and photogrammetry**

Currently, semantic segmentation is essential for understanding image details and provides pixel-level classification by assigning a label (e.g., "tree," "object," "dog"). This technique helps us to interpret the data, understand how to represent it, correctly differentiate objects of various classes, and work with the information within the images to ensure consistency between pixel labels [11]. This segmentation technique is commonly used in computer vision and aerial image analysis, as it allows for accurate analysis of images containing irregular shapes, something that other segmentation techniques have more difficulty with. However, one of the challenges it faces is recognizing the characteristics of different factors, such as image scenes, lighting conditions, and data quality.

These semantic segmentation and photogrammetry techniques information to be extracted from photographs or digital images. In other words, it is used to determine the shape, dimensions, and position of objects and terrain by analyzing photographs. It is also used in various fields because of its accuracy and speed, considering the problems where it is applied for disaster prevention and management and used for geography,



landscape description, coastal studies, archaeology, etc. [12], driven by advances in computer vision and image processing data, provides a cost-effective solution for accurate ecosystem monitoring and land use planning.

With the mentioned, it is necessary to extract the information, as Linder says, considering some geometrical principles: camera, focal length, height mentioned in Fig.1 this relationship is used to obtain equation 1, corresponding ground sample distance (GSD), which allows them to convert pixels to any unit of measurement, thus applying the techniques previously exposed. In this case, from the decimal metric system, the centimeter-pixel ratio is applied, which represents the actual distance on the ground corresponding to the width or length of a pixel in the digital image, allowing accurate calculation of the image scale and reliable measurements. This technique depends on several parameters. The size of the pixel in the image and the characteristics of the camera, such as the resolution, the focal length defined by the camera sensor according to the manufacturer, and the flight altitude defined in the flight plan, are related to ensure the accuracy of the GSD on the ground [13].

In this case, we will focus on Ground Sample Distance (GSD), which allows the conversion of pixels to any unit of measurement, thus applying the techniques described above. In this case, the centimeter-to-pixel ratio is applied using a photogrammetric technique called Ground Sample Distance (GSD). This technique represents the actual distance on the ground corresponding to the width or length of a pixel in the digital image, allowing the image scale to be accurately calculated and reliable measurements to be made. The calculation of the GSD depends on several parameters. The GSD relates the pixel size in the image to camera characteristics such as resolution and focal length as defined by the camera sensor according to the manufacturer, and flight altitude as defined in the flight plan to ensure accuracy on the ground.

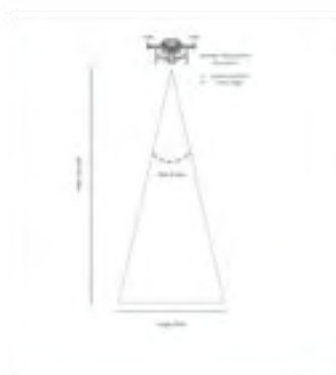


Fig.1 Representation of variables to obtain the GSD

$$GSD = \frac{\text{Pixel size} \times \text{Altitude}}{\text{Focal Length}} \quad (1)$$

It should be noted that the maximum possible GSD for aerial surveys depends on several factors, such as camera exposure interval, blur due to image motion, and altitude. The higher the altitude, the lower the accuracy. It also depends on what the flight is being conducted with. For example, analysis shows that a minimum GSD of 0.86 m is required to detect most aircraft accurately, and that performance decreases at coarser resolutions, indicating that finer GSDs improve the detection of smaller targets [15]

In the next section, show some work that proposes the use of segmentation and photogrammetry in different areas of work and its application, while highlighting the importance of the ground sample distance for the dataset, the methodology, and the characteristics that must meet the images used in the proposed work. It also discusses how these techniques are used to optimize and combine these techniques in different areas in conjunction with deep learning, which facilitates the segmentation[16] and has also improved the accuracy [17].

### 3 Geospatial mapping and analysis

#### 3.1 Guidelines to Compare Semantic Segmentation Maps at Different Resolutions

The use of GSD and semantic segmentation to evaluate the accuracy of models at different spatial resolutions Ayala (2024)[18] proposes to compare maps by integrating pixel-wise metrics at both scene and region levels. The objective is to establish an evaluation process that includes different spatial resolutions and enhances comprehension of the different GSD values applied to building and pool detection problems. This shows that it is possible to optimize the balance between the computational resources and the accuracy of the results.

#### 3.2 Generalized Sparse Convolutional Neural Networks for Semantic Segmentation of Point Clouds Derived from Tri-Stereo Satellite Imagery

Bachhofner (2020)[19] develops a neural network architecture based on U-Net that emphasizes applying point clouds derived from 0.7 m resolution (GSD) images obtained from photogrammetry to approach semantic segmentation using deep learning techniques. The methodology consists of the generation of digital surface models (DSM) and the application of experiments that adjust, median weighting of classes to mitigate information imbalance. Ultimately, the research results indicate that color aggregation optimizes class performance and increases the overall accuracy of the sparse convolutional network. The best performance was achieved with FCN-8s network, and for road classification, a decision tree achieved slightly better accuracy.



## **4 Environment**

### **4.1 VEPL Dataset: A Vegetation Encroachment in Power Line Corridors Dataset for Semantic Segmentation of Drone Aerial Orthomosaics**

Cano-Solis 2023 [20] proposes a method based on the combination of UAV imagery and deep learning for semantic segmentation of vegetation to automate the detection and facilitate the maintenance of power lines, using photogrammetry to generate high-resolution orthomosaics with a Ground Sample Distance (GSD) between 0.9 and 1.3 cm, and methods to increase the number of available examples performed by geometric and spectral augmentation on the original dataset. As a result, this approach facilitates the accurate identification of vegetation in power corridors, allowing for more economical and near real-time monitoring compared to techniques relying on satellite imagery or LiDAR.

### **4.2 Deep Learning Application for Fracture Segmentation Over Outcrop Images From UAV-Based Digital Photogrammetry**

Fractures affect properties of reservoir geologies, so their characterization is crucial for fluid flow modeling in 2021 Junior A[21] proposed that used images captured with drones and processed with digital photogrammetry, the automatic and accurate detection of fracture networks and validate two popular convolutional neural networks (CNNs), SegNet and U-Net, employed consist of image processing with segmentation techniques to identify fractures in outcrops and The results obtained show that both models achieved acceptable values presenting the U-Net presented closer segmented images than the SegNet model, with reduced learning time.

## **5 Town planning**

### **5.1 Cross-city matters: A multimodal remote sensing benchmark dataset for cross-city semantic segmentation using high-resolution domain adaptation networks.**

In the study in 2023, Hong D [8] proposes a method based on HighDAN, which aims to improve the generalization capability in semantic segmentation applied to cities. Of the main limitations are the traditional methods, which are usually designed for specific cases of cities and, therefore, have difficulties being applied in multiple regions. The methodology of the study is based on the use of hyperspectral, multispectral, and SAR images with a GSD of 10, allowing a better discrimination of classes. The results obtained in extensive experiments on C2Seg show that HighDAN outperforms other methods and demonstrate that it can be applied in different regions.

## **5.2 HAGDAVS: Height-Augmented Geo-Located Dataset for Detection and Semantic Segmentation of Vehicles in Drone Aerial Orthomosaics**

This paper explains that semantic segmentation vehicle detection has applications in security, traffic and parking management, urban planning, logistics and transportation, among others. Ballesteros (2022) [22] proposes a method that integrates RGB spectral channel data with the Digital Surface Model (DSM) to obtain an accurate representation of the scene. The main idea is to improve the accuracy of deep learning models by incorporating additional height variables and Ground Sample Distance (GSD) information, which allows a more accurate differentiation between classes, and the methodology developed includes image acquisition and the generation of photogrammetric products. In addition, neural networks are used, and parameters are adjusted to optimize semantic segmentation and vehicle detection. The results of the study show that the fusion of RG-DSM data and the application of deep learning techniques allow for overcoming challenges such as occlusion and the presence of noise, providing a robust solution for vehicle detection, classification, and geo-localization.

## **5.3 Deep learning-based UAV image segmentation and inpainting for generating vehicle-free orthomosaic**

In this work, Park (2022) [23] focuses on transportation infrastructure management and the objective is to eliminate vehicle interference in aerial images. A method based on photogrammetric UAVs is used, using images with a GSD of 0.94 cm/pixel, where deep learning and semantic segmentation techniques are applied to improve the quality of the orthomosaics. The objective is to remove these vehicles from each image individually, using segmentation with the Mask R-CNN model, and then reconstruct the removed areas. The methodology consists of preprocessing the images to avoid the appearance of undesired pixels, ensuring a correct joining of the photographs in the rest of the mosaic.

# **6 Civil Engineering and Architecture**

## **6.1 Semi-autonomous inspection for concrete structures using digital models and a hybrid approach based on deep learning and photogrammetry**

Mirzazade (2023) [24] presents a methodology that uses photogrammetry and deep learning to evaluate deterioration in concrete buildings, including bridges and tunnel linings. The main objective is to utilize photogrammetry to compute essential parameters such as Ground Sampling Distance (GSD) and Field of View (FOV), optimizing image resolution at varying distances. Additionally, convolutional neural networks (CNN) are employed for semantic segmentation and crack detection in the examined surfaces. The results show that this hybrid approach can assist human inspectors in detecting, locating, and quantifying damage in concrete infrastructure.

## **6.2 Semantic segmentation and photogrammetry of crowdsourced images to monitor historic facades**

Lui Z 2022 [25] proposed that combining semantic segmentation and photogrammetry of crowdsourced images can be used to remotely monitor and measure changes in historic building facades, thus reducing the human and financial resources dedicated to on-site inspections comparing neural network architectures DeepLab family and DeeplabV3 integrating photogrammetry to build a model, allowing to measure the expansion of biological growth and experiments show that the selected model achieves an IoU of 66.9% in the segmentation of seven classes, with specific values of 54.6% for vegetation in the one-stage model and 56.2% in the two-stage model and demonstrates that the combination of photogrammetry and semantic segmentation to reduce distortions in the images but with a high computational cost, especially in the optimization of the model and integration with photogrammetry.

## **6.3 Towards Mesh-Based Deep Learning for Semantic Segmentation in Photogrammetry**

In this work, Knott (2021)[6] applies MeshCNN, a deep learning model specifically designed for 3D triangular meshes, to the field of photogrammetry and incorporates photometric features, and the experiments performed show that the inclusion of color information significantly improves the model performance in segmentation tasks. Finally, considering the computational cost and complexity required to optimize the model configuration, performance could be significantly improved by introducing a high-quality benchmark.

## **6.4 Photogrammetric Techniques and Image Segmentation via Machine Learning as Supporting Tools in Paving Asphalt Mixtures Studies**

This work focuses on the study of the formulation asphalt mixtures for the construction of roads in Piemonte (2022) [26], proposing a method based on photogrammetry to obtain information, taking advantage of photogrammetric techniques to analyze displacements and textures in asphalt samples, guaranteeing a GSD of 0.1 mm, and using Machine Learning for automatic segmentation of images, achieving less than 2% error in the classification of the classes of interest. It is important to note that although the use of ML algorithms for semantic segmentation is mentioned.

## **7 Conclusions**

As previously mentioned, it is evident that numerous applications currently exist in different areas, each utilizing photogrammetry and semantic segmentation while proposing distinct methodologies and avenues for enhancement. Some implicitly indicate



that the application of Ground Sample Distance (GSD) to the dataset is a critical variable for assessing the value of a pixel within the image and the precision of object representation. One of the primary obstacles in implementing photogrammetric approaches is the necessity for specialized sensors, which may require distinct instruments for each task, such as customized sensors or specialist cameras for projects. Should the goal be continuously monitored, depending solely on these methods for measurements may prove intricate and expensive. However, if the goal is to compute regions within images, a standard camera can be used by translating pixels into a specific unit of measurement. Using these strategies and considering the camera's characteristics, this methodology can be applied to different contexts, ensuring its relevance across different areas, identifying best practices, finding innovative solutions to their needs, and inspiring new advances in the different areas.

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# Modifying the synthesis of the soft margin optimal hyperplane for support vector machines

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**Abstract.** This paper presents a modification to the Optimal Hyperplane synthesis to improve the linear separating properties of Support Vector Machines. The proposed modification is based on a modified optimization criterion, which is extended to non-linearly separable training data via the Soft Margin Optimal Hyperplane. Performance metrics demonstrate that the proposed modification maximizes the margin during hyperplane construction by increasing the average distance of both training patterns and support vectors, thereby improving classification accuracy.

**Keywords:** Support Vector Machine, Soft Margin Hyperplane, Optimization, Pattern Classification

## 1 Introduction

Pattern classification is the process of assigning objects to predefined categories. This process relies on classifiers: software tools designed for accurate categorization. These classifiers utilize carefully selected input features that effectively represent and distinguish between classes within the input space [1]. Support Vector Machines (SVMs), a prominent supervised learning technique used in a wide range of applications, are recognized for their powerful computational capabilities in classification [2]. Despite their development in the 1990s [3], SVMs continue to be relevant and applicable to diverse problems. SVMs operate on the principle of non-linearly mapping input vectors into a high-dimensional feature space, within which a linear decision surface is constructed. Specific properties of this surface promote strong generalization performance. The foundational concept of SVMs is the identification of an optimal separating hyperplane in the

<https://doi.org/10.61728/AE20254933>



restricted case of linearly separable training data. Subsequently, this approach is generalized to accommodate non-separable data through the introduction of the soft margin hyperplane. They have shown particularly strong performance in areas such as image classification for breast cancer detection, frequently surpassing other methods [4], and have also been successfully combined with artificial neural networks for electrocardiogram heartbeat classification [5]. A comparative analysis by [6] evaluated several machine learning algorithms, including K-Nearest Neighbor, Genetic Algorithms, Decision Tree, Long Short Term Memory networks, and SVMs. Across various problems, SVMs and Long Short Term Memory networks demonstrated superior performance in both qualitative and quantitative assessments.

Recent years have seen the development of novel approaches and modifications aimed at enhancing the performance of SVMs, driven by the continued growth of artificial intelligence and advances in soft computing. One such approach is the Firefly Algorithm-optimized SVM, which has demonstrated improved classification accuracy compared to other methods [7]. A hybrid variable mode decomposition-support vector machine model, coupled with a novel input selection framework, has demonstrated its utility and efficacy for hydrological prediction under climate change scenarios [8]. SVMs integrated with meta-heuristic algorithms have gained prominence, as exemplified by the Hybrid Grey Wolf Optimizer-Improved Sine Cosine Algorithm-enhanced SVM for electroencephalography signal classification. Experimental results demonstrate high classification rates indicating the system's potential for epilepsy classification [9]. Improved Fuzzy Least Squares Twin Support Vector Machine are introduced in [10] and improves upon traditional SVMs for pattern classification by using both structural and empirical risk minimization. This method provides benefits in terms of speed and generalization. Quantum Support Vector Machine Feature selection is an innovative method developed in [11] that merges quantum SVMs with multi-objective genetic algorithms. The goal of this technique is to decrease the dimensionality of data while boosting the effectiveness and precision of machine learning models.

In the present paper, authors propose a modification to the criterion usually utilized to determine optimal separating hyperplane or soft margin optimal hyperplane in synthesis of SVMs, [12]. This modification improves properties of SVMs, for linearly and non-linearly separable patterns. In order to do so, respective optimization process prioritizes to minimize effects corresponding to large classification errors. Furthermore, simulation results for this new optimization criterion are obtained, using Quadratic Programming (QP). This algorithm is tested using the well-known Pima Indians Diabetes database [13].

Paper structure presents in Section 2 the mathematical preliminaries where the construction of Optimal Hyperplane (OH) and Soft Margin Optimal Hyperplane (SMOH) for SVMs are presented. In Section 3, proposed modification for synthesis of optimal hyperplane named PSMOH is introduced and new objective functions to acquire correspond parameter of model are developed. Section 4 presents simulation results employing the Pima Indians Diabetes Database

[13] to compare performance of conventional methods and proposed new one, where distances of patterns with obtained hyperplane for each case and average distance of the support vectors are analyzed. Furthermore, metrics such as precision, sensitivity and specificity for classification are obtained. Finally, Section 5 describes conclusions of proposed PSMOH and future works for particular cases where  $p > 2$ .

## 2 Mathematical Preliminaries

In this section main concepts for construction of OH for simple case of linearly separable patterns are described [3]. Following with a more difficult case of non-linearly separable patterns where the SMOH is introduced.

### 2.1 Optimal Hyperplane of SVM

SVM is commonly used for two class classification problems where a training set is used to train the model. Training set  $O$  of  $M$  training examples can be defined as follows:

$$O = \{(X_1, y_1), (X_2, y_2), \dots, (X_M, y_M)\} \quad (1)$$

where  $X_i \in R^n$  is the input pattern for  $i^{th}$  example and  $y_i \in \{-1, 1\}$  is a class label with  $i = 1, 2, \dots, M$ . Correct classification of data points in a linearly separable case is done by

$$W^T X_i + b \geq 1, \text{ for } y_i = 1 \quad (2)$$

$$W^T X_i + b < -1, \text{ for } y_i = -1 \quad (3)$$

Equations (2) and (3) can be combined into one set of inequalities:

$$y_i(W^T X_i + b) \geq 1, \quad i = 1, 2, \dots, M \quad (4)$$

Signed distance  $G_i$ , between  $X_i$  and the OH, can be calculated by:

$$G(X_i) = G_i = \frac{(W^T X_i + b)}{\|W\|} \quad (5)$$

where  $\|W\|$  is the Euclidean norm of  $W$ . In order to maximize distance between classes and  $W$ , its norm should be minimized satisfying (2) at the same time according to [3].  $W$  norm can be minimized by means of:

$$F(W) = \frac{W^T W}{2} \quad (6)$$

Then, by [3] to determine  $W$  and  $b$  for the OH it is required to minimize (6) satisfying constraint (4). Lagrange multiplier approach can be applied [12,14] as:

$$L(W, b, A) = \frac{W^T W}{2} - \sum_{i=1}^M \alpha_i [y_i (W^T X_i + b) - 1] \quad (7)$$

where  $A = (\alpha_1, \alpha_2, \dots, \alpha_M)$  is the Lagrange multipliers vector subject to  $\alpha_i \geq 0$  for  $i = 1, 2, \dots, M$ . To minimize (7) with respect to  $W$ ,  $b$  and  $A$ , the respective saddle point should be determined by minimizing it with respect to  $W$  and  $b$ , and maximizing it with respect to the Lagrange multipliers. According to [3, 15], after obtaining the respective minimization, then (7) can be transformed to  $LL(A)$  as:

$$LL(A) = L(W, b, A) = \sum_{i=1}^M \alpha_i - \frac{A^T D A}{2} \quad (8)$$

with  $D$  as a positive semi-definite matrix [3], with  $i = 1, 2, \dots, M$  defined by:

$$D = \sum_{i=1}^M \sum_{j=1}^M y_i y_j X_i^T X_j \quad (9)$$

$LL(A)$  depends only on (1) and Lagrange multipliers; therefore, minimization of (6), including constraints (4), is reduced to maximize  $LL(A)$  by means of Lagrange multipliers ( $\alpha_i$ ) satisfying:

$$\sum_{i=1}^M \alpha_i y_i = 0, \quad (10)$$

$$\alpha_i \geq 0 \quad (11)$$

with  $i = 1, 2, \dots, M$ . It is worth noting that (10) is derived from the minimization of (7) with respect to  $b$ . If the solution of  $LL(A)$  exists, then it defines  $W$  and  $b$  for OH, and  $W$  can be formulated as a function of optimal Lagrange multipliers as follows:

$$W = \sum_{i=1}^M \alpha_i y_i X_i \quad (12)$$

with, again  $i = 1, 2, \dots, M$ . Although the OH has seen application in several works, its effectiveness is limited to linearly separable data [1].



## 2.2 Soft Margin Optimal Hyperplane

SMOH is introduced in [15, 16] as an alternative to relax the linearly separable classes condition. The respective constraints are specified as:

$$y_i(W^T X_i + b) \geq 1 - \xi_i, \quad i = 1, 2, \dots, M \quad (13)$$

with  $E = (\xi_1, \xi_2, \dots, \xi_M)^T$  and  $\xi_i \geq 0$  for  $i = 1, 2, \dots, M$ . Search region for (13) is larger than one for (4), allowing to find a better solution for optimization. The  $e_i$  values could be interpreted as deviations from SMOH and they are minimized by means of the following criterion:

$$H = \sum_{i=1}^M e_i^\sigma \quad \text{with} \quad \sigma > 0 \quad (14)$$

In [15], it is also recommended to select  $\sigma$  "sufficiently small". In [16], the following statement is presented: "For computational reasons, however, in this work it is consider the case  $\sigma = 1$ . This case corresponds to the smallest  $\sigma > 0$  that is still computationally simple". For  $\sigma < 1$ , respective optimization problem may not be convex, due to computational complexity. Then  $\sigma = 1$  is the smallest value which can guarantee computational feasibility, and so it is selected for (14).  $W$  and  $b$  for the SMOH can be determined by minimization of (15) with constraint (13)

$$SMF(W) = \frac{W^T W}{2} + C \sum_{i=1}^M e_i \quad (15)$$

where  $C > 0$  is arbitrarily defined according to the problem to be solved. In fact, it is a weighting factor to balance the importance of two components in (15). To solve  $SMF(W)$ , Lagrange multipliers can be applied, whose solution corresponds to the problem:

$$SMLL(A) = \sum_{i=1}^M \alpha_i - \frac{A^T D A}{2} \quad (16)$$

subject to

$$\sum_{i=1}^M \alpha_i y_i = 0 \quad (17)$$

$$0 \leq \alpha_i \leq C \quad (18)$$

where  $D$  is a positive semi-definite matrix given by (9). Maximization of (16), with constraints (17) and (18), is a quadratic programming (QP) problem that can be easily solved [14]. When comparing the two dual maximization problems, OH (8) and SMOH (16), it can be seen that they are very similar; the only differences are the respective constraints (11) and (18).



### 3 Proposed Modification PSMOH

Optimization results depend on the respective criterion, which should be adequate to the problem to be solved. In Fig. 1, the effects of  $e > 0$  on the function  $e^\sigma$  are illustrated for different positive values of  $\sigma$ . There, "a" corresponds to  $e = 0.1$ , "b" to  $e = 0.5$ , "c" to  $e = 0.9$  and "x" to  $e = 1.1$ . From the effects obtained of  $e$  it is evident that for criterion (14), when  $\sigma < 1$ , the effect is similar and independent of the values of  $e$ , and the function  $e^\sigma$  converges to 1. Then, using (14), the optimization process considers small  $e$  values (which do not produce classification errors) in a similar way, which means that (14) is not an adequate criterion for classification.

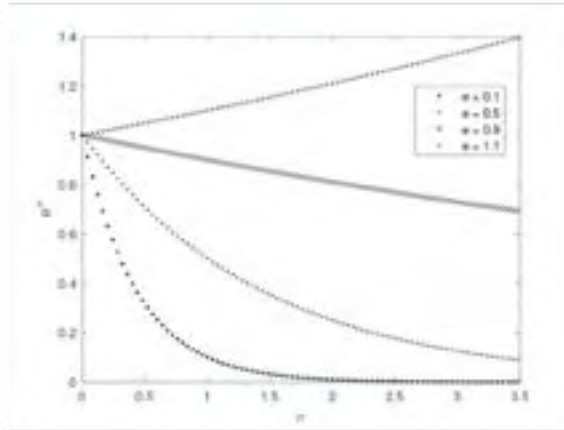


Fig. 1.  $e$  effect on  $e^\sigma$  function.

In order to select a more adequate criterion, its respective optimization process should be in priority minimize the effects corresponding to large  $e$  (producing classification errors). In order to do so, the following criterion could be used:

$$K = \sum_{i=1}^M Q_i e_i \quad (19)$$

Now the weight values are defined such that they will be larger for large  $e$  values, and smaller for small ones, as follows:

$$Q_i = e_i^{p-1} \quad (20)$$

for  $i = 1, 2, \dots, M$  and  $p > 1$ . Substituting (20) in (19), the following criterion is obtained:

$$K = \sum_{i=1}^M Q_i e_i = \sum_{i=1}^M e_i^{p-1} e_i = \sum_{i=1}^M e_i^p \quad (21)$$

with  $p > 1$ . From (21), the respective optimization process prioritizes large  $c$  values, which produce classification errors.

In Fig. 1, it is possible to see difference of influences for large values of  $p$  (or  $\sigma$  as described in the figure) and also for small increases of  $c$  when  $p$  is large; hence, the proposed criterion (21) is very different from criterion (14) in [15]. In fact for (21)  $p$  should be big enough; instead of  $\sigma$  small enough as stated in (14). Then,  $\sigma = 1$  (as suggested in [1]) is the maximum value for criterion (14), and  $p = 1$  is the minimum one for criterion (21). Additionally, in [16] it is stated that due to computationally, efficiency  $\sigma = 1$  is the only allowable value for (14). Due to similar considerations, for (21),  $p$  can take any integer value bigger or equal to 1 ( $p \geq 1$ ), its specific value depends on the problem to be solved.

To define the SMOH parameters, on the basis of criterion (21), it is required to minimize the following function, named  $PSMF(W)$ .

$$PSMF(W) = \frac{W^T W}{2} + C \sum_{i=1}^M c_i^p \quad (22)$$

with  $p \geq 1$  and  $C > 0$  where  $C$  is arbitrarily defined according to the problem to be solved. In fact, it is a weighting factor case as it explained for (15). In order to guarantee convexity,  $p$  can be any integer value larger or equal to 1. Considering that  $PSMF(W)$  is convex and (13) depends linearly on  $W, b$  and  $c_i$ , then to solve this minimization problem no negative Lagrange multipliers ( $\alpha$ ) can be applied [3], with the respective function formulated as:

$$PSML(W, b, A) = \frac{W^T W}{2} + C \sum_{i=1}^M c_i^p - \sum_{i=1}^M \alpha_i [y_i (w^T X_i + b) - 1 + c_i] - \sum_{i=1}^M m_i c_i \quad (23)$$

where  $\alpha_i$  are the Lagrange multipliers for (13), and  $m_i$  are the ones for  $c_i > 0$ . To solve (22), with constrains (13), the Lagrange multipliers can be applied, whose solution corresponds to the respective saddle point of (23), obtained by minimizing with respect to  $w, b$  and  $c_i$ , and simultaneously, maximizing with respect to the Lagrange multipliers.

The conditions for the minimum of  $PSML$  (23) are:

$$\frac{\partial PSML}{\partial W} = W - \sum_{i=1}^M \alpha_i y_i X_i = 0 \quad (24)$$

$$\frac{\partial PSML}{\partial b} = - \sum_{i=1}^M \alpha_i y_i = 0 \quad (25)$$

$$\frac{\partial PSML}{\partial c_i} = p C c_i^{p-1} - \alpha_i - m_i = 0 \quad (26)$$

From (24),  $W$  can be obtained as:

$$W = \sum_{i=1}^M \alpha_i y_i X_i = 0 \quad (27)$$

and from (25) the following constraint is defined:

$$\sum_{i=1}^M \alpha_i y_i = 0 \quad (28)$$

According to K uhn-Tucker conditions [3], the optimum point for  $e_i \neq 0$  corresponds to  $m_i = 0$ ; then from (26),  $e_i$  is formulated as:

$$e_i = \frac{\alpha_i}{pC}^{\frac{1}{p-1}} \quad (29)$$

Substituting (27)-(29) in (23), and then transforming it, the following function is obtained:

$$\begin{aligned} PSMLL(A) &= \sum_{i=1}^M \alpha_i - \frac{\Delta^T D A}{2} + \left[ \frac{C}{(pC)^{\frac{p}{p-1}}} - \frac{1}{pC}^{\frac{1}{p-1}} \right] \sum_i^M \alpha_i^{\frac{p}{p-1}} \\ &= \sum_{i=1}^M \alpha_i - \frac{\Delta^T D A}{2} + C(1-p) \sum_i^M \left[ \frac{\alpha_i}{pC} \right]^{\frac{p}{p-1}} \end{aligned} \quad (30)$$

$PSMLL(A)$  depends only on the training examples (1) and the Lagrange multipliers. Hence, the minimization of (22) with constraints (13) is transformed to maximization of  $PSMLL(A)$ , with constraints (11) and (28). The values of the PSMOH parameters can be determined by means of (13), (27) and (29), and the optimal values of the Lagrange multipliers.

In particular, the optimal value for  $b$  is calculated using the following equation:

$$b = \frac{(1 - (\frac{\alpha_i}{pC})^{\frac{p}{p-1}})}{y_i} - W^T X_i \quad (31)$$

In connection with (1), minimizing the functional in (22) includes  $N + M$  variables, whereas its dual (30) requires only  $M$  variables. Considering (32) and  $p = 1$  in (30), hence,

$$\frac{\alpha_i}{C} \leq 1 \quad (32)$$

For  $i = 1, \dots, M$ .

### 3.1 First case of the proposed modification, $p = 1$

Consider the scenario wherein the parameter  $p$  approaches the value of 1 from the right-hand side. In order to prevent the final term of equation (30) from becoming excessively large, it is necessary to:

$$PSMLL_1(A) = \sum_{i=1}^M \alpha_i - \frac{\Delta^T D A}{2} \quad (33)$$

Moreover, constraint (11) must be converted into constraint (18). Consequently, when  $p = 1$ , the dual problem (30) associated with PSMOH simplifies to the dual problem (16) related to SMOH, incorporating constraints (17) and (18), as outlined in references [15, 16].

### 3.2 Second case of the proposed modification, $p = 2$

Considering  $p = 2$  in (30), then:

$$PSMML_2(A) = \sum_{i=1}^M \alpha_i - \frac{A^T(D + \frac{9}{2}I)A}{2} \quad (34)$$

where  $I$  is the identity matrix. The problem to maximize (34) considering restriction (11) and (28) is a typical problem of QP.

### 3.3 Third case of the proposed modification, $p = 3$

Considering  $p = 3$  in (30), then:

$$PSMML_3(A) = \sum_{i=1}^M \alpha_i - \frac{A^T D A}{2} - 2C \sum_{i=1}^M \left[ \frac{\alpha_i}{3C} \right]^{\frac{3}{2}} \quad (35)$$

### 3.4 Forth case of the proposed modification, $p = 4$

In this case  $p = 4$  in (30) resulting:

$$PSMML_4(A) = \sum_i \frac{\alpha_i - A^T D A}{2} - 3C \sum_{i=1}^M \left[ \frac{\alpha_i}{4C} \right]^{\frac{4}{3}} \quad (36)$$

Although Sections 3.3 and 3.4 introduce new functions to be maximized under constraints (11) and (28), they cannot be resolved using QP. In instances where  $p > 2$ , as established in (35) for  $p > 3$  and (36)  $p > 4$  an alternative method must be employed to solve them. For classification problems, the distance between the training examples and OH, SMOH and PS MOH can be calculated using (5). It is easy to see that these distances are different for a diverse vector, except for support ones. Due to this fact, it is very important to compare the Generalized Proximity Measure (GPM) for OH, SMOH and PS MOH.

$$GPM = \frac{1}{M} \sum_{i=1}^M |(G_i)| \quad (37)$$

where  $|(G_i)|$  is the absolute value of  $G_i$ .

## 4 Simulation Results

In this section the proposed modification for identifying the optimal hyperplane (PSMOH) in SVM considering  $p = 2$  with the QP as optimization approach is applied to the Pima Indians Diabetes Database from the UCI Repository of Machine Learning Databases [13] and compared to the obtained results with OH, and SMOH. A dataset of 768 samples with 8 attributes is employed in this

study. These attributes are detailed in Table 1. A class value of 1 indicates a positive test result for diabetes. The class distribution comprises 500 samples classified as negative (class -1) and 268 samples classified as positive (class 1), for a total of 768 samples.

**Table 1.** Attributes of Pima Indians Diabetes Database used for OH, SMOH, and PSMOH methods.

| Number | Attribute                                                         |
|--------|-------------------------------------------------------------------|
| 1      | Number of times pregnant                                          |
| 2      | Plasma glucose concentration (2-hour oral glucose tolerance test) |
| 3      | Diastolic blood pressure (mm Hg)                                  |
| 4      | Triceps skin fold thickness (mm)                                  |
| 5      | 2-hour serum insulin ( $\mu\text{U}/\text{ml}$ )                  |
| 6      | Body mass index (weight in $\text{kg}/\text{m}^2$ )               |
| 7      | Diabetes pedigree function                                        |
| 8      | Age (years)                                                       |
| 9      | Class variable (-1,1)                                             |

#### 4.1 Optimization via quadratic programming

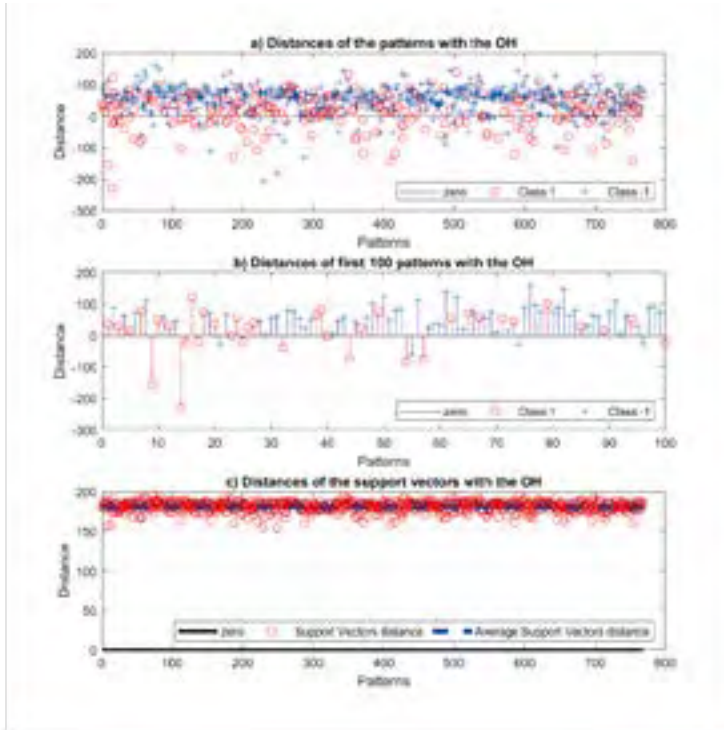
This section presents a comparative performance analysis of the proposed modification, PSMOH, against the OH and SMOH algorithms. Sensitivity, specificity, and accuracy metrics were calculated for each approach. Furthermore, GPM of training patterns and resulting support vectors, along with constructed hyperplane, are presented.

Since PSMOH with  $p = 2$  remains a QP problem, similar to OH and SMOH formulations, all three approaches are evaluated under comparable conditions. Simulation is performed using the following parameters:  $N = 8$  (number of attributes),  $M = 768$  (number of samples), and  $C = 7680$  (soft margin weighting factor). The value of  $C$  is selected empirically, based on the number of training patterns, and used in the construction of both SMOH and PSMOH models.

#### 4.2 Optimal Hyperplane (OH) Analysis

Results obtained for the classification of the training patterns illustrate optimization performance of (8) using the QP. In Fig. 2 a) and b) measured distance of patterns and support vectors with OH illustrates that patterns are quite far from the optimal hyperplane. In this case, OH is not adequate for non-linearly separable data presented in patterns, resulting in low accuracy of classification and all patterns are considered as support vector to construct the hyperplane, which in this case have an average distance between the support vector and hyperplane of around 180 presented in Fig. 2 c).





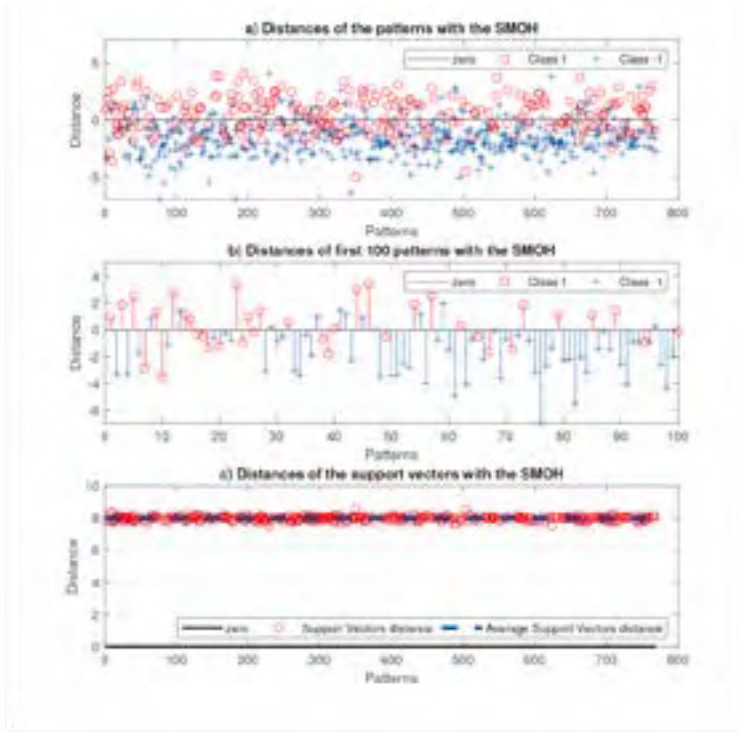
**Fig. 2.** a) Distances between patterns and optimal hyperplane using OH method b) Distances of the first 100 patterns with the OH, c) Distances between support vector machines and optimal hyperplane using OH method.

#### 4.3 Soft Margin Optimal Hyperplane (SMOH) Analysis

SMOH is implemented for classification of training patterns. Contrarily to OH classification accuracy with SMOH method presents better results in performance metrics. In Figure 3 a) and b) the signed distances of all patterns and first 100 patterns with SMOH are described, where values are now smaller compared to the ones presented in the OH analysis. Additionally, support vectors for margin of the SMOH are better selected as the  $C$  parameter is adjusted for training data with distance of support vector with the SMOH and average distance presented in Figure 3 c).

#### 4.4 Proposed Modification of the Optimal Hyperplane (PSMOH) Analysis

The PSMOH method presents better results compared to other two conventional methods. In this case, as described in the beginning of this section,  $p = 2$  is



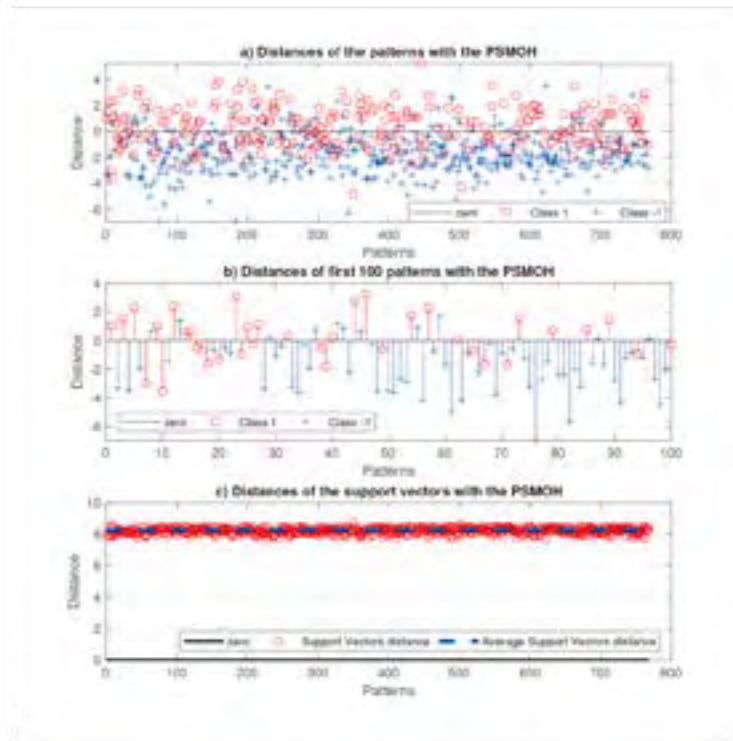
**Fig. 3.** a) Distances between patterns and optimal hyperplane using SMOH method, b) Distances of the first 100 patterns with the SMOH, c) Distances between support vector machines and optimal hyperplane using SMOH method

selected for (22) resulting the following function:

$$PSMF(W) = \frac{W^T W}{2} + C \sum_{i=1}^M \epsilon_i^2 \quad (38)$$

with the dual problem given by the objective function (34). In Figure 4 a) and b) distances of patterns with the PSMOH constructed hyperplane and support vectors distances including their average distances are illustrated. Finally, Figure 4 c) presents distances between support vectors and constructed hyperplane with PSMOH method. In Table 2, PSMOH shows superior classification performance compared to OH and SMOH. Although OH exhibits high sensitivity (69.7761%), it has low specificity (10.8%) and accuracy (31.3802%). In contrast, PSMOH achieves higher accuracy (78.2552%) with balanced sensitivity (59.3280%) and significantly improved specificity (89.20%), even surpassing SMOH in accuracy (77.3437%), sensitivity (59.3280%), and specificity (80%). This improved perfor-

mance is attributed to the construction of a more robust decision hyperplane, as evidenced in Table 3 by reduced GPM and ADSV values (1.6932 and 8.21, respectively) compared to OH (large GPM, ADSV 181.0552) and SMOH (1.6480 and 7.9920). These metrics indicate enhanced margin and class separation for PSMOH, effectively minimizing classification errors in non-linearly separable data.



**Fig. 4.** a) Distances between patterns and optimal hyperplane using PSMOH method. b) Distances of the first 100 patterns with the PSMOH, c) Distances between support vector machines and optimal hyperplane using PSMOH method

## 5 Conclusions

Proposed modification to optimal hyperplane synthesis for support vector machines offers an advantageous alternative due to its expanded restriction domains compared to the OH and SMOH methods. This improvement stems from proposed criterion (21) and extension of restriction domain (4) to encompass

**Table 2.** Classification metrics for the OH, SMOH, and PSMOH methods.

| Method | Sensitivity (%) | Specificity (%) | Accuracy (%) |
|--------|-----------------|-----------------|--------------|
| OH     | 69.7761         | 10.8000         | 31.3802      |
| SMOH   | 59.3280         | 80.0000         | 77.3437      |
| PSMOH  | 57.8359         | 89.2000         | 78.2552      |

**Table 3.** The obtained GPM and ADSV for OH, SMOH, and PSMOH methods.

| Method | GPM     | ADSV     |
|--------|---------|----------|
| OH     | 54.3583 | 181.0556 |
| SMOH   | 1.6480  | 7.9920   |
| PSMOH  | 1.6032  | 8.2144   |

that of (13), leading to improved global optimal computing. PSMOH exhibits enhanced classification accuracy due to maximized margin during hyperplane construction, achieved by increasing the average distance of training patterns and support vectors. This superior performance and generalization, compared to OH and SMOH, results from its optimized criterion, prioritizing minimization of significant classification errors and margin maximization. Future work will explore the  $p > 2$  cases using alternative optimization algorithms. Genetic and bio-inspired algorithms, which have demonstrated efficacy in minimizing and maximizing complex objective functions (as exemplified in (35) and (36)), will be considered. These investigations will encompass further functions, including potential special cases of the PSMOH method and analysis with the addition of kernels functions to enhance the classification performance of non-linearly separable data.

## 6 Note added

Initial analysis of this novel method has been conducted by Dr. Evgen Shelomov, whose untimely passing occurred in November 2011. This paper extends his initial analysis of the synthesis and explores its potential application to diverse areas, including pattern classification.

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# Results on finite-time teleoperation of robotic systems

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**Abstract.** A bilateral teleoperation system comprises a network of two manipulators, with the primary objective of achieving position synchronization between them. This paper proposes a novel continuous-time finite-time (FT) controller to solve the problem of bilateral teleoperation for a class of fully-actuated Euler-Lagrange (EL) systems in joint space. For this, the control law is designed to ensure global asymptotic stability (GAS) and then, finite-time stability (FTS) through a homogeneous approximation of negative degree. To handle the external forces that arise from environmental interactions, it is assumed that these forces define passive velocity-to-force maps, enabling the proof of bounded position errors and velocities. The resulting controller is an easy-to-implement proportional plus damping injection (P+d) scheme with a gravity cancellation term. Experimental results with a teleoperation system composed of two robotic manipulators with six Degrees-of-Freedom (DoF) are presented to validate the performance of the proposed scheme.

**Keywords:** Finite-time control · Euler-Lagrange systems · Robotics.

## 1 Introduction

A bilateral teleoperation system consists of the interconnection of a local and a remote manipulator, where the interaction of external forces should be considered [3]. As it is typically described, a human operator interacts with the local manipulator to change its position, then, this interaction is transmitted to the remote manipulator in order to mimic the movements of the local. The result of this collaboration, is to extend the capabilities of the operator to control the behavior of a remote manipulator in order to execute task in another location, which is considered prone to environmental disturbances.

To this day, teleoperation system have been of particular interest in engineering due to its large amount of applications [10, 15], with notable success in the medical industry [7]. As a result, numerous studies have addressed the teleoperation problem. However, most existing solutions only guarantee asymptotic stability (AS) [1, 9, 11].

<https://doi.org/10.61728/AE20254940>



This work focuses on controllers that achieve finite-time stability (FTS). In addition to their convergence properties, finite-time controllers offer faster transient responses, improved precision, and enhanced robustness compared to conventional asymptotic controllers [5]; These advantages make finite-time controllers particularly appealing for teleoperation systems, motivating the development of novel control strategies to leverage these benefits.

Current FT solutions are mostly based in discontinuous controllers, in particular, the sliding-mode technique: among these works it is possible to find controllers that only ensure FT convergence to a vicinity of the origin [6, 16], while solutions that achieve global FT convergence are not that common [14, 17]; in any case, the main disadvantage of these controllers is the chattering effect that ends to deteriorate the systems actuator due to its aggressive control law [12]. Solutions using a continuous-time control law are found in [8, 18], but again, they only ensure FT convergence to a vicinity of the origin.

This paper presents a continuous-time control solution that ensures global finite-time convergence. The proposed controller combines a proportional term for position error, a damping injection term, and gravity compensation to cancel gravitational effects. Under the assumption that the remote environment and the human operator define passive velocity-to-force maps, it is demonstrated that while external forces act on the system, the position error between the local and remote manipulators, as well as their velocities, remain bounded. On the other hand, in the absence of external forces, both the position error and the velocities converge to zero in finite-time. To test the performance of the controller, it is presented experimental results from a teleoperation system composed of two Kinova<sup>®</sup> robots with six DoF, furthermore, it is also presented a comparison against a similar asymptotic scheme.

## 2 Foundations

This article uses the following *notation*:

- $\mathbb{R} := (-\infty, \infty)$ ;  $\mathbb{R}_{\geq 0} := [0, \infty)$ ;  $\mathbb{N} := \{1, 2, 3, \dots\}$ ; and  $\bar{n} := \{1, 2, \dots, n\}$  for all  $n \in \mathbb{N}$ .
- For  $x \in \mathbb{R}$ ,  $|x|$  is its absolute value. For  $\mathbf{x} \in \mathbb{R}^m$  :  $m \in \mathbb{N}$ ,  $\|\mathbf{x}\|$  refers to the Euclidean norm.
- For all  $\delta \in \mathbb{R}_{>0}$ ,  $B_\delta := \{\mathbf{x} \in \mathbb{R}^m : \|\mathbf{x}\| < \delta\}$  and  $S_\delta^{m-1} := \{\mathbf{x} \in \mathbb{R}^m : \|\mathbf{x}\| = \delta\}$ , are an open ball and a sphere of dimension  $m - 1$ , respectively, with their center in the origin and a radius of  $\delta$ .
- A function  $\mathbf{f}(t) : \mathbb{R}_{\geq 0} \mapsto \mathbb{R}^m$  is said to be class  $C^k$ , for all  $k \in \mathbb{N}$ , if its derivatives  $\dot{\mathbf{f}}, \ddot{\mathbf{f}}(t), \dots, \mathbf{f}^{(k)}$  exist and are continuous.

For all  $x \in \mathbb{R}$  and  $p \in \mathbb{R}_{>0}$ , we define the function *signed power*  $[x]^p : \mathbb{R} \mapsto \mathbb{R}$  as an odd strictly increasing function  $[x]^p := |x|^p \text{sign}(x)$ , where  $\text{sign}(x)$  is the standard *sign function*. The *signed power* function have the next properties:

*Property 1.* For each  $p \in [0, 1]$ ,  $[x]^p$  is differentiable  $\forall x \neq 0$ ,  $[x]^p \in C^1$  if  $p \in [1, 2]$  and  $[x]^p \in C^2$  if  $p \in (2, \infty)$ .

*Property 2.*  $\partial_x[x]^p = p|x|^{p-1}$  and  $\partial_x|x|^p = p|x|^{p-1}$ ,  $\forall x \neq 0$ .

## 2.1 Finite-time Stability

Consider a dynamic system described by

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}), \quad \mathbf{x}(0) = \mathbf{x}_0 \quad (1)$$

where  $\mathbf{x} \in \mathbb{R}^m$  is the state vector,  $\mathbf{f} : \mathbb{R}^m \mapsto \mathbb{R}^m$  is the continuous vector field associated, and  $m \in \mathbb{N}$ . Assume the origin is the equilibrium point, i.e.  $\mathbf{f}(\mathbf{0}) = \mathbf{0}$ .

**Definition 1.** The origin of (1) is finite-time stable if it is Lyapunov stable and if exists a local-bounded function  $T : B_\delta \mapsto \mathbb{R}_{\geq 0}$  (called the settling-time function) such that for each  $\mathbf{x}_0 \in B_\delta \setminus \{\mathbf{0}\}$ , every solution  $\mathbf{x}(t, \mathbf{x}_0)$  of (1) is defined in  $t \in [0, T(\mathbf{x}_0))$  and  $\mathbf{x}(t, \mathbf{x}_0) = \mathbf{0}$  for all  $t \geq T(\mathbf{x}_0)$ . If  $B_\delta = \mathbb{R}^m$ ,  $\mathbf{x} = \mathbf{0}$  is globally FTS [4, 5].

**Definition 2.** Let's define  $r_i > 0$ ,  $i \in \bar{m}$  as the weights of the elements  $x_i$  of  $\mathbf{x} \in \mathbb{R}^m$ , and the vector of weights  $\mathbf{r} := [r_1, \dots, r_m]^\top \in \mathbb{R}^m$ . Also, it is defined the dilation operator  $\Delta_\epsilon^{\mathbf{r}}$ , such that  $\Delta_\epsilon^{\mathbf{r}} \mathbf{x} := [\epsilon^{r_1} x_1, \dots, \epsilon^{r_m} x_m]^\top$ . A function  $V : \mathbb{R}^m \mapsto \mathbb{R}$  (resp. a vector field  $\mathbf{f} : \mathbb{R}^m \mapsto \mathbb{R}^m$ ) is  $\mathbf{r}$ -homogeneous of degree  $l \in \mathbb{R}$ , or  $(\mathbf{r}, l)$ -homogeneous, if for all  $\epsilon \in \mathbb{R}_{>0}$  and  $\mathbf{x} \in \mathbb{R}^m$  satisfies the equality  $V(\Delta_\epsilon^{\mathbf{r}} \mathbf{x}) = \epsilon^l V(\mathbf{x})$  (resp.,  $\mathbf{f}(\Delta_\epsilon^{\mathbf{r}} \mathbf{x}) = \epsilon^l \Delta_\epsilon^{\mathbf{r}} \mathbf{f}(\mathbf{x})$ ). The system (1) is called  $(\mathbf{r}, l)$ -homogeneous if the vector field  $\mathbf{f}$  is  $(\mathbf{r}, l)$ -homogeneous [2].

**Lemma 1.** Consider the system (1) with  $\mathbf{f}(\mathbf{x}) = \mathbf{f}_H(\mathbf{x}) + \mathbf{f}_{NH}(\mathbf{x})$ . Suppose  $\mathbf{f}_H(\mathbf{x})$  is a continuous vector field  $(\mathbf{r}, l)$ -homogeneous such that  $\mathbf{f}_H(\mathbf{0}) = \mathbf{0}$  is a locally asymptotically stable (AS) equilibrium point of  $\dot{\mathbf{x}} = \mathbf{f}_H(\mathbf{x})$ . Assume  $\mathbf{f}_{NH}(\mathbf{x})$  is a continuous vector field that  $\mathbf{f}_{NH}(\mathbf{0}) = \mathbf{0}$  and the next vanishing condition

$$\lim_{\epsilon \rightarrow 0} \epsilon^{-(l+r_i)} \mathbf{f}_{NH}(\Delta_\epsilon^{\mathbf{r}} \mathbf{x}) = \mathbf{0}$$

is uniformly satisfied with respect to  $\mathbf{x} \in S_\delta^{m-1}$  for  $\delta \in \mathbb{R}_{>0}$  and all  $i \in \bar{m}$ . Then, the origin of (1) is locally AS. Also, if  $l = 0$  and every  $r_i = 1$ , the origin is locally and exponentially stable (ES); and if  $l < 0$ , the origin is FTS [2].

**Lemma 2.** Assume that the system (1) admits an homogeneous approximation of the form  $\dot{\mathbf{x}} = \mathbf{f}_H(\mathbf{x})$  such that the vector field  $\mathbf{f}_H(\mathbf{x})$  is  $(\mathbf{r}, l)$ -homogeneous and  $\mathbf{x} = \mathbf{0}$  is AS. Also, if  $\mathbf{x} = \mathbf{0}$  is globally AS for system (1), then, the origin of (1) is globally AS and locally ES if  $l = 0$  y  $r_i = 1$ ; and it is globally FTS if  $l < 0$ .

**Remark 1.** In the stability proofs, the resulting closed-loop system can be written as (1), and always can be separated into homogeneous and not homogeneous terms. Then,  $\mathbf{f}_H(\mathbf{x})$  always can be found in such a way that the system (1) is converted to  $\dot{\mathbf{x}} = \mathbf{f}_H(\mathbf{x}) + \mathbf{f}_{NH}(\mathbf{x})$ . In this case,  $\mathbf{f}_{NH}(\mathbf{x}) = \mathbf{f}(\mathbf{x}) - \mathbf{f}_H(\mathbf{x})$ , and the vanishing condition is equivalent to  $\lim_{\epsilon \rightarrow 0} \sup_{\mathbf{x} \in S_\delta^{m-1}} \|\epsilon^{-l} (\Delta_\epsilon^{\mathbf{r}})^{-1} \mathbf{f}(\Delta_\epsilon^{\mathbf{r}} \mathbf{x}) - \mathbf{f}_H(\mathbf{x})\| = 0$ .



## 2.2 The Dynamic Model

The local and remote manipulators that constitute the teleoperation system are modeled as a set of rigid links connected in series with  $n$  fully-actuated revolution joints that allow the movement in  $n$  degrees-of-freedom. The Euler-Lagrange equations that describe the dynamic of each manipulator are:

$$\begin{aligned} \mathbf{M}_l(\mathbf{q}_l)\ddot{\mathbf{q}}_l + \mathbf{C}_l(\mathbf{q}_l, \dot{\mathbf{q}}_l)\dot{\mathbf{q}}_l + \nabla_{\mathbf{q}_l}\mathcal{U}_l(\mathbf{q}_l) &= \boldsymbol{\tau}_l + \boldsymbol{\tau}_h, \\ \mathbf{M}_r(\mathbf{q}_r)\ddot{\mathbf{q}}_r + \mathbf{C}_r(\mathbf{q}_r, \dot{\mathbf{q}}_r)\dot{\mathbf{q}}_r + \nabla_{\mathbf{q}_r}\mathcal{U}_r(\mathbf{q}_r) &= \boldsymbol{\tau}_r + \boldsymbol{\tau}_e, \end{aligned} \quad (2)$$

where  $\mathbf{q}_i, \dot{\mathbf{q}}_i$  and  $\ddot{\mathbf{q}}_i \in \mathbb{R}^n$  with  $i \in \{l, r\}$  are the joint position, velocity and acceleration, respectively.  $\mathbf{M}_i(\mathbf{q}_i) \in \mathbb{R}^{n \times n}$  is the inertia matrix,  $\mathbf{C}_i(\mathbf{q}_i, \dot{\mathbf{q}}_i) \in \mathbb{R}^{n \times n}$  the Coriolis and centrifugal forces matrix, defined by the Christoffel symbols of first kind.  $\mathcal{U}_i$  is the potential energy for each manipulator,  $\boldsymbol{\tau}_i \in \mathbb{R}^n$  are the control signals,  $\boldsymbol{\tau}_h \in \mathbb{R}^n$  and  $\boldsymbol{\tau}_e \in \mathbb{R}^n$  are the joints forces caused by the human operator and the environmental interactions, respectively. The previous model has the following properties:

*Property 3.* Exist strictly positive constants  $m_{1i}$  y  $m_{2i}$ , such that  $m_{1i} \leq \mathbf{M}_i(\mathbf{q}_i) \leq m_{2i}$ , for all  $\mathbf{q}_i \in \mathbb{R}^n$  for  $i \in \{l, r\}$ .

*Property 4.* The matrix  $\dot{\mathbf{M}}_i(\mathbf{q}_i) - 2\mathbf{C}_i(\mathbf{q}_i, \dot{\mathbf{q}}_i)$  is skew-symmetric and exist  $L_{ci} > 0$  such that  $\|\mathbf{C}_i(\mathbf{q}_i, \dot{\mathbf{q}}_i)\dot{\mathbf{q}}_i\| \leq L_{ci}\|\dot{\mathbf{q}}_i\|^2$ .

Also, we make the following assumption, which is ubiquitous in the control of teleoperation systems via passivity-based techniques [11].

**Assumption 1.** *The human operator and the environment define passive (velocity to force) maps, this is, there exist  $\kappa_l$  and  $\kappa_r \in \mathbb{R}_{\geq 0}$ , such that:*

$$\int_0^t \dot{\mathbf{q}}_l^\top(\sigma)\boldsymbol{\tau}_h(\sigma)d\sigma \leq \kappa_l, \quad \int_0^t \dot{\mathbf{q}}_r^\top(\sigma)\boldsymbol{\tau}_e(\sigma)d\sigma \leq \kappa_r, \quad (3)$$

for all  $t \geq 0$ .

## 3 The Teleoperation System

### 3.1 Problem Statement

For a teleoperation system define as (2), the objective is to design a controller that ensures that the position error between manipulators and their corresponding velocities remain bounded, i.e.,  $\mathbf{q}_l - \mathbf{q}_r, \dot{\mathbf{q}}_l, \dot{\mathbf{q}}_r \in \mathcal{L}_\infty$ . Then, when this forces vanishes ( $\boldsymbol{\tau}_h = \boldsymbol{\tau}_e = 0$ ), both manipulator must reach a constant consensus position, this is, there exist a constant  $\mathbf{q}_* \in \mathbb{R}^n$ , such that:

$$\lim_{t \rightarrow T_i(\mathbf{q}_i(0), \dot{\mathbf{q}}_i(0))} \mathbf{q}_i(t) = \mathbf{q}_*, \quad \lim_{t \rightarrow T_i(\mathbf{q}_i(0), \dot{\mathbf{q}}_i(0))} |\dot{\mathbf{q}}_i(t)| = 0, \quad (4)$$

where  $i := \{l, r\}$  and  $T_i(\mathbf{q}_i(0), \dot{\mathbf{q}}_i(0)) < \infty$  is a settling-time function.



Considering this, the following control law is proposed:

$$\begin{aligned}\tau_l &= -K_l[\mathbf{q}_l - \mathbf{q}_r]^{p_l} - B_l[\dot{\mathbf{q}}_l]^{p_f} + \nabla_{\mathbf{q}_l} \mathcal{U}_l(\mathbf{q}_l), \\ \tau_r &= -K_r[\mathbf{q}_r - \mathbf{q}_l]^{p_r} - B_r[\dot{\mathbf{q}}_r]^{p_f} + \nabla_{\mathbf{q}_r} \mathcal{U}_r(\mathbf{q}_r),\end{aligned}\quad (5)$$

where  $K_l, K_r \in \mathbb{R}_{>0}$  are the proportional gains;  $B_l, B_r \in \mathbb{R}_{>0}$  are the damping injection gains; and the coefficients  $p_l, p_f \in (0, 1)$  are the key to guarantee FT stability, and are defined as:

$$p_l = \frac{2r_2 - r_1}{r_1}, \quad p_f = \frac{2r_2 - r_1}{r_2}, \quad (6)$$

with  $r_1, r_2 \in \mathbb{R}_{>0}$  satisfying:

$$2r_2 > r_1 > r_2 > 0. \quad (7)$$

With this, the control law (5) solves the finite-time teleoperation problem. Before presenting the proof of this claim, it is important to notice that showing global FT convergence to (4) is equivalent to prove global FTS to:

$$(\mathbf{q}_l - \mathbf{q}_r, \dot{\mathbf{q}}_l, \dot{\mathbf{q}}_r) = (\mathbf{0}, \mathbf{0}, \mathbf{0}). \quad (8)$$

Now, we are ready to present the main result of this work.

**Proposition 1.** *Consider the bilateral teleoperated system (2), set the control law (5) with  $\tau_h$  and  $\tau_e$  meeting Assumption 1, choose  $p_l$  and  $p_f$  as in (6) and (7), then:*

- A. *Position error and velocities remain bounded  $\mathbf{q}_l - \mathbf{q}_r, \dot{\mathbf{q}}_l, \dot{\mathbf{q}}_r \in \mathcal{L}_\infty$ .*
- B. *In addition, if  $\tau_h = 0$  and  $\tau_e = 0$ , then, the equilibrium point (8) is globally FTS.*

*Proof.* Consider the following non-negative function  $\mathcal{V}(t)$ , which is in function of the coordinates of the equilibrium point (8):

$$\begin{aligned}\mathcal{V}(t) &= \frac{1}{2} \dot{\mathbf{q}}_l^\top \mathbf{M}_l \dot{\mathbf{q}}_l + \frac{K_l}{2K_r} \dot{\mathbf{q}}_r^\top \mathbf{M}_r \dot{\mathbf{q}}_r + \frac{K_l}{p_l + 1} (\mathbf{q}_r - \mathbf{q}_l)^\top [\mathbf{q}_l - \mathbf{q}_r]^{p_l} \\ &\quad + \kappa_l + \frac{K_l}{K_r} \kappa_r - \int_0^t \left( \dot{\mathbf{q}}_l^\top(\sigma) \tau_h(\sigma) + \frac{K_l}{K_r} \dot{\mathbf{q}}_r^\top(\sigma) \tau_e(\sigma) \right) d\sigma.\end{aligned}\quad (9)$$

Then, use Property 4 and evaluate (9) along the system trajectories (2):

$$\dot{\mathcal{V}}(t) = -B_l \dot{\mathbf{q}}_l^\top [\dot{\mathbf{q}}_l]^{p_f} - \frac{K_l}{K_r} B_r \dot{\mathbf{q}}_r^\top [\dot{\mathbf{q}}_r]^{p_f} \leq 0. \quad (10)$$

Now, time-integrate  $\dot{\mathcal{V}}(t)$  from 0 to  $t$  and get:

$$\mathcal{V}(t) - \mathcal{V}(0) = - \int_0^t \left( B_l \dot{\mathbf{q}}_l^\top [\dot{\mathbf{q}}_l]^{p_f} + \frac{K_l}{K_r} B_r \dot{\mathbf{q}}_r^\top [\dot{\mathbf{q}}_r]^{p_f} \right) d\sigma, \quad (11)$$

and notice that the term inside the integral in (11) is always non-negative, making possible to find an upper-bound for  $\mathcal{V}(t)$  as:

$$\mathcal{V}(t) \leq \mathcal{V}(0) < \infty,$$

this implies that vectors  $\mathbf{q}_l - \mathbf{q}_r$ ,  $\dot{\mathbf{q}}_l$ ,  $\dot{\mathbf{q}}_r \in \mathcal{L}_\infty$ , proving conclusion A of Proposition 1.

Now, we consider the case of no external forces, for this, take equation (9) with  $\tau_h = 0$  and  $\tau_e = 0$ , and also consider  $\kappa_l = 0$  and  $\kappa_r = 0$ :

$$V(t) = \frac{1}{2} \dot{\mathbf{q}}_l^\top \mathbf{M}_l \dot{\mathbf{q}}_l + \frac{K_l}{2K_r} \dot{\mathbf{q}}_r^\top \mathbf{M}_r \dot{\mathbf{q}}_r + \frac{K_l}{p_d + 1} (\mathbf{q}_r - \mathbf{q}_l)^\top [\mathbf{q}_l - \mathbf{q}_r]^{p_d}, \quad (12)$$

as before, taking the time-derivative of  $V(t)$  leads to the same expression (10). Then, using LaSalle's Invariance Principle we can conclude global AS of (8).

To achieve global FTS it is necessary to prove that the teleoperation system along with the controller admits and homogeneous approximation of negative degree. First, we will express the closed-loop system in a state-space representation  $\Sigma : \dot{\mathbf{x}} = \mathbf{f}(\mathbf{x})$  as follows:

$$\Sigma := \begin{cases} \dot{\tilde{\mathbf{q}}}_l = \dot{\mathbf{q}}_l \\ \dot{\tilde{\mathbf{q}}}_r = \dot{\mathbf{q}}_r \\ \tilde{\mathbf{q}}_l = -\mathbf{M}_l^{-1}(\tilde{\mathbf{q}}_l + \mathbf{q}_*) \left[ K_l [\tilde{\mathbf{q}}_l - \tilde{\mathbf{q}}_r]^{p_d} + B_l [\dot{\tilde{\mathbf{q}}}_l]^{p_f} + C_l (\tilde{\mathbf{q}}_l + \mathbf{q}_*, \dot{\tilde{\mathbf{q}}}_l) \dot{\tilde{\mathbf{q}}}_l \right] \\ \tilde{\mathbf{q}}_r = -\mathbf{M}_r^{-1}(\tilde{\mathbf{q}}_r + \mathbf{q}_*) \left[ K_r [\tilde{\mathbf{q}}_r - \tilde{\mathbf{q}}_l]^{p_d} + B_r [\dot{\tilde{\mathbf{q}}}_r]^{p_f} + C_r (\tilde{\mathbf{q}}_r + \mathbf{q}_*, \dot{\tilde{\mathbf{q}}}_r) \dot{\tilde{\mathbf{q}}}_r \right] \end{cases} \quad (13)$$

where  $\tilde{\mathbf{q}}_l = \mathbf{q}_l - \mathbf{q}_*$  y  $\tilde{\mathbf{q}}_r = \mathbf{q}_r - \mathbf{q}_*$  are the errors between the joint position of each manipulator with respect to the consensus position.

Now, we split  $\mathbf{f}(\mathbf{x})$  into homogeneous and non-homogeneous terms, such that  $\mathbf{f}(\mathbf{x}) = \mathbf{f}_H(\mathbf{x}) + \mathbf{f}_{NH}(\mathbf{x})$ , where  $\mathbf{f}_H(\mathbf{0}) = \mathbf{0}$  must be an AS equilibrium point for system  $\Sigma_H : \dot{\mathbf{x}} = \mathbf{f}_H(\mathbf{x})$  and be homogeneous of negative degree. So, the homogeneous system  $\Sigma_H$  is selected this way:

$$\Sigma_H := \begin{cases} \dot{\tilde{\mathbf{q}}}_l = \dot{\mathbf{q}}_l \\ \dot{\tilde{\mathbf{q}}}_r = \dot{\mathbf{q}}_r \\ \tilde{\mathbf{q}}_l = -\mathbf{M}_l^{-1}(\mathbf{q}_*) \left[ K_l [\tilde{\mathbf{q}}_l - \tilde{\mathbf{q}}_r]^{p_d} + B_l [\dot{\tilde{\mathbf{q}}}_l]^{p_f} \right] \\ \tilde{\mathbf{q}}_r = -\mathbf{M}_r^{-1}(\mathbf{q}_*) \left[ K_r [\tilde{\mathbf{q}}_r - \tilde{\mathbf{q}}_l]^{p_d} + B_r [\dot{\tilde{\mathbf{q}}}_r]^{p_f} \right] \end{cases} \quad (14)$$

and the homogeneity weights  $\mathbf{r} = [r_1 \ r_1 \ r_2 \ r_2]$  are assigned to the vector field. This choice gives that  $\Sigma_H$  is  $(r, r_2 - r_1)$ -homogeneous and, if  $r_1$  and  $r_2$  meet (7), then it is homogeneous of negative degree.

The next step is to prove that  $\mathbf{f}_H(\mathbf{0}) = \mathbf{0}$  is AS, for this, consider the following function, which is the homogeneous version of (9):

$$V_H = \frac{1}{2} \dot{\tilde{\mathbf{q}}}_l^\top \mathbf{M}_l(\mathbf{q}_*) \dot{\tilde{\mathbf{q}}}_l + \frac{K_l}{2K_r} \dot{\tilde{\mathbf{q}}}_r^\top \mathbf{M}_r(\mathbf{q}_*) \dot{\tilde{\mathbf{q}}}_r + \frac{K_l}{p_d + 1} (\mathbf{q}_r - \mathbf{q}_l)^\top [\mathbf{q}_l - \mathbf{q}_r]^{p_d} \quad (15)$$

and its time-derivative gives:

$$\dot{V}_H = -B_l \dot{\tilde{\mathbf{q}}}_l^\top [\dot{\tilde{\mathbf{q}}}_l]^{p_f} - \frac{K_l}{K_r} B_r \dot{\tilde{\mathbf{q}}}_r^\top [\dot{\tilde{\mathbf{q}}}_r]^{p_f} \leq 0 \quad (16)$$

and using LaSalle's Invariance Principle it is proved that (8) is AS for  $\Sigma_H$ .

The last step is to prove that  $\Sigma_H$  is a valid homogeneous approximation of system  $\Sigma$ . For this, it is required that the non-homogeneous terms  $\mathbf{f}_{NH}(\mathbf{x}) = \mathbf{f}(\mathbf{x}) - \mathbf{f}_H(\mathbf{x})$  meet the *vanishing conditions*. To start, notice that the first elements  $\mathbf{f}_{NH1} = 0$  and  $\mathbf{f}_{NH2} = 0$  already satisfy this conditions. Then, using algebra manipulations we can obtain the following expression for  $\mathbf{f}_{NH3}$ :

$$\begin{aligned} \mathbf{f}_{NH3} = & - [\mathbf{M}_l^{-1}(\tilde{\mathbf{q}}_l + \mathbf{q}_*) - \mathbf{M}_l^{-1}(\mathbf{q}_*)] [K_l[\tilde{\mathbf{q}}_l - \tilde{\mathbf{q}}_r]^{p_l} + B_l[\dot{\tilde{\mathbf{q}}}_l]^{p_f}] \\ & - \mathbf{M}_l^{-1}(\tilde{\mathbf{q}}_l + \mathbf{q}_*) \mathbf{C}_l(\tilde{\mathbf{q}}_l + \mathbf{q}_*, \dot{\tilde{\mathbf{q}}}_l) \dot{\tilde{\mathbf{q}}}_l. \end{aligned}$$

To prove that  $\mathbf{f}_{NH3}$  meets the vanishing conditions, we will prove that each element inside it also meets them, starting with the first element:

$$\lim_{\epsilon \rightarrow 0} \frac{\| [\mathbf{M}_l^{-1}(\epsilon^{r_1} \tilde{\mathbf{q}}_l + \mathbf{q}_*) - \mathbf{M}_l^{-1}(\mathbf{q}_*)] [K_l[\epsilon^{r_1} \tilde{\mathbf{q}}_l - \epsilon^{r_1} \tilde{\mathbf{q}}_r]^{p_l} + B_l[\epsilon^{r_2} \dot{\tilde{\mathbf{q}}}_l]^{p_f}] \|}{\epsilon^{2r_2 - r_1}},$$

here, notice that  $K_l[\epsilon^{r_1} \tilde{\mathbf{q}}_l - \epsilon^{r_1} \tilde{\mathbf{q}}_r]^{p_l} = \epsilon^{r_1 p_l} K_l[\tilde{\mathbf{q}}_l - \tilde{\mathbf{q}}_r]^{p_l}$  and  $B_l[\epsilon^{r_2} \dot{\tilde{\mathbf{q}}}_l]^{p_f} = \epsilon^{r_2 p_f} B_l[\dot{\tilde{\mathbf{q}}}_l]^{p_f}$  and, if (6) holds, we get:

$$\begin{aligned} & \lim_{\epsilon \rightarrow 0} \| [\mathbf{M}_l^{-1}(\epsilon^{r_1} \tilde{\mathbf{q}}_l + \mathbf{q}_*) - \mathbf{M}_l^{-1}(\mathbf{q}_*)] [K_l[\tilde{\mathbf{q}}_l - \tilde{\mathbf{q}}_r]^{p_l} + B_l[\dot{\tilde{\mathbf{q}}}_l]^{p_f}] \| \\ & = \| [\mathbf{M}_l^{-1}(\mathbf{q}_*) - \mathbf{M}_l^{-1}(\mathbf{q}_*)] [K_l[\tilde{\mathbf{q}}_l - \tilde{\mathbf{q}}_r]^{p_l} + B_l[\dot{\tilde{\mathbf{q}}}_l]^{p_f}] \| = 0. \end{aligned}$$

Using Property 3 and 4 we can shown that the second term in  $\mathbf{f}_{NH3}$  also vanishes:

$$\begin{aligned} & \lim_{\epsilon \rightarrow 0} \frac{\| \mathbf{M}_l^{-1}(\epsilon^{r_1} \tilde{\mathbf{q}}_l + \mathbf{q}_*) \mathbf{C}_l(\epsilon^{r_1} \tilde{\mathbf{q}}_l + \mathbf{q}_*, \epsilon^{r_2} \dot{\tilde{\mathbf{q}}}_l) \epsilon^{r_2} \dot{\tilde{\mathbf{q}}}_l \|}{\epsilon^{2r_2 - r_1}} \\ & \leq \lim_{\epsilon \rightarrow 0} m_2 L_c \frac{\| \epsilon^{r_2} \dot{\tilde{\mathbf{q}}}_l \|^2}{\epsilon^{2r_2 - r_1}} = m_2 L_c \|\dot{\tilde{\mathbf{q}}}_l\|^2 \lim_{\epsilon \rightarrow 0} \epsilon^{r_1} = 0. \end{aligned}$$

Lastly, it only rest to prove that the non-homogeneous term  $\mathbf{f}_{NH4}$  meets the *vanishing conditions*:

$$\begin{aligned} \mathbf{f}_{NH4} = & - [\mathbf{M}_r^{-1}(\tilde{\mathbf{q}}_r + \mathbf{q}_*) - \mathbf{M}_r^{-1}(\mathbf{q}_*)] [K_r[\tilde{\mathbf{q}}_r - \tilde{\mathbf{q}}_l]^{p_r} + B_r[\dot{\tilde{\mathbf{q}}}_r]^{p_f}] \\ & - \mathbf{M}_r^{-1}(\tilde{\mathbf{q}}_r + \mathbf{q}_*) \mathbf{C}_r(\tilde{\mathbf{q}}_r + \mathbf{q}_*, \dot{\tilde{\mathbf{q}}}_r) \dot{\tilde{\mathbf{q}}}_r \end{aligned}$$

which proof follows the same steps as  $\mathbf{f}_{NH3}$ . With this, it only rest to invoke Lemma 2 to finish the proof of conclusion B and Proposition 1.

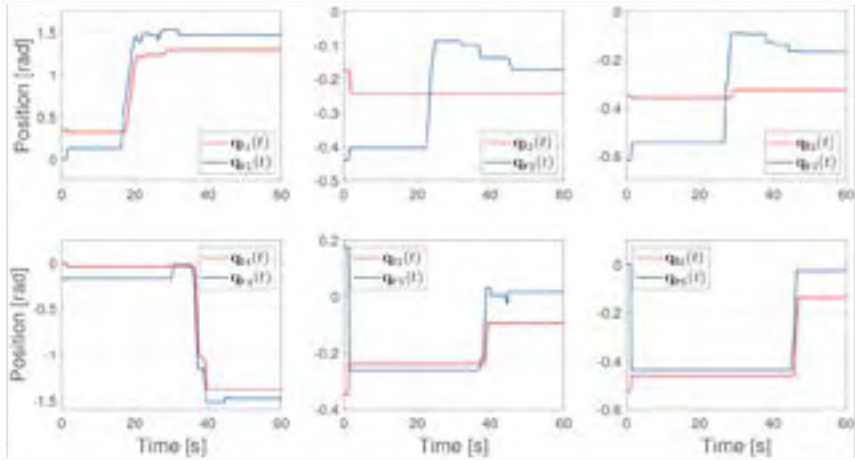
## 4 Experimental results

In this section, we present a comparison between the controller described in Proposition 1 against the well-known linear P+d controller with gravity cancellation [13]. For this, we used a six DoF teleoperation system composed of a local Kinova<sup>®</sup> Gen3 Ultra-lightweight and a remote Kinova<sup>®</sup> Gen3 Lite robotic arm. The experimental procedure consists in the following stages:

- First, both robots start at different positions,  $q_l = [-20, 10, 20, 0, 20, 30] \frac{\pi}{180}$  for the local robot and  $q_r = [0, 25, 35, 10, -10, 0] \frac{\pi}{180}$  for the remote.
- Then, the teleoperation system will try to minimize the position error between the robots, driving them to a consensus position.
- Finally, when the robots reach a common constant position, a human operator will apply external forces on the robots, showing the bounded behavior of the teleoperation system and the tracking capabilities of the controller.

Since the robots are composed of different motor sizes, it was necessary to set individual gains for each joint. The controller's gains selected for the experiments are:  $K_r = [3, 17, 4, 1.5, 1.5, 1.5]$ ,  $B_r = [0.5, 0.3, 0.3, 0.1, 0.2, 0.1]$ ,  $K_l = [15, 15, 15, 15, 15, 15]$ ,  $B_l = [2, 2, 2, 2, 2, 2]$ ,  $r_1 = 1.5$  and  $r_2 = 1$ . For the linear scheme, we used the same gains  $K_l$ ,  $K_r$ ,  $B_l$  and  $B_r$ .

We started by testing the linear scheme. In Figure 1, we present the evolution of the joint position during the test for both manipulator. For the first 20 second of the experiment, it is observed how both robots tried to reach a consensus position, but ended in a steady state error. After 20 seconds, external forces were introduced in the system, showing lack of tracking capabilities for the linear scheme. Then, at 50 seconds the external forces ceased; however, the robots were not able to reach a common position.



**Fig. 1.** Linear scheme; joint position for the local and remote robot.

In Figures 2, 3 and 4, we present a graph of the joint position of the robots and their corresponding velocities during the experiment that use the controller presented in Proposition 1. In the first 10 second, we see that both robots started at different positions and quickly reached a consensus position. After 10 seconds,



we introduced external forces in every joint, where it can be seen that the controller was able to keep their positions synchronized with minimal error. Then, when the forces disappeared at around 40 seconds, both robots reach a consensus position again.

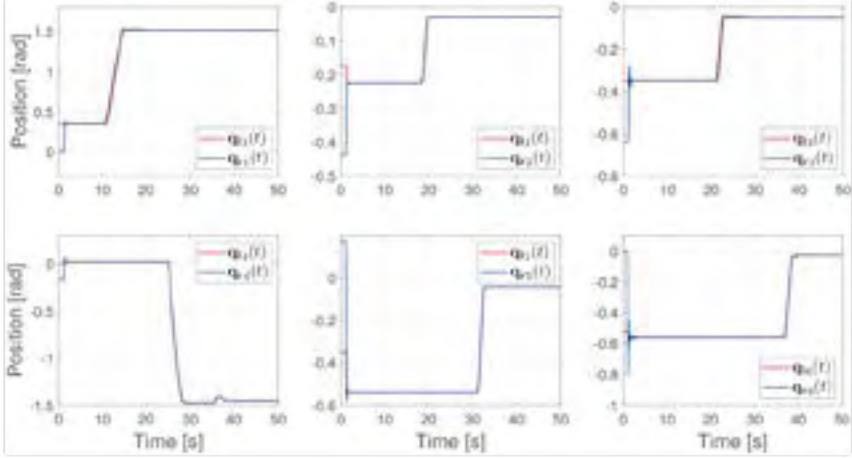


Fig. 2. Finite-time scheme: joint position for the local and remote robot.

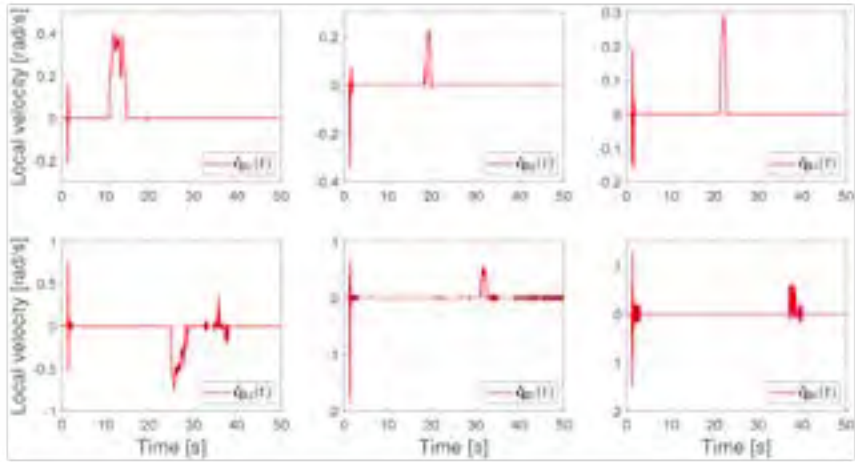
## 5 Conclusions

This article proposed a continuous finite-time controller for bilateral teleoperation of fully actuated Euler-Lagrange systems. The control scheme, based on a proportional plus damping injection (P+d) approach with gravity compensation, ensures global finite-time convergence under the assumption of passive human-operator and remote-environment interactions. The theoretical analysis demonstrates that the position error and velocities remain bounded in the presence of external forces, while converging to zero in finite-time in their absence. Experimental results with a 6-DoF teleoperation system validate the effectiveness of the proposed controller, showcasing improved performance compared to a traditional linear P+d scheme. Future work will address practical challenges, such as the absence of velocity measurements and actuator force limitations.

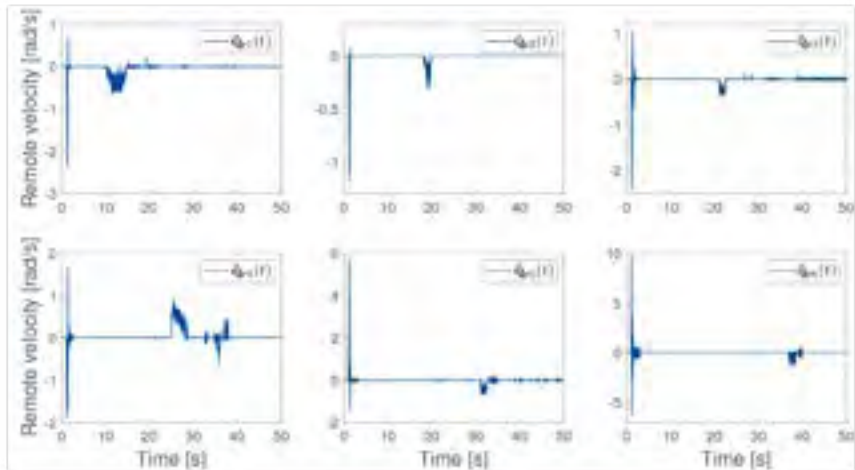
**Acknowledgments.** This work has been supported by the Mexican SECITI Grant CBF2023-2024-1964. The work of L. Torres has been supported by a SECITI Scholarship, Grant 1319340.

**Disclosure of Interests.** The authors have no competing interests to declare that are relevant to the content of this article.





**Fig. 3.** Finite-time scheme: joint velocity for the local robot.



**Fig. 4.** Finite-time scheme: joint velocity for the remote robot.

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# Computational Approach to Investigating Electronic Transport in Graphene Multibarrier Structures

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**Abstract.** Numerical study of electronic transport in graphene-based structures with electrostatic multipotentials. A mathematical model based on the transfer matrix formalism was employed, implemented through an algorithm to calculate the transmission coefficient and conductance for different multibarrier structure in a graphene monolayer. The results show that the number of barriers, the dimensions of the barriers, and the angle of incidence significantly affect the physical properties of graphene. These findings open perspectives for experimentalists to develop electronic devices.

**Keywords:** Electronic transport · Graphene · Superlattice · Numerical study.

## 1 Introduction

Computational methods play a fundamental role in modern physics [1, 2], enabling the simulation, modeling, and analysis of complex systems that are often inaccessible through purely analytical approaches or experimental techniques. These methods are used across various subfields, including condensed matter physics [3], and materials science [4], enabling for instance, both qualitative and quantitative studies of transport properties of materials such as graphene.

Graphene is a two-dimensional material based on carbon atoms which are arranged in an hexagonal crystalline lattice, and behaves as a conductor [5, 6]. It possesses many remarkable and exotic properties, which have been the subject of extensive research. Notable among these are the Klein tunneling phenomenon, the Hall effect, and others [7, 8]. However, controlling electrons in graphene has also been extensively investigated. One of the methods used to this end, involves

<https://doi.org/10.61728/AE20254957>



applying electrostatic potentials or using substrates, which have proven to be key tools for modulating the band structure, redistributing the density of states, and creating energy regions with accumulated energy levels [9–11]. Since the discovery of graphene, it has opened the door to countless possibilities for applications in various fields. Numerous prototypes of transistors, sensors, and batteries have been developed and published [12, 13], etc...

In this study, we have numerically investigated electron transport in multi-barrier structures on a graphene layer using the following formalism: The Dirac equation and transfer matrix along with the Landauer-Büttiker approximation. The transmission coefficient and conductance as a function of electron energy were calculated for three generated configurations of the structure.

## 2 Methodology

The graphene-based structures (see Fig. 1) are described as follows: each structure is characterized by a specific number of barriers with distinct dimensions and heights. In order to generate the  $G_3$  configuration, the structure consists of 4 barriers, each with a width of  $W_B = 148$  Å and a height of  $V_0 = 0.04$  eV. In the next configuration,  $G_4$ , the number of barriers increases to 8, and these barriers are narrower and shorter when compared to those in the  $G_3$  configuration, for instance, with a width of  $W_B = 49$  Å and a height of  $V_0 = 0.02$  eV. Finally, in the last configuration  $G_5$ , the structure consists of 16 barriers with the smallest dimensions, having a width of  $W_B = 16$  Å and a height of  $V_0 = 0.01$  eV.

The top gate (electrostatic barrier) significantly influences the physical properties of graphene. When an external voltage is applied to graphene through a top gate, an electrostatic potential is generated which acts as an electrostatic barrier for the electrons in graphene. The height of this electrostatic barrier is proportional to the applied voltage due to the direct relationship between the generated electrostatic potential and the electric field induced by the voltage. This electrostatic barrier affects the energy of the electrons and specifically, induces a shift in the Dirac cone, as the energy level of the electrons in graphene is modified by the external potential [5, 7].

Because electrons in graphene behave as relativistic mass zero particles, the Dirac equation can be applied to study their transport properties [14, 20]. To this end, the following formula is used:

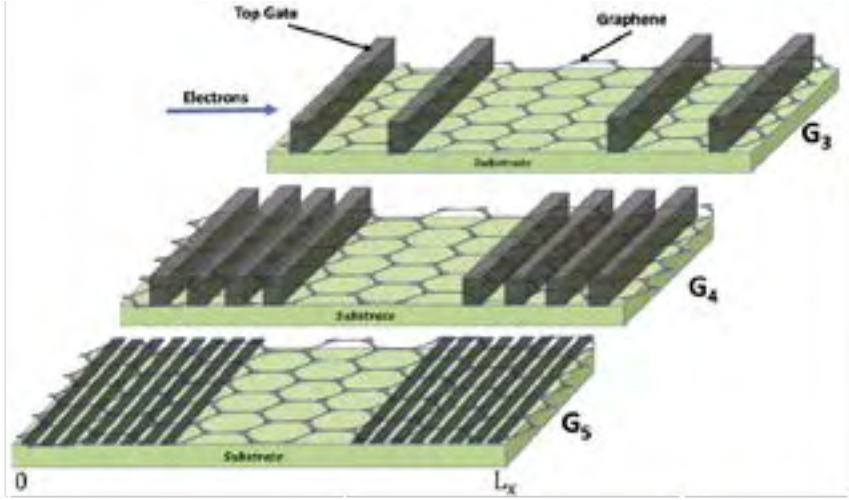
$$[v_F(\boldsymbol{\sigma}_i \cdot \mathbf{p}) + V_0]\psi = E\psi, \quad (1)$$

where  $\boldsymbol{\sigma}_i$  with  $i = x, y, z$  is the  $i^{\text{th}}$  Pauli matrix,  $v_F$  is the Fermi velocity and  $V_0$  voltage applied, and  $\vec{p}$  is the momentum.

By solving Eqn. 1, the eigenfunctions and eigenvalues can be computed. To this end, electrons are being considered in the plane wave approximation, permitting to be represented in the barrier regions as:

$$\psi_{q_j}^{\pm}(x, y) = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ v_j^{\pm} \end{pmatrix} e^{\pm i q_x x \mp i q_y y}, \quad (2)$$





**Fig. 1.** Illustration of the multi-barrier structure based on graphene, whereas  $G_3$ ,  $G_4$ ,  $G_5$  refer to the generated configuration respectively. The electrostatic barriers are represented by top gate.

where  $q_j$  ( $j = 1, 2, \dots$ ) is the wave vector and  $v_j^\pm$  are the wave function components given by:

$$v_j^\pm = \frac{E - V_{0,j}}{\hbar v_F (\pm q_{x,j} - i q_{y,j})}. \quad (3)$$

For the case of well regions (No applied voltage), the wave function can be assumed as:

$$\psi_{k_j}^\pm(x, y) = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ u_j^\pm \end{pmatrix} e^{\pm i k_{x,j} x + i k_{y,j} y}, \quad (4)$$

where  $k_j$  ( $j = 1, 2, \dots$ ) is the wave vector and  $u_j^\pm$  are the wave function components given by:

$$k_j^\pm = \pm \text{sign}(E) e^{\pm i \theta}. \quad (5)$$

The linear dispersion relation corresponding to the barrier regions where the voltage is applied can be cast into:

$$E - V_0 = \pm \hbar v_F q, \quad (6)$$

where  $\pm$  represents electrons and holes, respectively.

Both transmitted ( $A_{trans}$ ) and incident ( $A_{incid}$ ) wave amplitudes were computed using the continuity condition of the wave function at each well-barrier interface, along with the conservation of momentum along the  $y$ -coordinate ( $q_{y,j} = k_y$ ). Noteworthy, these amplitudes are related through the transfer matrix

method, which provides a systematic framework for analyzing wave propagation in such structures [14]:

$$\begin{pmatrix} A_{incid} \\ B_{incid} \end{pmatrix} = M \begin{pmatrix} A_{trans} \\ 0 \end{pmatrix}, \quad (7)$$

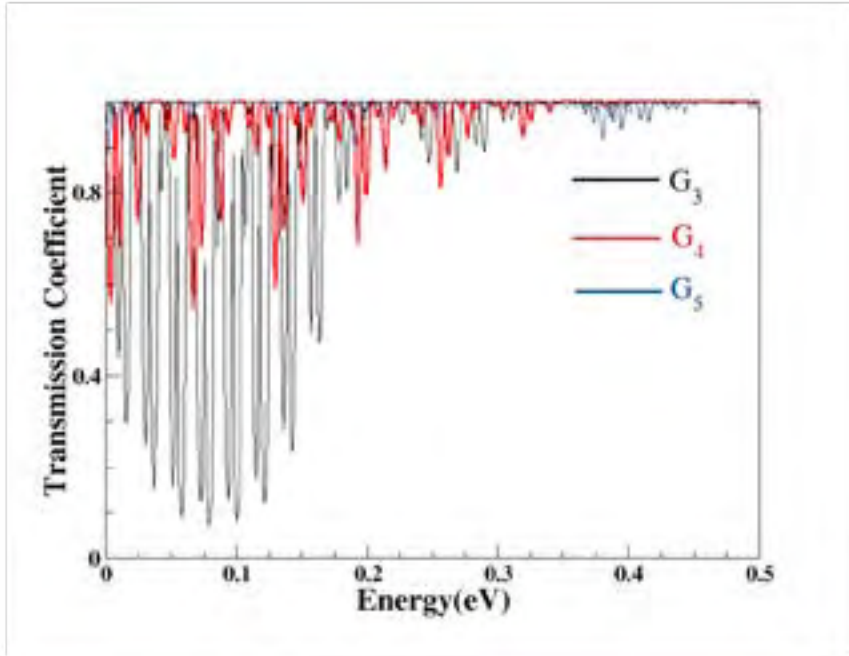
with

$$M(E, \theta) = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}, \quad (8)$$

After computing the transfer matrix, the transmission probability can be directly determined using the following expression:

$$T(E, \theta) = \left| \frac{A_{trans}}{A_{incid}} \right|^2 = \frac{1}{|M_{11}|^2}, \quad (9)$$

where  $M_{11}$  is the first element of the transfer matrix.



**Fig. 2.** Transmission coefficient as a function of the energy of electrons for three different generated configurations  $G_3, G_4, G_5$

The calculation of conductance is performed through the transmission coefficient using the Landauer-Büttiker formalism [18]. For a graphene monolayer,

the conductance can be expressed as:

$$G(E_F^*) = \frac{G}{G_0} = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} E_F^* T(E_F^*, \theta) \cos \theta d\theta, \quad (10)$$

where  $E_F^* = \frac{E_F}{V_0}$  is the Fermi energy scaled to the height of the main barrier  $V_0$ ,  $G_0 = \frac{2e^2 L_y V_0}{h^2 v_F}$  is the conductance fundamental factor,  $L_y$  is the width of the system in the transverse direction  $y$  and  $\theta$  is the angle of incidence of electrons with respect to the propagation along direction  $x$ .

Despite the transmission coefficient for a single barrier can be calculated analytically, for multiple barriers, it is computed numerically using the transfer matrix (TM) formalism [22]. Due to its versatility and simplicity, the TM method is widely used to calculate transport properties in quantum systems. One of its key advantages of the TM is its ability to reduce the problem of computing the transmission and reflection coefficients of complex multi-barrier structures by to solving the continuity equations at the interfaces.

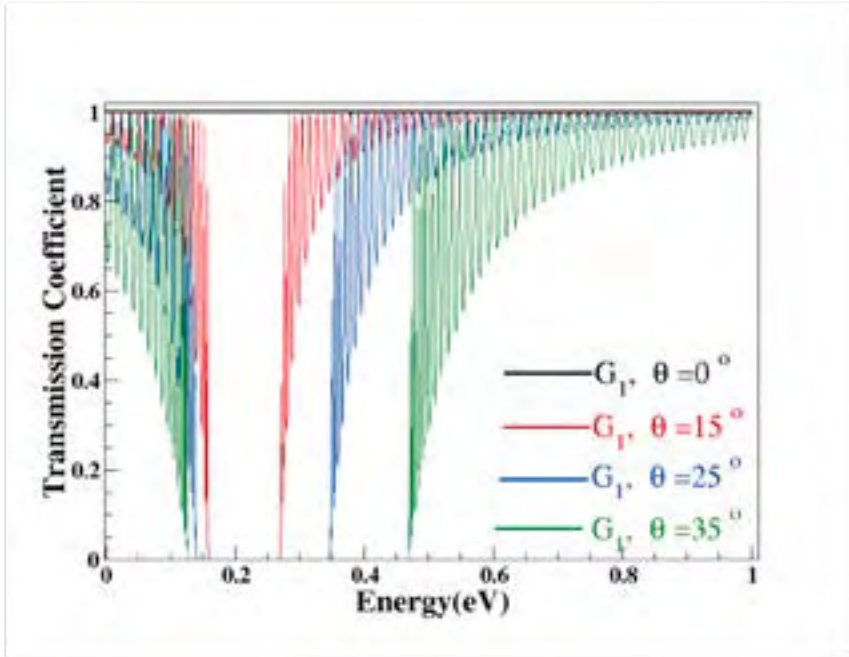
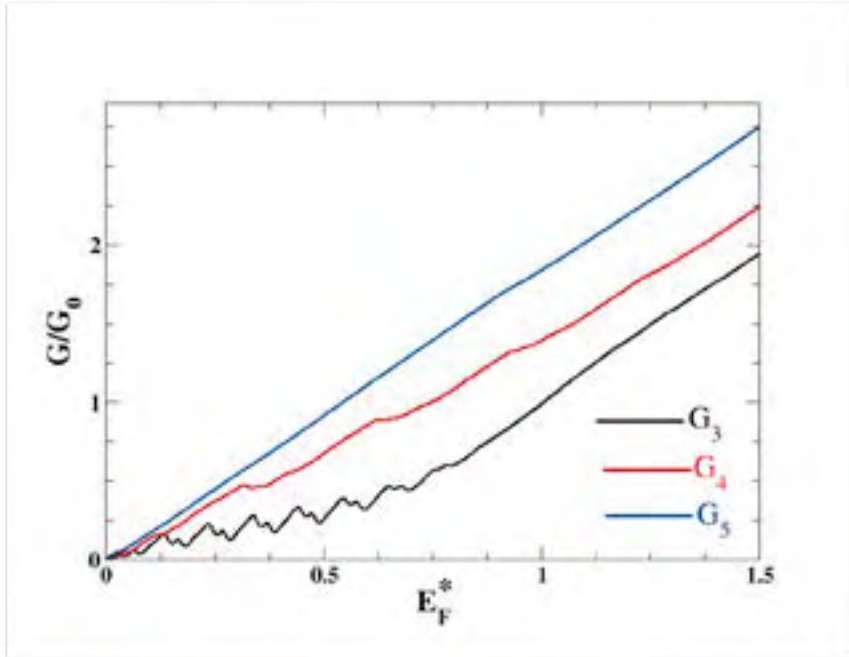


Fig. 3. The transmission coefficient as a function of energy of the first generation with only one barrier, and different angles of incidence.

Furthermore, it is computationally efficient for one-dimensional systems and provides clear physical insights into the scattering and tunneling processes. However, the method has its limitations. It is best suited for systems with one-dimensional potential profiles, and its accuracy decreases for large-scale systems or when dealing with very complex barriers. Such inconveniences result from numerical instabilities associated with the expansion or contraction of waves functions used as a basis to diagonalize the matrix electronic wave equation. From a computational standpoint, the TM may become expensive for systems with a large number of barriers because the size of the matrix product increases and precision errors accumulate. Despite these drawbacks, the method remains a useful tool for studying quantum transport, particularly in systems like graphene or superlattice-based structures.

Considering the above-mentioned comments about the TM formalism, the results are obtained combining an algorithm that simulates the solutions of the Dirac equation and the TM formalism. For instance, this approach is used to calculate the transmission coefficient for different barrier configurations ( $G_3$ ), ( $G_4$ ), and ( $G_5$ ), from where, the conductance is determined, considering the angle of electron incidence  $\theta = 15^\circ$ .



**Fig. 4.** The conductance as a function of Fermi energy scaled to the height of the barrier for generated configurations  $G_3$ ,  $G_4$ , and  $G_5$  respectively.



### 3 Results

The results are presented in Figure 2. The transmission coefficient for the  $G_3$  generation shows the probability of electron transmission in the graphene-based structure, passing through four barriers. The transmission curve reveals energies with both maximum and minimum transmission. Noteworthy, the Klein paradox effect (when a Dirac-like particle is incident to a step potential with its height larger than twice the particle's rest mass) is not observed in this case due to the non-normal angles of incidence. As the generated configurations increases from  $G_3$  to  $G_4$  and  $G_5$ , an increase in the transmission coefficient is observed. In other words, the energies with maximum transmission also increase. This effect can be explained by the progressive reduction in barrier widths, despite the increase in the number of barriers.

The second case of study is presented in Figure 3. In this case, the transmission coefficient is calculated for a first-generated configuration ( $G_1$ ), containing only a single barrier. By varying the angle of incidence of the electron, we observe that for  $\theta = 0^\circ$ , the Klein paradox is clearly evident, with a perfect transmission. In fact, this effect does not depend on the number or width of the barriers. As the angle of incidence increases, a gap emerges where the transmission energy is zero. With further increases in the angle of incidence, this gap expands, suggesting that the gap has some dependence on the angle of incidence.

The third case investigates the conductance for the  $G_3$ ,  $G_4$ , and  $G_5$  generations. Figure 4 shows the conductance as a function of Fermi energy. For the  $G_3$  generation, it is observed that the conductance increases as the energy increases, clearly demonstrating an energy dependence in this case. As the generation increases, meaning more barriers are added, the conductance also increases for larger generations.

### 4 Conclusion

In summary, the electronic properties of graphene were investigated numerically considering three cases of interest. It was demonstrated that the energies associated with maximum transmission increase as the number of barriers increases, considering that the barriers in generations  $G_3$  to  $G_4$  become progressively wider. This is clear from results for the transmission coefficient, which show an increasing trend. Additionally, the transmission coefficient was studied for a single barrier with different electron angles of incidence. It was observed that Klein tunneling is present at angles with normal incidence; however, this phenomenon disappears as the incidence angle increases, a result that has been extensively studied by different groups, as discussed in [21]. Additionally, we calculated the conductance for the three mentioned generated configurations ( $G_3$ ,  $G_4$ , and  $G_5$ ), demonstrating that the conductance increases as the generation increases. A dependence of the conductance on the Fermi energy was also observed. These types of structures serve as a testbed for modulating the band gap, redistributing the density of states, and generating energy regions with an accumulation of energy levels in graphene monolayers. Finally, the TM is a highly useful method, as it



allows complex systems to be represented using simple and combinable matrices. However, it is important to mention that for systems with a large number of matrices barriers, it can become numerically complex, leading to numerical errors that must be addressed in the most effective way possible.

**Acknowledgments.** This work was supported by SECIHTI Postdoctoral Program (POSDOC). We thank UAN for the facility to use the infrastructure.

**Disclosure of Interests.** The authors have no competing interests to declare that are relevant to the content of this article.

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# Convolutional Neural Networks for Robust Time Series Cleaning and Filtering

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**Abstract.** Time series analysis involves identifying patterns, trends, and seasonal variations in data collected at specific intervals, with applications in finance, economics, and weather forecasting. A critical challenge in time series analysis is handling missing data, which can arise from non-response, errors, or equipment malfunctions. Missing data can bias results and reduce accuracy, necessitating effective techniques such as deletion, imputation (e.g., mean, regression, or multiple imputation), and algorithms capable of handling missing values natively. The choice of method depends on the nature of the missing data—Missing Completely at Random (MCAR), Missing at Random (MAR), or Missing Not at Random (MNAR). Advanced techniques like regressive, autoregressive, and vector autoregressive models have been employed for imputation in various domains, including healthcare and environmental monitoring.

This paper introduces a novel Deep Neural Network (DNN) approach for cleaning and filtering time series data, outperforming nine classical techniques such as linear interpolation, spline, and moving mean/median. The proposed DNN, a 1D convolutional autoencoder, processes noisy data directly without requiring preprocessing steps like outlier removal. Evaluated on temperature time series data from a compressor, the DNN achieved a Root Mean Square Error (RMSE) of 6°C, significantly lower than the best classical method (45°C). The DNN's ability to accurately impute missing data and follow trends, even with large gaps, demonstrates its robustness and superiority over traditional methods. This study highlights the potential of DNNs in enhancing time series data analysis and imputation.

**Keywords:** Time Series, Deep Neural Network, Filters-Clean.

## 1 Introduction

Time series refers to data points collected or recorded at specific time intervals. The analysis of them implies identify patterns, trends, and seasonal variations in the data. It is particularly useful in fields like finance, economics, and weather forecasting. The absence of data points in a data set can occur for various reasons, such as non-response, data entry errors, or malfunction equipment. It is essential to handle missing

<https://doi.org/10.61728/AE20254964>



data because it can bias results and reduce the accuracy of analysis. Techniques to handle missing data include:

- **Deletion:** Removing records with missing data, which can be done listwise (removing entire records) or pairwise (removing only the missing data points).
- **Imputation:** Filling in missing data using statistical methods like mean or median imputation, regression imputation, or more advanced techniques like multiple imputation [1–6].
- **Using Algorithms:** Some machine learning algorithms can handle missing data natively.

It is crucial to select the appropriate method to handle missing data based on its nature whether it is Missing Completely at Random (MCAR), Missing at Random (MAR), or Missing Not at Random (MNAR) [4,5].

Time-series techniques are used to fill gaps in data. For example, Murad et al.[5] employed time-dependent covariates in a Cox model with Multiple Imputations by Chained Equations to address missing data related to diabetes and some cancers, showing feasibility only for small groups of contiguous missing data. Regressive, autoregressive, vector autoregressive (VAR), and autoregressive moving average (ARMA) models have also been used for imputation. Bashir and Wei[7] developed a VAR-based algorithm for multivariate time-series missing data, tested on ECG signals with 10% and 20% Missing Completely at Random (MCAR) datasets, requiring stationary time-series. Zhang[3] used a regressive model to impute clinical data in blood pressure and lactate, preserving relationships between missing values and variables. Liu & Molenaar[6] recovered missing electrodermal activity data with a VAR model, fitting it to complete data and examining directional influence between child and therapist. Dunsmaier & Robinson[8] estimated stationary time-series data with ARMA models for pollution levels with minimal missing data. Anava et al.[9] predicted time-series online with AR models, focusing on time-series prediction with missing data. Pedreschi et al.[10] evaluated methods for missing values in gel-based proteomics data, concluding BPCA showed the best results among studied methods. Choong et al.[11] proposed a new algorithm.

In this paper, we propose a novel Deep Neural Network (DNN) approach for cleaning and filtering time series data. To validate the effectiveness of our method, we conduct a comprehensive comparison with nine classical techniques, demonstrating the superior performance of our DNN-based solution.

## 2 Experiment Data Preparation

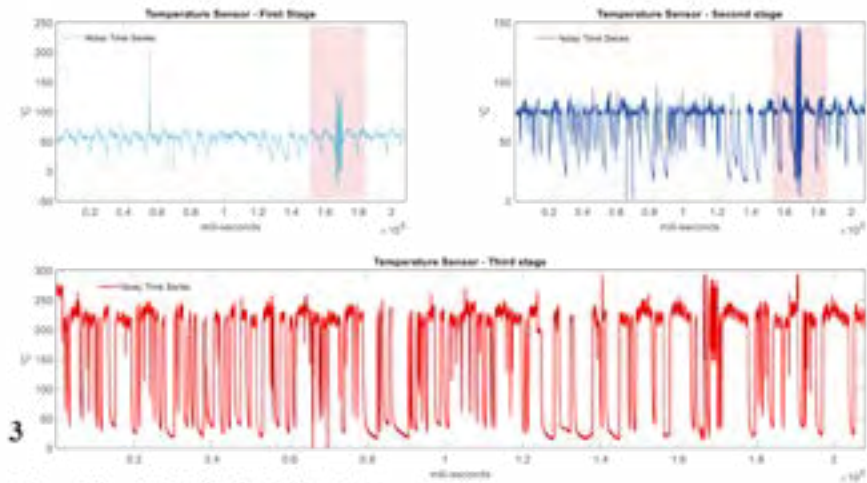
To evaluate the performance of the DNN, we utilized three temperature time series records obtained from a compressor, each comprising 207,887 data points. The time series were contaminated with noise within the range of 165,984 to 170,141, corresponding to 4,158 noisy data points. For the implementation of classical models, the noisy data segments were removed to ensure accurate analysis. In contrast, the DNN



approach does not require the removal of noisy data, showcasing its robustness and ability to handle contaminated time series directly.

Fig. 1 displays the temperature across the various stages of the compressor, with the red rectangle highlighting the noisy data.

Fig. 1. Time Series – Three Stage Compressor Temperatures



### 3.1 Classic Method to Filter Data

The classic method implemented here are listed below:

1. **Previous:** Fills missing values using the last observed value.
2. **Next:** Fills missing values using the next observed value.
3. **Nearest:** Fills missing values using the closest observed value (either previous or next).
4. **Linear Interpolation:** Estimates missing values by drawing a straight line between neighboring points.
5. **Spline:** Uses smooth polynomial functions to interpolate missing values.
6. **PCchip:** Piecewise Cubic Hermite Interpolation—preserves shape and monotonicity of the data.
7. **Makima:** Modified Akima interpolation—smoother than linear but less oscillatory than spline.
8. **Moving Mean:** Fills missing values using the rolling average of nearby data points.
9. **Moving Median:** Fills missing values using the rolling median of nearby data points, reducing outlier impact.

### 3.2 Deep Neural Network

Deep neural networks can be used to classify data and filter out data that does not meet certain criteria and imputation of missing data. For example:

- **Spam detection:** A neural network can classify emails as spam or not spam, automatically filtering out unwanted ones.
- **Content filtering:** On social networks, DNNs can identify and filter inappropriate or malicious content.
- **Imputation of missing data:** GANs can learn to fill in missing values in datasets.
- **Synthetic data generation:** Create clean and realistic data to train other models.

The presenting network is a 1D convolutional autoencoder with an encoder-decoder architecture, specifically designed to process one-dimensional signals. The input consists of a multi-channel sequence, which is passed through three convolutional layers in the encoder. These layers progressively reduce the dimensionality of the signal based on the number of down sampling levels. The decoder then reconstructs the signal using three transposed convolutional layers, gradually increasing the number of filters in each layer until the original structure is restored. A final transposed convolutional layer produces the output, matching the number of channels in the input. This architecture is well-suited for tasks such as noise removal, data compression, and synthetic signal generation. The network architecture is summarized in Table 1.

Table 1. Architecture of the Proposed Deep Neural Network.

| Layer                      | Type                   | Filters/Channels                                     | Filter Fixed |
|----------------------------|------------------------|------------------------------------------------------|--------------|
| Input                      | Sequence input layer   | Number of channels                                   | *            |
| Convolution 1D (Encoder) 1 | Convolution 1 Layer    | $\text{numFilter} * (\text{numDownSamples} + 1 - i)$ | 17           |
| Convolution 1D (Encoder) 2 | Convolution 1 Layer    | $\text{numFilter} * (\text{numDownSamples})$         | 17           |
| Convolution 1D (Encoder) 3 | Convolution 1 Layer    | $\text{numFilter} * (\text{numDownSamples} - 1)$     | 17           |
| Convolution 1D (Decoder) 1 | TransposedConv1D Layer | numFilters                                           | 17           |
| Convolution 1D (Decoder) 2 | TransposedConv1D Layer | $2 * \text{numFilters}$                              | 17           |
| Convolution 1D (Decoder) 3 | TransposedConv1D Layer | $3 * \text{numFilters}$                              | 17           |
| Output                     | TransposedConv1D Layer | numChannels                                          | 17           |

## 4 Results and conclusions

Table 2 presents the Root Mean Square Error (RMSE) in degrees Celsius ( $^{\circ}\text{C}$ ) for classic forecasting methods and Deep Neural Network (DNN) models. The best result among the classic methods is  $45^{\circ}\text{C}$ , achieved by the moving mean technique, while the DNN achieves a significantly lower RMSE of  $6^{\circ}\text{C}$ . These results demonstrate that classic methods are unable to compete with the performance of DNN-based approaches.

**Table 2.** Root Mean Square Error (RMSE) in Degrees Celsius ( $^{\circ}\text{C}$ ) for Classic Forecasting Methods and Deep Neural Network (DNN) Models

| Previous | Next | Nearest | Linear | Spline | PChip | Makima | Moving Mean | Moving Median | DNN |
|----------|------|---------|--------|--------|-------|--------|-------------|---------------|-----|
| 95       | 80   | 85      | 86     | 404    | 86    | 87     | 45          | 46            | 6   |

**Fig. 2.** Imputed Data (Moving Mean) vs. Original Data

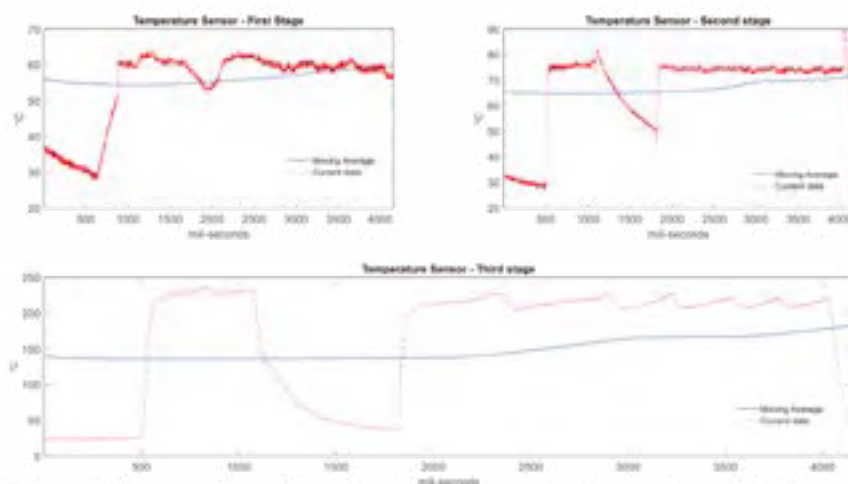
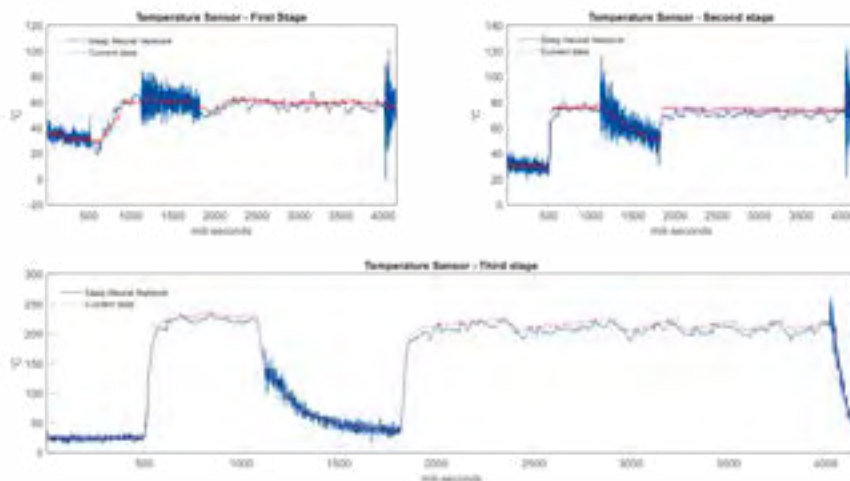


Figure 2 illustrates the results of data imputation using the classic method. To apply this method, outlier values must first be identified and replaced with imputed values. In this case, the moving mean—which yielded the best RMSE among classic methods—was used for imputation. However, due to the large volume of outlier data, the imputed data behaves more like an average, deviating from the original data's characteristics.

In contrast, Figure 3 demonstrates the DNN's ability to accurately follow the data trend, even in the presence of significant data gaps. A key advantage of the DNN over classic methods is its ability to impute data without the need for prior outlier detection. Unlike classic approaches, the DNN does not require preprocessing steps such as z-score normalization or other outlier-cleaning techniques, streamlining the imputation process.

Fig. 3. Imputed Data (DNN) vs. Original Data



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# RFDiffusion performance benchmarking for local high-end workstation computers

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**Abstract.** RFDiffusion is a denoising diffusion model that allows users to create de novo protein structures from tridimensional Gaussian noise. This model is continuously revolutionizing the way we design proteins that are potentially capable of approaching an immense variety of modern day problems such as drug design, drug delivery, residue management, biological manufacturing and vaccine design. However, given that no information related to the computational performance of this tool is provided neither in the original Github repository created by the bakerlab nor in the literature related to it and also the lack of a cloud-based version of this tool makes its use a risky task as there is no way to find out if the local computers specifications of a laboratory will be enough to drive a proper protein design experiment. In order to evaluate the computational performance of RFDiffusion we installed it in a high-end workstation hosted in our laboratory and performed a series of hallucination experiments, these experiments consisted in fixing a lower limit for the protein's length in 100 amino acids and if the computer did not display any kind of error in the terminal then 50 additional aminoacids are added to the lower limit. The results show that the operational limit of RFDiffusion is around the 1600 amino acids in length which can be considered an acceptable limit given that most of proteins do not surpass the 1000 amino acids of length and if they do it is in the form of proteic complexes.

**Keywords:** Hallucination models · Protein design · Artificial Intelligence · Benchmark.

## Introduction

RFDiffusion is a denoising diffusion model that allows the creation of de novo tridimensional protein structures by using a cloud of tridimensional Gaussian noise[5, 19]. RFDiffusion uses the protein folder model RoseTTAFold to predict

<https://doi.org/10.61728/AE20254971>



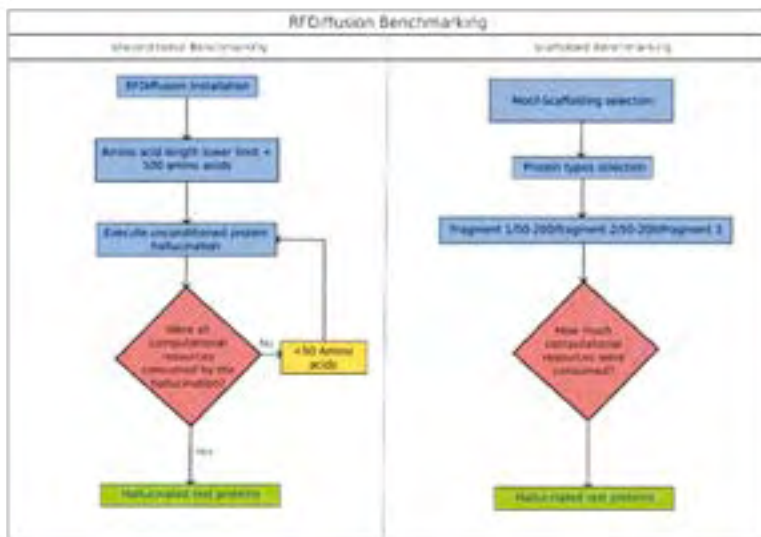
the tridimensional structures for fragments of already known proteins contained inside a database, in turn, these predicted protein fragments are used by the diffusion denoising part of the model as tridimensional templates to reshape the Gaussian noise once and then discarded to generate a new tridimensional template and repeat this process iteratively until a number of iterations automatically determined by RFDiffusion is reached and the protein hallucination process is stopped.[18, 7] With this process RFDiffusion is capable of creating protein structures that do not exist in the nature and that can be designed to approach a wide variety of functions such as drug delivery mechanisms, residue management, biological manufacturing and vaccine design[6]. However; with the computationally expensive costs that are associated with running a generative artificial intelligence model the questions about the availability of local use for RFDiffusion arise and the lack of an online version for this tool only fuel these questions even more. To respond these questions in this work we installed RFDiffusion using the provided instructions in the official GitHub in a workstation computer with a high-end GPU inside and made an experiment where we hallucinated proteins with a iteratively-increasing amino acid chain length to find out where are the limits of the RFDiffusion and if we can generate proteins within those limits.

## Materials & Methods

Given the fact that the generative artificial intelligence models rely heavily on the GPU capabilities of the computer where they are installed we decided that the experiments must be done in a workstation computer as they are more powerful than a conventional computer but more accessible than an entire dedicated server. The Biodigital Innovation Laboratory allowed the access to one of their most powerful high-end workstations in order to make the RFDiffusion benchmarking. The workstation specifications are depicted in the table 1 meanwhile the benchmarking experiment is illustrated in the figure 1.

**Table 1.** Computational specifications. These specifications correspond to the workstation computer used for the benchmarking of the RFDiffusion tool.

| Component | Model                     | Features   |
|-----------|---------------------------|------------|
| CPU       | Intel Xeon(R) Silver      | 40 cores   |
| GPU       | Nvidia GeForce RTX 3090   | 24 GB VRAM |
| RAM       | Kingston 9965757-004.A00G | 270 GB RAM |
| OS        | System76 Pop!_OS          | 22.04 LTS  |



**Fig. 1.** Schematic representation of the steps used for the RFDiffusion performance benchmarking. These experiments are intended to find the quantity of amino acids where RFDiffusion is no longer capable to generate hallucinated proteins due to a lack of available computational resources and also see the quantity of resources consumed when the hallucination process takes fragments of an already known protein structure as templates.

## 1 RFDiffusion Installation

We installed the RFDiffusion tool by using the instructions contained inside the official GitHub (<https://github.com/RosettaCommons/RFDiffusion>) provided by the bakerlab.

Summarizing the contents of the instructions we first cloned the RFDiffusion repository into our test workstation. Consequently we downloaded all of the 8 necessary model weights to run this tool properly. Later we set up a conda environment to contain the SE(3) transformer that RFDiffusion requires to work. Finally, via the command terminal we activated such environment and downloaded the actual SE(3) transformer into the test computer by using Python pip.

## 2 Lower limit definition

The lower limit for the hallucination experiment was determined by reading the original RFDiffusion paper where the authors stated that the tool was capable to hallucinate small proteins with a length of 100 aminoacids successfully.

## 3 Unconditioned benchmarking

With the tool installed in the test computer we proceeded to activate the conda environment that contains the SE(3) transformer and executed the following command lines into the Linux terminal:

```
./scripts/run_inference.py 'contigmap,contigs=[i-i]'  
inference.output_prefix=test_outputs/test  
inference.num_designs=1
```

Where  $i$  is the length of the amino acid chain to hallucinate, in this case the starting point was fixed to 100 amino acids. Given that RFDiffusion hallucinates unconditionated proteins with a length that varies randomly within a defined interval we set both ends of the interval to be the same number (that's why in contig map appears an  $[i-i]$ ), with this we ensure that the hallucinated proteins will have the same increasing length.

Now, as mentioned before this hallucination experiment is iterative and the condition to pass to the next iteration, in this case, to hallucinate a protein 50 amino acids larger than the previous one is that there must not be any error output in ther command terminal. Not having any kind of error output in the terminal means that the computer has not consumed all of the computational resources available (VRAM) to genereate a new protein, by other hand, if the computer consumes all of the resources available we obtain an error output where the process cannot continue and consequently we define this amino acid length as the operational limits of the tool.

## 4 Scaffolding benchmarking

To test the computational resources consumption of RFDiffusion when a series of protein structures is given to it as templates to hallucinate proteins based on them we downloaded 9 tridimensional structures corresponding to the different types of proteins described on the table 2 from the Protein Data Bank.



**Table 2.** Protein structures and types used for RFDiffusion Scaffolding benchmarking.

| Protein type | PDB ID | Description                      | Selected chain |
|--------------|--------|----------------------------------|----------------|
| Enzyme       | 1BPB   | DNA polymerase $\beta$ [11]      | A              |
| Structural   | 1K6F   | Collagen helices [2]             | A              |
| Signaling    | 1BEN   | Insulin [13]                     | D              |
| Regulatory   | 1AIE   | P53 tumor suppression factor [9] | A              |
| Transport    | 3GOU   | Hemoglobin [17]                  | A              |
| Sensorial    | 1NP7   | Cryptochrome [3]                 | A              |
| Motor        | 1GOJ   | Fast kinesin [14]                | A              |
| Defense      | 1FL5   | Antibody 28B4 [20]               | A              |
| Storage      | 1OVA   | Chicken Albumin [16]             | A              |

Given the fact that almost all of these downloaded structures represent protein complexes we selected only one of their respective chains to make the scaffolding benchmarking by splitting these structures into 3 fragments which are then connected by hallucinated protein fragments with a random length between the 50 and the 200 amino acids.

The conda environment that contains the SE(3) transformer was activated and the following command lines were introduced into the Linux terminal to direct RFDiffusion into using the motif-scaffolding mode:

```

../scripts/run_inference.py
inference.output_prefix=test_outputs/protein_benchmark_1
inference.input_pdb=1bpb.pdb
'contigmap.contigs=[A91-150/50-200/A152-175/50-200/A182-
inference.num_designs=1

../scripts/run_inference.py
inference.output_prefix=test_outputs/protein_benchmark_2
inference.input_pdb=1k6f.pdb
'contigmap.contigs=[A1-10/50-200/A11-20/50-200/A21-29]'
inference.num_designs=1

../scripts/run_inference.py
inference.output_prefix=test_outputs/protein_benchmark_3
inference.input_pdb=1ben.pdb
'contigmap.contigs=[D1-10/50-200/D11-20/50-200/D21-28]'
inference.num_designs=1

../scripts/run_inference.py
inference.output_prefix=test_outputs/protein_benchmark_4
inference.input_pdb=1aie.pdb
'contigmap.contigs=[A326-336/50-200/A337-346/50-200/A347

```

```
inference.num_designs=1

../scripts/run_inference.py
inference.output_prefix=test_outputs/protein_benchmark_5
inference.input_pdb=3gou.pdb
'contigmap.contigs=[A1-40/50-200/A41-80/50-200/A81-121]'
inference.num_designs=1

../scripts/run_inference.py
inference.output_prefix=test_outputs/protein_benchmark_6
inference.input_pdb=1ap7.pdb
'contigmap.contigs=[A1-150/50-200/A151-250/50-200/A251-483]'
inference.num_designs=1

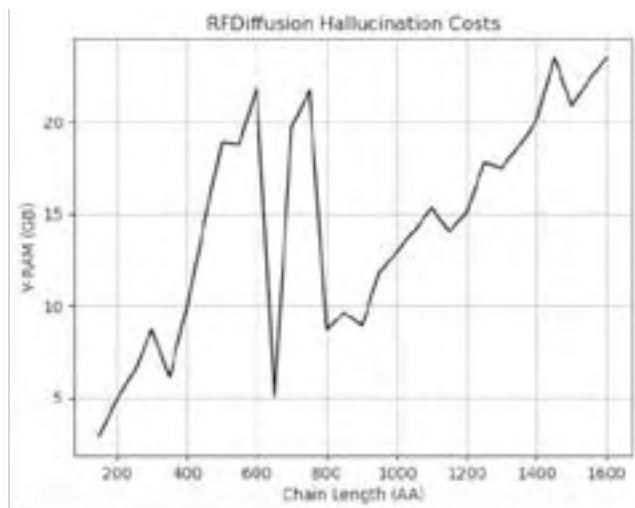
../scripts/run_inference.py
inference.output_prefix=test_outputs/protein_benchmark_7
inference.input_pdb=1goj.pdb
'contigmap.contigs=[A2-120/50-200/A121-250/50-200/A251-355]'
inference.num_designs=1

../scripts/run_inference.py
inference.output_prefix=test_outputs/protein_benchmark_8
inference.input_pdb=1fl5.pdb
'contigmap.contigs=[A1-70/50-200/A71-120/50-200/A121-212]'
inference.num_designs=1

../scripts/run_inference.py
inference.output_prefix=test_outputs/protein_benchmark_9
inference.input_pdb=1ova.pdb
'contigmap.contigs=[A23-150/50-200/A151-293/50-200/A294-391]'
inference.num_designs=1
```

## Results & Discussions

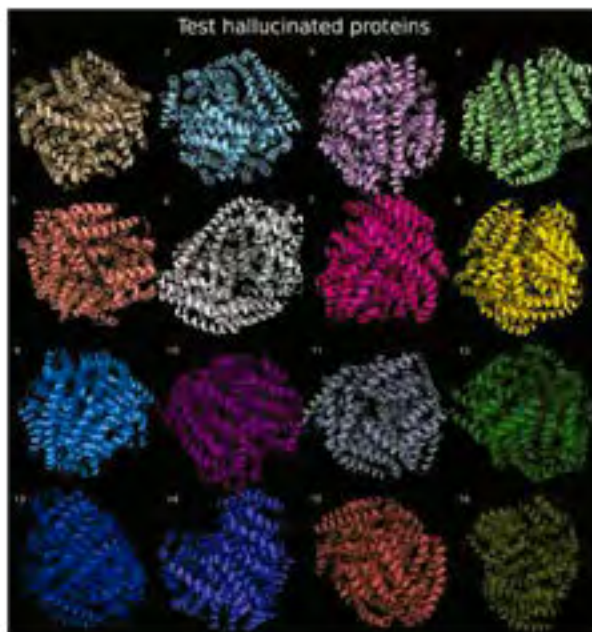
By executing the iterative hallucination experiment obtained an error output and consequently a terminal process abortion related to the lack of available VRAM at the 1600 amino acids of length, thus we estimated the operational limit for protein hallucination with RFDiffusion in this same quantity. As the reader can see in figure 4 there is a linear tendency between the use of graphic memory (VRAM) and the quantity of aminoacids that compose the hallucinated protein (AA→ amino acids), however; we also must recognize the appearance of two consecutive peaks in the consume of VRAM when the hallucinated protein length is between the 600 and 800 amino acids.



**Fig. 2.** Unconditionated benchmarking results graphic. As the reader can see the the consume of graphic memory (VRAM) is linear with respect to the length in amino acids of the protein to hallucinate with the exception of a pair consumption peaks that appear between the 600 and 800 aminoacids.

The explanation to these peaks in the computational costs of hallucinating proteins with these lengths could reside in the fact that RFDiffusion has an intricate mechanism that evaluates the quality of the hallucinated proteins by using the AlphaFold and ESMFold models, also the original RFDiffusion paper mentions that the complexity limit for this evaluation mechanism is around the 600 amino acids and therefore the first consumption peak is justified as internal works of the hallucination tool[18]. Meanwhile, the second consumption peak and its posterior drop in the VRAM usage could be seen as attempts by the tool to evaluate the quality of hallucinated proteins higher than 600 amino acids but given the increasing complexity of the generated protein the model decides to discard the quality evaluation mechanism in order to save computational resources and consequently begins to hallucinate proteins that have a much higher possibility of one: having no biological reliance and two: having no true functions at all.

With the purpose of display what kind of protein structures can hallucinate RFDiffusion when it is near its operational limit we show 16 different hallucinated test proteins in the figure 3.



**Fig. 3.** Test hallucinated proteins. These proteins were hallucinated with a length 50 amino acids below the operational limit of RFDiffusion (1550 amino acids) with the purpose of display the results of a large protein hallucination.

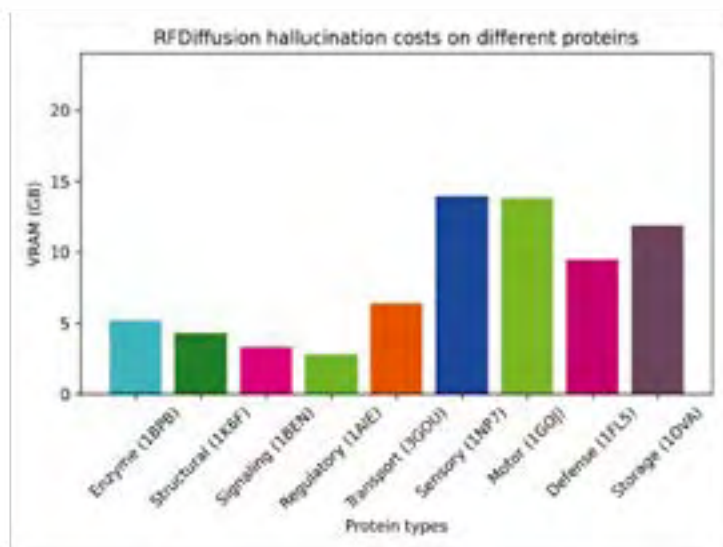
At simple sight all of the hallucinated proteins have a sphere-like tridimensional structure with little variations between them, however; when we take a closer look into them we realize that all of these proteins are composed almost entirely of  $\alpha$ -helices and a only some of them, such as the 8th and the 15th designs, have  $\beta$ -sheets that are well hidden in the interior of the hallucinated proteins.

This is rare given the fact that the  $\alpha$ -helices trend to be composed by hydrophobic amino acids while the  $\beta$ -sheets trend to be composed of hydrophilic aminoacids[12, 4, 15, 1, 8, 10], so finding that the tridimensional structures of the hallucinated proteins are spheres of  $\alpha$ -helices with no entrances to their interior nor any particular socket to accomodate other molecules to them reaffirms the possibility that when we hallucinate large proteins (>600 amino acids) with RFDiffusion the results have no biological sense.

The results of the scaffolded benchmarking of RFDiffusion can be seen in the figure 4. The graphic memory (VRAM) cost of these hallucinations reached almost of 14 GB when using the transport and sensorial proteins as templates but did not reach the 5 GB when the structural, signaling and regulatory pro-



teins were used as templates as well. To explain this situation we propose that the computational cost increase along with the complexity of the protein that is being used as template, given that the proteins that compose the chains selected from the downloaded structures are significantly different in length, 141 aminoacids in the case of chain A selected from the hemoglobin and 355 amino acids in the case of the chain A selected from the fast kinesin, the length of the hallucinated protein fragments made by RFDiffusion approached or already reached the upper limit of 200 amino acids and therefore with more the amino acids to generate the more computational resources were needed in spite of the template used.



**Fig. 4.** Scaffolded benchmarking results graphic. The highest VRAM consumption peaks were registrated while hallucinating proteins using the cryptochrome (sensory) and the kinesin (motor) proteins as templates.

In the figure 5 the resultant protein structures from this scaffolded benchmarking are shown. By comparing these structures with the ones generated in the unconditionated RFDiffusion benchmarking the reader can realise that there is more diversity in the secondary structures present in these scaffolded structures than just  $\alpha$ -helices this is caused by two factors, being the first one that we are taking fragments of already known tridimensional structures that have particular secondary structures distributions and the second one being that the length of the hallucinated protein fragments do not surpass the 600 amino acids threshold reported in the original paper of RFDiffusion and therefore the generated



segments can be evaluated and reshaped in order to have a biological sense with respect to the used template structures used in their design.



**Fig. 5.** Scaffolding benchmark test hallucinated proteins. The already known protein structures used in the hallucination of these proteins are signaled with red while the other colorful parts indicate the structures generated by RFDiffusion during the hallucination.

In order to confirm our suspicions about the results exposed in this work we would need to do a deep-dive into the source code of RFDiffusion, which is a time and resource consuming task and also is not the scope of this work as we just wanted to know if the tool works in a local workstation computer.

## Conclusions

The RFDiffusion model can work properly when installed into a workstation computer that has a high-end GPU and therefore making it the go-to tool to design de novo proteins in the absence of an online version. Even if it does not make this model accessible to the conventional computer users it allows to all

the scientists with access to this type of computers to design their desired proteins locally. The reader is advised to take extreme caution when the proteins hallucinated with RFDiffusion exceed the 600 amino acids in length due to the fact that no quality evaluation mechanism is applied to these proteins due to the increasing complexity and computational costs that this task implies.

However, this problem can be overcome by adopting a protein complex design approach, we mean by this that the user can design small proteins that accomplish an specific step in a process and that do not exceed the 600 amino acids threshold and finally put these hallucinated pieces together to form a greater structure that fulfills the function of interest. With this the true potential of RFDiffusion can be unleashed as a model that can create proteins with a specific function that could not exist naturally while consuming a reasonable quantity of computational resources.

**Acknowledgments.** This paper was possible thanks to the biodigital innovation laboratory that allowed the access to the workstation computers where the experiments were made.

**Disclosure of Interests.** None of the authors of this paper have declared any kind of conflict of interests.

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# Mango Leaf Disease Classification using Deep Learning: A Comprehensive Survey

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**Abstract.** Mango cultivation plays a pivotal role in the development and growth of a country, contributing significantly to its economy and agricultural sector. The cultivation of mangoes not only provides a valuable source of income for farmers but also boosts export opportunities, fostering economic stability. However, the impact of mango leaf diseases poses a serious threat to global mango production. Diseases like anthracnose, powdery mildew, sooty mould, and gall midge can lead to reduced yields, diminished fruit quality, and economic losses for farmers. The timely detection and management of these diseases are crucial for mitigating their adverse effects. Fortunately, advanced technology, especially deep learning, has shown up as an effective ally in the early detection of these diseases. Therefore, the aim of this study is to present an updated survey report on this topic.

**Keywords:** Deep Learning, Mango, CNN, Agriculture, Plant Disease, Leaf Disease, Review

## 1 Introduction

India is the leading mango-producing nation globally, contributing to an estimated 40% of the total mango production. Mango is widely favoured by people around the world due to its remarkable versatility, substantial nutritional content, diverse assortment, delectable flavour, and exceptional aroma. Mango cultivation plays a vital role in global agriculture, serving as a major source of not just the nutrition but income as

<https://doi.org/10.61728/AE20254988>



well as employment. However, Mango plants are susceptible to various diseases [1] that can impact their health and yield. Leaves being the food basis for plants, disease in leaf thereby affects the process of photosynthesis in so doing leading to plant death. The type of disease is identified by the symptoms and leaf area affected, so the rapid and accurate identification of mango leaf diseases is an imperative aspect [2] of agricultural management as it allows for early intervention and deterrence of prevalent infections.

Some of the common diseases affecting mango plants include Anthracnose, Red Rust, Downy Mildew, Sooty Mold, Powdery Mildew, Bacterial Canker, Die Back, Phoma Blight, Alternaria leaf spots or Alternaria leaf Blight, Alternaria leaf spots, Leaf Gall, and many more. The description of the same is depicted in Table 1.

Most of these diseases show up on the leaves of mango trees. They cause problems like spots, weird growth, or changes in color on the leaves. This can affect how the tree grows and produces fruit. Keeping an eye on the leaves is significant to identify these problems early and take care of the trees. As per the research conducted, Anthracnose affects around 39% of mango trees [3]. 23% of trees are harmed by Powdery Mildew whereas Bacterial Canker [3] is a really bad disease that can completely ruin mango harvests, from 10% to even 100%. Therefore, it is rather crucial to understand that, these leaf issues at early stage else it can seriously impact on yield of mangoes. The application area of mango leaf disease identification stretches across innumerable areas of research, agriculture and technology encouraging efficient management of mango orchards for improving the yield as well as for employment. The integration of technology in agriculture continues to evolve, offering innovative solutions for disease management and improved crop yield. In recent years, advancements in computer vision and machine learning (ML), particularly the application of Convolutional Neural Networks (CNNs) [4, 5], Agricultural management [6], IoT and sensor technologies [7], and many more have demonstrated significant promise in automating the classification and identification of plant diseases. The main objective of the survey paper titled "Mango Leaf Disease classification using Convolutional Neural Networks: A survey and comparative study" is to explore and summarize the existing research, on how Convolutional Neural Networks (CNNs) are employed for classifying diseases in mango leaves. Convolutional Neural Networks (CNNs) are the class of ML model specifically designed for analyzing and processing visual data, such as images and videos.

**Table 1.** Some of the common mango leaf disease.

| Disease      | Another Name                   | Disease Symptoms                                                                           |
|--------------|--------------------------------|--------------------------------------------------------------------------------------------|
| Anthracnose  | Colletotrichum gloeosporioides | Leaves with asymmetrical shaped lesions with dark borders further spreading towards fruit. |
| Red Rust     | Cephaleuros Virescens          | Leaves with rusty red spots on its upper surface causing leaf discoloration.               |
| Downy Mildew | Pseudoperonospora              | Leaves with yellow lesions on its                                                          |

|                       |                                           |                                                                                                                                                                               |
|-----------------------|-------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                       | Cubensis                                  | upper surface whereas the lower surface has a downy (furry) growth.                                                                                                           |
| Sooty mold            | Meliola Mangiferae                        | Leaves with black dusty mould (fungus) on the leaf surface causing the plant to completely turn black.                                                                        |
| Powdery Mildew        | Oidium Mangiferae                         | Leaves with white superficial powdery fungal growth causing premature fruit drop.                                                                                             |
| Black                 | Botryodiplodia (Lasiodiplodia) Theobromae | Leaves turn brown and the edge roll up causing the branch dies and leaf fall.                                                                                                 |
| Phoma Blight          | Phoma Glomerata                           | Only on old leaves; Leaves with angular and minute lesion initially, color changes from brown to cinnamon as lesions enlarges causing complete withering.                     |
| Bacterial Canker      | Xanthomonas Campestriis                   | Leaves with numerous lesions combined to form irregular cankerous patches causing leaves to turn yellow and finally leaf drop.                                                |
| Alternaria Leaf spots | Alternaria leaf Blight                    | Leaves with several circular spots causing leaves to turn yellow and finally leaf drop.                                                                                       |
| Leaf Gall             | Eriophyes Leiosoma                        | Leaves with formation of swellings or galls caused by several factors including insects, bacteria or environmental stress causing abnormal swellings or outgrowths on leaves. |

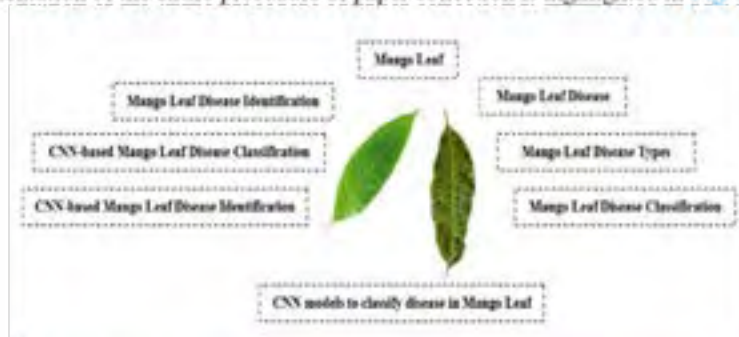
CNNs has emerged as the vital component in computer vision applications showcasing achievements in tasks such as image recognition, object detection and for classifying imagery. CNNs comprises of several layers namely: Convolutional layers, Pooling layers and fully connected layers. The key advantages of CNNs are: Feature Learning, Translation invariance, Parameter sharing, and Spatial Hierarchies among many others. The paper aims to give an overview of the methods and methodologies utilized this context providing valuable insights into diverse CNN based models. Through a study the authors intent to highpoint the efficacy of techniques enabling researchers and professionals in agriculture and computer vision fields to make well informed decisions when choosing a methodology, for classifying mango leaf diseases using CNNs. The review of the literature in this paper comprises of 41 research articles concerned with identification and classification of mango leaf disease using various CNN based models. These papers are enumerated in the reference section and are drawn from the last seven years i.e., for the period 2018-2024. In this paper, all work associated to the CNN based disease identification will be meticulously examined.



The remaining part of this study are structured in the following manner. The research methodology and survey taxonomy are depicted in [Section 2](#). An in-depth literature survey of CNN based models for mango leaf disease classification is illustrated as well as summarized in [Section 3](#). Finally, this paper concludes and recommends some of the probable future research directions, which is available in [Section 4](#).

## 2 Research Methodology and Survey Taxonomy

This review work typically focuses on identifying various research work carried forwarded by numerous researchers using various CNN-based models to identify and further classify the various types of diseases in mango leaves. In order to do so, this work classically encompasses an organized approach to gather, scrutinize, and compare information related to the use of CNNs for the same and furthermore endorse the best CNN model for classifying the disease in mango leaf. The standard search mechanism is employed in order to assemble the research articles from different renowned online search engines namely Google Scholar, ScienceDirect, SpringerLink, IEEE Xplore, ACM Digital Library and many more, which provides access to full-text academic literature across innumerable publication fields. The search was typically performed using some (Not limited to) terminologies as depicted in [Fig. 1](#). The pictorial representation of the entire procedure of paper collection is highlighted in [Fig. 2](#).



**Fig. 1.** Terminologies used to identify research articles related to CNN-based mango leaf disease classification.



**Fig. 2.** Pictorial representation of the research article collection process.

In doing so, all the duplicate and irrelevant research papers were weeded out. Total 57 research articles were finalized that were published by prominent publishers including IEEE, Elsevier, Springer, MDPI, and Taylor & Francis.

Fig. 3(a) shows that year-wise publication count of mango leaf disease detection using CNN models. It can be noticed that publication count is increasing from 2018 to 2025 which reflects the good research interest of this topic. Publication percentage by different publishers like IEEE, Springer, Elsevier, Taylor & Francis, IOP, Inderscience, etc. is presented in Fig. 3(b). Fig. 4(a) highlighting the top three publishers with year wise publication. It can be seen that IEEE has the highest publication count especially in the year of 2023 and 2024. On the other hand, Fig. 4(b) is the demonstration of the top three publishers with publication type. It can be noticed that most of the conference paper (nearly 25) is published by IEEE in the year 2024. Whereas the journal articles are mostly published by Springer and Elsevier.

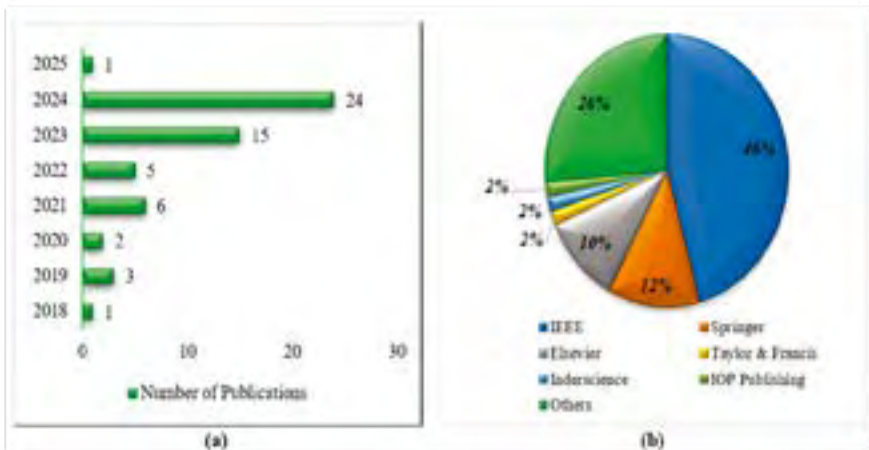
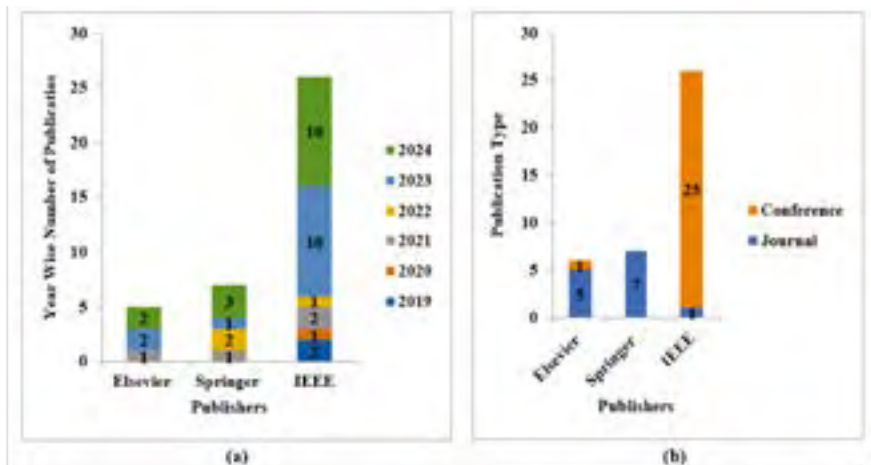


Fig. 3. (a) Year-wise publication count; (b) Publishers with publication percentages.

Table 2 presents the three popular datasets of the mango leaf disease and these are MangoLeafBD, MLDID, and MLDD. The image count of each dataset with class details are presented in that table. Total eight classes are considered here and total 4000, 3000, and 2336 images present in the MangoLeafBD, MLDID, and MLDD dataset, respectively. Most popular is MangoLeafBD dataset with 53 citations according to Google Scholar till 30.01.2025. A significant constraint of this study is that the utilized MangoLeafBD dataset images were not taken in a real-world environment.





**Fig. 4.** (a) Top three publishers with year wise publications; (b) Top three publishers with publication type.

**Table 2.** Three Popular Datasets for Mango Leaf Disease.

| SL.   | Disease Name     | Image Count of MangoLeafBD Dataset [8]<br>YEAR: 2023 | Image Count of MLDID Dataset [9]<br>YEAR: 2024 | Image Count of MLDD Dataset [10]<br>YEAR: 2024 |
|-------|------------------|------------------------------------------------------|------------------------------------------------|------------------------------------------------|
| 1     | Anthracnose      | 500                                                  | 600                                            | 326                                            |
| 2     | Bacterial Canker | 500                                                  | 600                                            | 343                                            |
| 3     | Cutting Weevil   | 500                                                  | ...                                            | 307                                            |
| 4     | Die Back         | 500                                                  | 600                                            | 320                                            |
| 5     | Gall Midge       | 500                                                  | 600                                            | 319                                            |
| 6     | Healthy          | 500                                                  | 600                                            | 250                                            |
| 7     | Powdery Mildew   | 500                                                  | ...                                            | 206                                            |
| 8     | Sooty Mould      | 500                                                  | ...                                            | 265                                            |
| Total |                  | 4000                                                 | 3000                                           | 2336                                           |

### 3 Literature Survey

This section presents the up-to-date literature survey of CNN based mango leaf disease detection and classification field. However, only journal articles are discussed here. A Multilayer CNN was developed by Singh et al. [11] in the year 2019 for the purpose of classifying mango leaves affected with Anthracnose disease. The dataset used for training and testing the MCNN consisted of 1070 real-time images collected at Shri Mata Vaishno Devi University, located in Katra, Jammu and Kashmir, India. The experimental outcome showed that the proposed method attained higher accuracy of 97.93% when compared with other state-of-art approaches namely PSO, SVM, and RBFNN. Saleem et al. in the year 2021 [12] presented a CNN model for segmenting the diseased part of mango leaves and the same was evaluated on the real dataset collected by the mango research institute, Multan, Pakistan. Resizing, contrast enhancement, followed by image augmentation, and ground-truth synthesis of the input image were performed as part of the pre-processing. The suggested approach was used for segmentation. Prior to feature fusion, feature extraction and fusion, and PCA-based feature reduction were completed. Several classifiers were then used to complete the classification process. The experimental conclusion evidently highlighted that the presented model produced a good performance in terms of accuracy of 98.9% when compared with other models namely CNN, MCNN and Manganet. Rajbongshi et al. in 2021 [13] proposed a work that focused on mango leaf disease (Anthracnose, Gall Machi, Powdery Mildew, Redrust) identification using numerous CNN models namely DenseNet201, ResNet50, ResNet152V2, InceptionResNetV2, InceptionV3, and Xception with transfer learning techniques. The presented method was evaluated on real dataset comprising of 1500 images and the result obtained revealed that the different CNN models employed generated high performance with DenseNet201 model outperformed by attaining the high accuracy of 98.00% than other models. Chowdary and Puviarasi in 2022 [14] compared the CNN with Fuzzy means algorithm for the purpose of disease namely Bacteria blight identification in mango leaves making use of 10 images from the seed buzz website. The feature extraction technique involved applying the transform algorithm to the pre-processed data. Subsequently, the diseased leaf images of mango were classified using CNN. The CNN-based system achieved an accuracy of 95.2%, surpassing the 93.5% accuracy achieved by the Fuzz Mean approach. Prabu and Chelliah al. in the year 2022 [15] proposed a CNN framework optimized by crossover-based levy flight distribution (CROLFD) algorithm for the purpose of mango leaf disease identification and classification considering 380 images taken from the farms of Andhra Pradesh, India. Data augmentation technique to prevent overfitting, for feature selection CNN with CROLFD, MobileNetV2 model was considered for learning phase and SVM for disease classification. The experimental result demonstrated that the proposed model generates high accuracy of 94.5% in comparison with other models namely NN with SVM-72.63%, BBDC-92.67%, ML-78.32%, MCNN-92.30%, ANN-80.4% and CNN-84.13%. Sharma et al. in the year 2022 [16] proposed a Deep Learning techniques, CNN for the identification of mango leaf diseases namely Anthracnose, Red rust and Powdery mildew, considering 980 images from Sher-e-Kashmir University of Agriculture Sciences and Technology,

Jammu (SKUAST-J). Different image augmentation methodology was used on the dataset, CNN was further employed on the augmented data for the classification of mango diseased leaves. The experimental results indicated that the presented model successfully detected and identified mango leaf disease with an accuracy of 90.36%. A novel CNN model named as LeafNet was introduced by Rizvee et al. in the year 2023 [17] for sensing 7 different mango leaf diseases by considering 1800 images from MangoLeafBD dataset. The proposed model produced the accuracy of 99.55% compared to other tested models namely AlexNet-99.25%, VGG 16-78.4%. Salamai et al. in the year 2023 [18] elaborated a deep learning approach, visual modulation network that was basically proposed to enhance the diagnosis process of mango diseases considering images from MangoLeafBD dataset (1800 images) and Harumanis Mango Leaves Dataset (1395 images). The proposed work basically focusses on introducing a visual modulation network that would have the ability to identify and learn the visual representation of the diseased leaves through active linear layers. In order to handle the discontinuity of non-overlapped patching, overlapped patching embedding mechanism was employed, visual modulators were used to help the model learn the feature of diseased leaf in the process, and finally features identified were summarized with a global average pooling layer to classify the diseases of mango leaf. The proposed model attained an accuracy of 99.23%. Rani and Gowrishankar [19] deployed five versions of the ConvNeXt model: ConvNeXtBase, ConvNeXt-Large, ConvNeXtXLarge, ConvNeXtTiny, and ConvNeXtSmall, on the MangoLeafBD Dataset for leaf disease diagnosis. Experimental findings demonstrated that larger models often surpassed smaller models, signifying their capacity to learn intricate properties. The ConvNeXtXLarge model had the highest accuracy: 98.79% for mango pests, 100% for mango diseases, and 99.17% for the aggregated dataset. Hari and Singh [20] proposed a lightweight CNN model for detecting defective leaves in banana, guava, and mango was developed. The model introduced the principle of feature reutilization at three distinct stages. The investigation revealed that the approach employs 101,000 parameters and attains a 99.14% accuracy in identifying disease-affected leaves. Furthermore, it surpasses 15 distinct cutting-edge pre-trained CNN models regarding its precision and degree of complexity. Vijay and Pushpalatha [21] developed a hybrid CNN model based on EfficientNetB4 and a Customized CNN model to detect the 8 classes of mango leaf diseases accurately. The proposed hybrid model achieved 93.01% accuracy by outperforming VGG-16 and EfficientNetB4. Hossain et al. [22] employed Vision Transformers (ViTs) for the detection of mango leaf diseases and conducted a comparison with CNN models. They suggested an optimised model utilising a pretrained Data-efficient Image Transformer (DeiT) architecture that attains 99.75% accuracy, surpassing numerous prevalent CNNs. They proved that ViTs can obtain optimal outcomes in fewer epochs than CNNs, resulting in less training duration. They also presented a smartphone application, utilizing the proposed model as a backbone. Bezabh et al. [23] enhanced the efficiency of classification by using preprocessing techniques (noise elimination, segmentation, and data augmentation) and feature extraction utilizing GoogLeNet and VGGNet. The classification model was subsequently developed with fully connected layer classifiers on the extracted features of mango leaf imagery. The ensemble model exhibited



excellent results with a testing accuracy of 99.21%. A comparative analysis of the effectiveness of CNN frameworks, specifically AlexNet, VGG-16, and ResNet-50, for the identification of mango leaf diseases was conducted in [24]. Comparisons were made between these models with and without the application of transfer learning methods. AlexNet achieved a testing accuracy of 94.54% while requiring less training time. ResNet-50 and VGG-16 achieved testing accuracies of 98.56% and 98.26%, respectively. Varma et al. [25] employed many pre-trained deep learning models, including VGG19, InceptionV3, ResNet152V2, DenseNet121, InceptionResNetV2, MobileNetV2, and Xception Models. The InceptionV3 model achieved the highest accuracy of 99.87%, surpassing other models. Singh et al. [26] devised a deep learning model, employing many intricate algorithms, datasets, and validation techniques, utilising the softmax activation function for training. The results indicated that the suggested model achieved an accuracy of 99.76% on the MangoLeafBD dataset. Gautam et al. [27] used an ensemble stacked deep learning model to automatically identify mango leaf diseases. The suggested technique involved initially segmenting the images for the area of greatest interest and subsequently inputting them into a series of diverse deep neural networks. The results of the proposed deep model were combined with a machine learning model to detect leaf disease. Selvakumar and Balasundaram [28] presented an automated method wherein input pictures were enhanced through a contrast enhancement method and subsequently segmented using optimized Fuzzy C Means (FCM). Parameter optimization was conducted using the Deviation-based Updated Dingo Optimizer (D-UDOX). The D-UDOX selected weighted features. The classifier of the Optimized Recurrent Neural Network (WO-RNN) received the weighted features. Deep features were extracted from a segmented image utilizing ResNet-150. The classification utilizing the extracted deep features was executed by WO-RNN. The parameter adjustment was executed utilizing D-UDOX for RNN and ResNet-150. The proposed model attained 96% accuracy and a 93% F1 score, demonstrating superior performance compared to current studies. Veling and Patil [29] created a multi-strategy model for the detection of mango leaf disease. The initial image contrast enhancement was executed using Contrast-Limited Adaptive Histogram Equalization (CLAHE). CNN were utilized for the profound feature extraction, with the features from both inputs concatenated for subsequent processing. The Adaptive Squirrel-Grey Wolf Search Optimization (AS-GWSO) was employed for weighted feature selection to identify the most significant features. Enhanced Long Short-Term Memory (LSTM) is utilized in the classification phase, with parameter optimization achieved through the same AS-GWSO to improve classification accuracy. Mahmud et al. [30] introduced a lightweight DenseNet model for the identification of mango leaf diseases. The findings indicated that the optimized DenseNet architecture (DenseNet78), combined with an appropriate growth rate, adjusted block size, and layer count, achieves maximum accuracy, yielding 99.47% in recognizing healthy and 99.44% in diagnosing different diseases. Vijay and Pushpalatha [31] came up with DVNet, a new kind of deep mutual learning model that combines the best parts of Densenet 121 and VGG19 neural networks. Particle Swarm Optimization (PSO) was used for hyperparameter optimization, a technique for determining optimal values. The suggested framework attains a remarkable accuracy of

94.72% in identifying diseased and healthy leaves. Zhang et al. [32] created a light-weight double branch inverted residual attention network (CBAM-DBIRNet) model that combines the inverted residual network with the attention mechanism to find out what stage of illness anthracnose is in mango leaves. The results showed that the CBAM-DBIRNet model was 98.42% accurate at identifying the stages of anthrax, 97.80% recall, and 97.89% proficient in its F1 score. The model's size and parameters were 0.64 MB and 0.15 million, respectively.

### 3.1 Discussion and Analysis

The literature review indicates that various primary CNN models, including AlexNet, Inception, ResNet, VGG, MobileNet, DenseNet, Xception, EfficientNet, Yolo, and their enhanced variants, have been employed for the classification of mango leaf diseases. Fig. 5 illustrates the proportion of the specified CNN models and their variants utilized in the domain of disease categorization. AlexNet, Inception, and ResNet are unequivocally the three foremost CNN models utilized for the identification and categorization of mango leaf diseases. Fig. 6(a) illustrates the mango leaf diseases predominantly examined by researchers. Anthracnose is clearly the predominant leaf disease in this domain. Transfer learning is a methodology that enables models to utilize previously learned information for new, related tasks, particularly beneficial when data is scarce for a novel challenge. In the realm of mango leaf disease detection and classification, the acquisition of a substantial dataset is a significant challenge. Consequently, researchers employed transfer learning-based CNN models in this domain. Fig. 6(b) illustrates the proportion of CNN models utilizing scratch training and transfer learning. Transfer learning is evidently underutilized in the domain of mango leaf disease detection. Therefore, researchers must concentrate on that. Fig. 7(a) depicts the proportion of traditional and lightweight CNN models employed for mango leaf disease detection. The advancement of lightweight CNN models is inadequate. Merely 15% of the total employed models are lightweight, necessitating researchers to concentrate on this area, since lightweight CNN models have yielded promising outcomes [30, 32]. Fig. 7(b), on the other hand, shows the percentage of classic CNN models and metaheuristics-optimized CNN models that were found in the literature review. It is evident that, although metaheuristic approaches are highly effective for optimizing weighting parameters, their application in CNN for mango leaf disease detection and classification is not frequent. Merely 18% of total CNN models are optimized with the application of metaheuristic techniques. Consequently, the advancement of metaheuristics optimized CNN models represents a promising future direction.



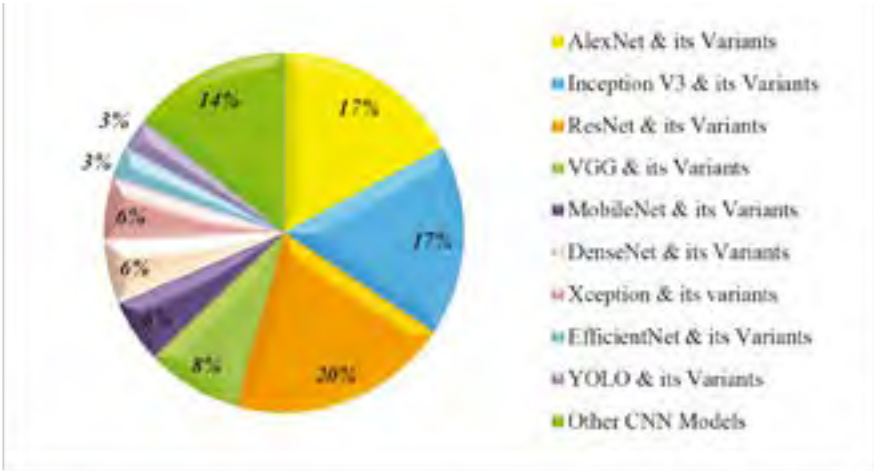


Fig. 5. Distribution of CNN models and its variants addressed in selected research articles.

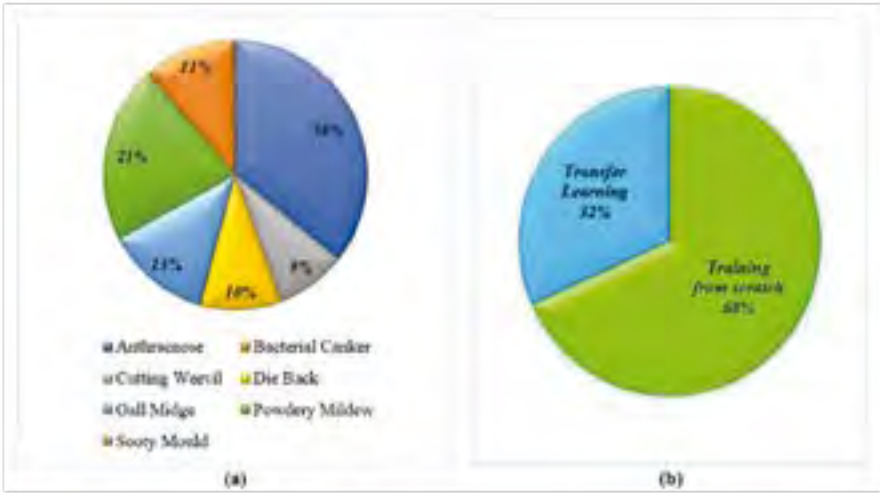
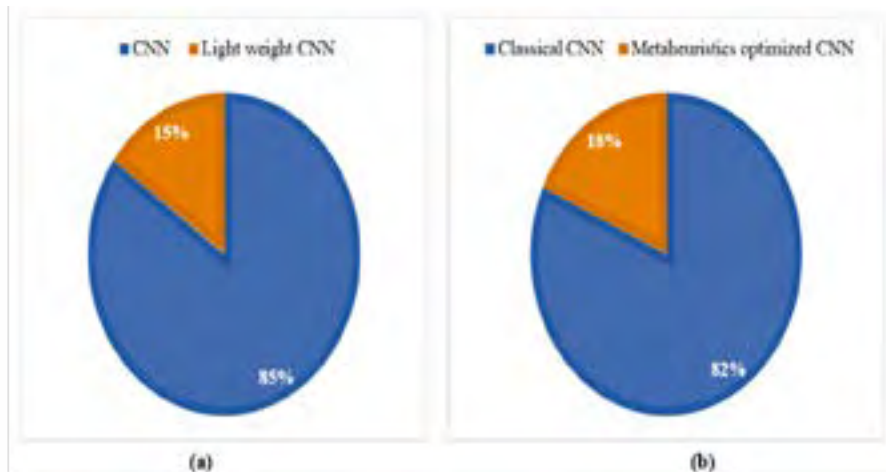


Fig. 6. (a) Disease considered by the researchers as per the survey; (b) Percentage of CNN models with Scratch training and Transfer learning.



**Fig. 7.** (a) Percentage of classical CNN and light weight CNN models; (b) Percentage of classical CNN and Metaheuristics optimized CNN models.

#### 4 Conclusion and Future Directions

Agriculture is a linchpin in the growth trajectory of developing countries, playing a vital role in fostering economic development and societal well-being. In these nations, a substantial portion of the population engages in agricultural activities, making it a cornerstone for livelihoods. The cultivation of crops not only contributes significantly to the country's Gross Domestic Product (GDP) but also generates employment opportunities across the agricultural value chain. The impact of mango cultivation, specifically, exemplifies the transformative potential of agriculture. Mangoes, with their high demand and popularity both domestically and internationally, become a key player in economic prosperity. The cultivation of mangoes not only adds value to the agricultural GDP but also diversifies the sector, mitigating risks associated with mono-cropping. Additionally, mango cultivation creates income avenues for farmers, fosters the growth of agro-processing industries, and opens up opportunities for export, enhancing the overall economic landscape of the developing country. In essence, agriculture, with a focus on crops like mangoes, serves as a catalyst for holistic growth, intertwining economic prosperity with sustainable development.

The production of mangoes faces significant challenges, among which leaf diseases pose a notable threat. Leaf diseases, such as anthracnose, powdery mildew, sooty mould, and gall midge can pose significant threats, causing defoliation, reduced photosynthesis, and lower yields. These diseases are often caused by fungal pathogens and are exacerbated by factors such as humidity, temperature fluctuations, and poor agricultural practices. However, advancements in technology, specifically the applica-

tion of DL models, offer a promising solution for early prediction and management of these diseases.

Several future works can be made to improve the mango leaf disease classification task which are as follows: (1) Obtaining the dataset from a real-world environment. This could enhance the performance of trained models, ensuring a more accurate identification of diseases affecting mango leaves. (2) Develop a novel hybrid DL architecture by using an attention-based mechanism or combining current DL models to enhance accuracy. (3) Additionally, Nature Inspired Optimization Algorithm (NIOA) can be incorporate for selecting the best hyper parameters automatically for fine-tuning the CNN model. (4) Create a model that will run efficiently in mobile environments that will help farmers to promptly detect plant diseases and take appropriate precautions. (5) Segmentation of leaf disease area plays an important role in disease detection and classification [33, 34, 35]. Therefore supervised [33, 34] and unsupervised [35] segmentation techniques can be utilized in future.

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# Integration of Generative AI into a Project-based Learning Activity in a Microcontrollers Course

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**Abstract.** The use of generative artificial intelligence by students has increased since the launch of powerful natural language processing tools such as ChatGPT. Several works have highlighted the strengths, weaknesses, opportunities, and threats of this technology in education, but there is a reduced amount of empirical research of its application in real academic scenarios. This work proposes the use of ChatGPT as a tool that could help engineering students solve highly complex problems more efficiently and accurately. In order to test this hypothesis, an experience with a group of students from a mechatronics engineering microcontrollers course was carried out using the project-based engineering approach. The results highlight the necessity of finding a balance between a learner's previous knowledge and the complexity of a new task and educating students about proper prompt engineering techniques and the use of ChatGPT and any other GAI only as a complement to their own knowledge and skills.

**Keywords:** ChatGPT, Engineering, Education.

## 1 Introduction

The exponential massification and diversification of artificial intelligence (AI) around the planet have brought applications of this technology in all fields of human activity, including education. In this area, those applications include administrative work, instruction or instructor support, and student's learning [1]. In the latter of these sub-areas, these applications include customizable learning platforms, chatbots, machine translation tools, and intelligent tutoring systems [1]. More recently, generative AI (GAI) platforms such as ChatGPT, Bing Chat, and Bard, have gained increasing popularity among students.

Since its release on November 30, 2022, the GAI ChatGPT has raised a myriad of reactions from all those involved in education. In fact, experts from this realm have highlighted both the benefits and drawbacks of this new technology when applied to the different dimensions of the education system at all levels, including teaching, learning, assessment, and curriculum. On one hand, ChatGPT brings many benefits into these areas, including its vast knowledge from all disciplines, flexibility in the

<https://doi.org/10.61728/AE20254995>



content generated, speed, low cost, and availability [2]. Conversely, the main weaknesses in the application of this technology include its possible generation of incorrect, false, or biased content difficult to identify by the user and the potential use by students to commit different forms of fraud in assignments [2]–[4]. Because of this diversity of possible outcomes, experts have also recommended a series of actions to deal with the many challenges that this new tool will bring into classrooms. Regarding faculty and educators' actions, experts suggest the application of activities where students need to integrate their personal experience, consult multiple sources, apply creativity and critical thinking, and complete their work without exclusive reliance on GAI [3], [4]. In the field of higher education, specifically engineering, reception from academics has been similar. For example, the author of [5] mentions various forms in which ChatGPT and other language models can be helpful for engineering education for both students and teachers, including language editing, tutoring, and generating and solving technical and non-technical questions. However, the author also highlights the false or incorrect information provided by these tools, making necessary the creation of standards and guidelines for proper use [6].

The rest of this article is organized as follows. The next section summarizes previous experimental results obtained in the integration of ChatGPT into engineering courses of diverse disciplines. Further, the research design proposed in this paper is detailed in all its steps, and the results obtained from the experiment are presented and discussed. Finally, conclusions and areas of future work are proposed, as well as the limitations contained in the proposed design.

## 2 Related Work

In engineering, there is some limited evidence of the impact of using ChatGPT in real-life educational scenarios. For example, software engineering students and professionals have provided positive feedback on the potentialities of this tool in coding activities despite its drawbacks [6], [7]. Research has also shown ChatGPT's capabilities for answering questions and generating code in a cybersecurity course [8] as well as generating code for the construction of a finite state machine [9], but in both cases, human expertise has been needed to properly evaluate and use the provided information. In the field of assessment, the authors of [10] noted ChatGPT's capabilities for the generation of biomedical engineering diagnostic exams, remarking that, however, the quality and reliability of each question should be evaluated. Similarly, the authors of [11] showed the implicit benefits when testing ChatGPT's support in the design of distillation columns for undergraduate chemical engineering education, highlighting the necessary verification of the provided information. Synthesizing, it is evident for most authors that ChatGPT and any other GAI will make sense as a learning and teaching tool only in conjunction with proper human skills and knowledge coming from users.

### 3 Research Design

#### 3.1 Students' Background

This experiment was carried out with 24 mechatronics engineering students of an eight-semester microcontrollers course at Universidad de Sonora, in Hermosillo, Mexico. At the beginning of the term, they were divided into four groups to carry out a series of project-based learning experiences, where the third of these activities was controlling the behavior of a robot to follow the route given by a thermal footprint. Fig. 1 shows one of the groups working on this project, which included building an electronic circuit and programming an STM32 NUCLEO board. The robot consisted of a crawler unit whose movement depended on two motors controlled by the NUCLEO board according to temperature measurements obtained from two thermistors. Through a Bluetooth module as part of the circuit, the students were also able to monitor the robot's behavior from their cellphones.



Fig. 1. A group of students working on the previous project.

#### 3.2 Experimental and Control Groups

Because of the proven effectivity of project-based learning in engineering courses [12]–[14], a fourth activity based on this paradigm was planned for the students to carry out. This project would be based on the already completed project described in section 3.1.

The same four groups would have an hour to solve a complex problem that required the application of abilities of the highest level according to the most recent

version of Bloom's Taxonomy. This problem would be related to the activity mentioned previously, but the groups would be separated to work under different conditions: Two groups (experimental group) would be allowed to use ChatGPT and digital online resources, and two groups (control group) would be allowed to use only the latter—with the use of ChatGPT and any other GAI forbidden.

Some days before the experience, all of the students watched two short videos covering the basics of digital literacy and prompt engineering when using ChatGPT, followed by answering a multiple-choice test that assessed their understanding of both topics. In the area of digital literacy, the video covered two main topics: a methodology for the evaluation of digital sources' reliability and the avoidance of predatory journals. Regarding ChatGPT, the video provided the following suggestions, most of which have also been provided by OpenAI [15]:

- being as clear and specific as possible when interacting with the GAI;
- asking context questions related to the topic before the question of interest;
- dividing a complex problem into sub-problems and making questions about these smaller, simpler problems;
- considering that besides written text, this GAI is capable of generating code and basic diagrams; and
- asking questions from topics in which they had previous knowledge in order to identify possible errors.

### 3.3 Experience

The four groups were informed of the tools they would be allowed to use the same day, a few hours before the experience. Then, they were given an hour to write a report proposing a methodology to make the robot follow a random route given by a thermal footprint through the shortest path and, at the same time, save the temperature values of the path in a lattice or vector. These values had to be sent to a second robot so it could follow the same route calculated by the first one. The students were requested to include a pseudocode algorithm to implement this behavior.

## 4 Results

The two groups that used ChatGPT along with digital resources performed poorly in high-order areas—content and structure—in their reports. In terms of content, as exemplified in Fig. 2, both groups chose to copy and paste ChatGPT answers directly without any attempt to integrate the information or even remove the use of the second person by the tool. The consequence of this approach was a document consisting of a sum of copied, isolated answers and lacking the level of depth expected for the activity.



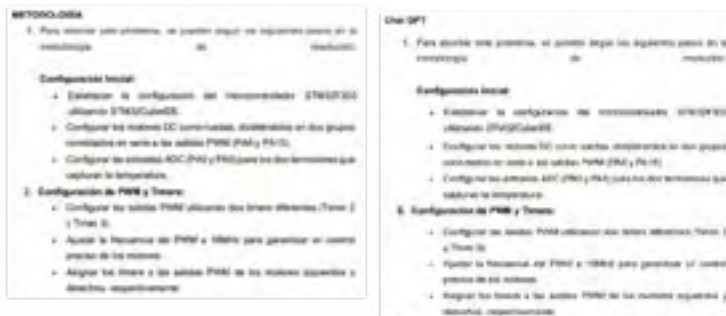


Fig. 2. Comparison of fragments of (a) a group's report and (b) a ChatGPT answer

Both groups allowed to use only digital resources created papers that were slightly more integrated and developed than those of their counterparts in terms of structure, even considering defects such as excessive quotations as well as grammar and punctuation errors. A comparison of the pseudocodes proposed by the four groups also shows a significant difference in the depth of their algorithms. Table 1 shows the pseudocode proposed by one of the groups that was only allowed to use digital resources without any GAI. As seen in the image, a *while* loop and several *if* statements were included, as well as clear variables and mathematical relationships between them.

**Table 1.** A pseudocode created by a group that did not use ChatGPT

| Students' proposed pseudocode                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Begin<br>While (true)<br>If (timer variable, for example, 10s)<br>Calculate and convert data to temperature from thermistors<br>Calculate changes as current measurement minus previous measurement over a span of 50 milliseconds<br>Store current value in previous value variable<br>Store change calculations for each thermistor<br>Store change data in the array<br>If (changeT1 < 3.0 AND changeT2 < 3.0)<br>Set robot to static with PWM for both motors at 0.0<br>End If<br>If (changeT1 > 3.0 AND changeT2 < 3.0)<br>Turn counterclockwise with motor 1 at higher PWM than motor 2<br>End If<br>If (changeT1 < 3.0 AND changeT2 > 3.0)<br>Turn clockwise with motor 2 at higher PWM than motor 1<br>End If<br>If (changeT1 > 3.0 AND changeT2 > 3.0)<br>Move robot straight forward with motor 1 and motor 2 at the same PWM<br>End If<br>End If<br>End If<br>Read array and send it via Bluetooth module to robot 2<br>Read array with a delay of 50 milliseconds for robot 2<br>End |

In contrast, Table 2 shows the algorithm of one of the groups that did use ChatGPT. Their proposal was in fact a verbatim copy of the GAI's answer, which only schematizes the behavior of the robots in a series of functions but does not provide details about their execution.

**Table 2.** A pseudocode created by a group that did use ChatGPT (translation)

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**Students' proposed pseudocode**

---

```
// Step 1: Capturing temperature trajectory from the first robot
Matrix temperature_robot_1
captureTemperature(temperature_robot_1) // Function that captures temperature along the route
// Step 2: Obtaining optimal route
Route optimal_route
optimal_route = findOptimalRoute(temperature_robot_1) // Function that finds the optimal route based on temperature
// Step 3: Displacement of the second robot
Matrix temperature_robot_2
transmitData(temperature_robot_1, temperature_robot_2) // Function that transmits data to the second robot
// Step 4: Implementing route following by the second robot
route route_second_robot
route_second_robot = followOptimalRoute(temperature_robot_2)
// Function that guides the second robot following the optimal route
// Specific functions
function captureTemperature(temperature_robot):
while robot is moving:
read temperature from thermistors
store temperature in the matrix temperature_robot
function findOptimalRoute(temperature_robot):
create graph based on temperature change:
apply optimal route search algorithm (such as Dijkstra or A*)
return optimal_route
function transmitData(temperature_robot_1, temperature_robot_2):
transmit temperature_robot_1 to second robot
temperature_robot_2 = receiveData()
function followOptimalRoute(temperature_robot):
follow the route defined by received temperature changes
return route followed by the second robot
```

---

The reports submitted by each group of students were assessed through the rubric presented in Table 3 according to three criteria: the level of integration of diverse academic disciplines in the proposed solution, the capacity to analyze the problem and then synthesize these solutions into one major solution, and the consideration of low-order concerns (grammar, punctuation, spelling, and word choice).

Table 3. Rubric created to assess the students' work

| Criteria                                               | 1                                                                                                                                                                                                                                                              | 2                                                                                                                                                             | 3                                                                                                                                       |
|--------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|
| 1. Integration of technical and scientific disciplines | The problem is approached from one or more of the technical and/or scientific disciplines involved in its resolution.                                                                                                                                          | The problem is approached from two to three technical and/or scientific disciplines involved in its resolution.                                               | The problem is approached from more than three technical and/or scientific disciplines involved in its resolution.                      |
| 2. Analysis and synthesis                              | Basic cognitive skills are applied in the resolution of the problem. In most cases, the written content is just a summary of information from different sources, but this information is not properly processed so that it can be useful to solve the problem. | There is a partial analysis of the problem as a division of sub-problems, but their solutions are not properly joined to create a major solution.             | The problem is properly divided into sub-problems, after which these are synthesized to create a final solution to the greater problem. |
| 3. Grammar, punctuation, spelling, and word choice     | There are several concerns in terms of grammar, punctuation, spelling, and word choice in the document that difficult its understanding.                                                                                                                       | Although understandable, concerns in grammar, punctuation, spelling and/or word choice lower the quality of the paper in an academic or professional context. | The document is free or mostly free of errors in grammar, punctuation, mechanics, and word choice.                                      |

Students from the experimental group had poor performance in Criterion 1 and 2, as their work was basically copy-pasted ChatGPT answers. Students from the control group had a slightly better performance in these criteria. Both the control and the experimental groups had a mid-level performance in terms of low-order concerns (Criterion 3). In the case of the former, the main reason behind this score is the presence of grammar, punctuation, and spelling mistakes. On the other hand, although the experimental group had a better performance in these areas, there are word-choice concerns caused by the use of the second person by ChatGPT, which was not removed from the submitted work.

## 5 Discussion

The results obtained from the experimental group show the failure of these students in using this tool in the intended form. Moreover, their approach was not only detrimental to the quality of the proposed methodology but also made explicit the students' own weaknesses in technical writing skills. These results highlight the necessity of providing clearer guidelines on the optimum use of ChatGPT and any GAI when integrating them into higher education. Besides resources such as the videos, students will probably comprehend this methodology better if they receive extensive preparation in prompt engineering, including exercising and seeing examples of its application in similar situations to clearly understand all the steps involved.

## **6 Conclusion**

This experience was an initial practical attempt to integrate a GAI into a classroom activity in an engineering course. Although the obtained results were not satisfactory, the inevitability of the use of ChatGPT and similar tools by students compels researchers to keep proposing and testing new strategies to work with this technology until desired results in terms of students' performance and learning are reached. For this reason, future areas of investigation should include the addition of prompt engineering as part of the academic curricula in engineering courses and the proposal of project-based activities that balance the necessity of higher-level cognitive skills and the application of previous knowledge from the students.

## **7 Limitations**

This study has some limitations that must be mentioned. The main one is the reduced number of students selected for the experiment, who were separated into groups that created a total of four reports. These four pieces of work are not statistically significant to generalize the insights gathered from their analysis. However, there are at least two measures that can avoid this limitation in the future. Firstly, a larger set of students would yield a more statistically significant sample representative of the totality of the population from this particular higher education institution. Secondly, having the students from each group divide their tasks into identifiable parts would increase the comparable samples, allowing a more accurate generalization.

There is a second limitation in the biased selection of students, who come from a particular course and career and particular generations, allowing a potential generalization for a very small group of students. This limitation can be mitigated by selecting subjects from courses with a larger group of students, such as basic sciences courses common to any engineering career.



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# Advances in Hollow Fiber Membranes Simulation for Multicomponent gas separation: Combining Physical Models and Neuro-Fuzzy Systems

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**Abstract.** The separation of Natural Gas/CO<sub>2</sub> using hollow fiber membranes is essential for industrial applications, particularly in the oil and gas sector. Traditional modeling approaches, such as "black-box" models based on artificial neural networks (ANNs), offer high accuracy in parameter estimation but lack physical interpretability, making them unreliable for large-scale applications with variable operating conditions. Conversely, "white-box" models, grounded in physical laws and conservation principles, provide better scalability and physical insight but often require complex derivations and exhibit high uncertainty when experimental data is insufficient or when key parameters, such as gas permeability, must be inferred from empirical correlations.

To address these limitations, this study introduces a "gray-box" approach using an Adaptive Neuro-Fuzzy Inference System (ANFIS), which combines the data-driven adaptability of ANNs with the interpretability of fuzzy logic systems. The proposed white-box model is enhanced with ANFIS-based optimization to improve CO<sub>2</sub>/CH<sub>4</sub> separation performance in hollow fiber membranes.

This study underscores the critical role of neuro-fuzzy systems in bridging physical modeling and machine learning, providing a robust and efficient approach for industrial gas separation. Integrating ANFIS with physical models enhances model reliability. It lays the foundation for scalable, real-world applications in the oil and gas industry, offering a more adaptive and data-efficient alternative to conventional approaches.

**Keywords:** Artificial Intelligence, Artificial Neural Networks, Adaptive Neuro-Fuzzy Inference System, Hollow Fiber Membranes, Gas Separation.

<https://doi.org/10.61728/AE20255008>



## 1 Introduction

Modeling membrane modules is a cornerstone for advancing gas separation technologies in industrial applications. By leveraging calculations and simulations, engineers can explore and optimize a wide range of configurations and operating parameters, enabling efficient systems to separate carbon dioxide ( $\text{CO}_2$ ) from natural gas, which primarily consists of methane ( $\text{CH}_4$ ) and other gases. These processes are particularly critical in the oil and gas industry, where their optimization directly impacts operational efficiency, cost-effectiveness, and environmental sustainability [1, 2].

Despite their importance, the separation of gases using membrane modules poses significant challenges that stem from the limitations of existing modeling approaches. In parallel, the oil and gas sector is undergoing a digital transformation driven by Industry 4.0, which integrates automation, data analysis, and modeling to meet operational and economic demands. This era, also known as the "age of intelligence", promotes the use of advanced technologies, such as artificial intelligence and machine learning, to improve resource management, reduce inefficiencies, and enable sustainable industrial practices [3]. Within this framework, membrane modeling plays a pivotal role in bridging simulation with strategic decision-making, establishing a foundation for developing advanced separation systems that align with the principles of sustainability and adaptability [2].

A key aspect of this transformation is incorporating intelligent systems in industrial applications, designed to mimic human cognitive processes. Inspired by biological structures, Artificial Neural Networks (ANNs) acquire knowledge through experience, allowing them to automate tasks and model nonlinear systems with significant complexity [4]. Introduced in 1959 by Frank Rosenblatt, the Perceptron was a milestone in neural computing, establishing the foundation for ANNs [5, 6]. Building on this foundation, modern approaches, such as the Adaptive Neuro-Fuzzy Inference System (ANFIS), combine the learning capabilities of ANNs with the rule-based interpretability of fuzzy logic systems. This hybrid architecture enables ANFIS to address imprecision and uncertainty while optimizing industrial processes, including separating  $\text{CO}_2$  from natural gas in hollow fiber membranes [7, 8].

Traditional "black-box" models, such as ANNs, excel at approximating complex nonlinear relationships. These models are called "black-box" because they operate based on input and output data without revealing the internal workings of the system. However, their lack of physical interpretability limits their application in industrial settings where extrapolation beyond the training data is essential [8, 9]. This shortfall makes black-box models unreliable for large-scale applications or scenarios involving variable operating conditions.

On the other hand, "white-box" models, grounded in physical laws and conservation principles, provide interpretability and scalability, allowing for robust predictions in diverse industrial scenarios. Yet, these models often require intricate derivations and



depend on precise parameter estimation, which can be challenging when key variables, such as gas permeability, cannot be measured directly and must be inferred from empirical correlations. This limitation introduces significant uncertainty, particularly in multicomponent systems like CO<sub>2</sub>/Natural Gas separation [7, 10].

To address these challenges, "gray-box" models that combine the strengths of black-box and white-box approaches have emerged as a promising solution. Among these, neuro-fuzzy systems, such as ANFIS, stand out for their ability to integrate data-driven adaptability with physical interpretability. Recent applications of ANFIS in gas separation demonstrate its effectiveness in addressing uncertainty and nonlinearity [8]. More importantly, ANFIS's ability to dynamically adapt to varying operating conditions instills confidence in its suitability for industrial environments. It achieves a balance between accuracy and scalability, making it an ideal tool for process optimization and control in industrial environments [9].

This study proposes a white-box model enhanced with ANFIS for the separation of CO<sub>2</sub>/Gas Natural in hollow fiber membranes. By integrating the physical foundation of white-box modeling with the adaptability of neuro-fuzzy systems, this approach overcomes the limitations of traditional modeling paradigms. The proposed framework aims to:

- Reduce parameter uncertainty by leveraging the strengths of physical models and ANFIS.
- Optimize membrane design to enhance separation efficiency.
- Provide scalable and robust solutions tailored to the operational demands of the oil and gas industry.

The integration of ANFIS with white-box models not only bridges the gap between interpretability and adaptability but also lays the groundwork for developing sustainable and efficient industrial gas separation processes [10].

## 2 Methodology

### 2.1 Mathematical modeling of hollow fiber membrane

This model aims to describe the behavior of the separation system through mathematical relationships that account for the gas properties and the membrane's characteristics. The most critical considerations in this model are described as follows:

- The membrane does not deform under the applied pressure.
- The gases involved are considered ideal in all phases of the process.
- The pressure drop on the permeate and retentate sides can be calculated using the Hagen-Poiseuille equation.
- The permeation of chemical species is considered constant.

The model is based on a set of differential equations that describe the variation of the component flow along the membrane. Equation (1) describes the rate of change of the molar flow of component  $i$  on the retentate side of the membrane in the flow direction. Equation (2) represents the rate of change of the molar flow of component  $i$  on the permeate side. Equation (3) details the pressure variation along the membrane on the retentate side, considering the dynamic viscosity of the mixture and the membrane geometry. Finally, Equation (4) describes the pressure variation on the permeate side [1, 11].

$$\frac{dv_i^R}{dz} = -Pm_i(p_i^R - p_i^P)D_o\pi N \quad (1)$$

$$\frac{du_i^P}{dz} = Pm_i(p_i^R - p_i^P)D_o\pi N \quad (2)$$

$$\frac{dP}{dz} = -\frac{192ND_o(D + ND_o)RT\mu_m}{\pi(D^2 - ND_o^2)^3P}u \quad (3)$$

$$\frac{dp}{dz} = \frac{128RT\mu_m}{\pi D_i^2 N p}v \quad (4)$$

Where  $Pm_i$  is Permeation of component  $i$   $\frac{\text{mol}}{\text{cm}^2 \cdot \text{atm} \cdot \text{min}}$ ,  $p_i^R$  and  $p_i^P$  denote partial pressures of component in the retentate and permeate section,  $\text{atm}$ ,  $\alpha$  is an ideal separation factor or permselectivity,  $N$  is the number of tubes or fibers,  $i$  is component index,  $u$  is flow rate on the permeate side ( $\text{mol} \cdot \text{s}$ ) and  $v$  is flow rate on the retentate side ( $\text{mol} \cdot \text{s}$ ). The internal diameter is denoted by  $D$  (m), while  $D_i$  and  $D_o$  refer to the internal and external diameter of the hollow fiber membrane (m),  $R$  is Ideal gas constant,  $T$  is temperatura and  $\mu_m$  is dynamic viscosity of the mixture ( $\text{Pa} \cdot \text{s}$ ).

To solve the differential equations, the MATLAB function *ode15s* was used. This function employs an adaptive implicit method based on Backward Differentiation Formulas (BDF). This approach is particularly suitable for stiff systems, as it can handle rapid and slow variations in a stable and efficient manner. First, the model equations and initial conditions were defined (see Tables 1 and 2). Then, error tolerances and the integration interval were configured. This setup allowed for precise and stable numerical solutions for the system of interest.

### Dynamic Determination of Viscosity

The viscosity of a pure fluid can be determined using the Chapman-Enskog solution, which is based on the Boltzmann transport equation. This approach assumes that molecular interactions can be approximated by those of Lennard-Jones particles with a potential function.

**Table 1.** Initial Conditions of the Process.

| Parameter                     | Value  | Unit  |
|-------------------------------|--------|-------|
| Initial Pressure in Retentate | 29.607 | atm   |
| Initial Pressure in Permeate  | 1      | atm   |
| Temperature                   | 298.15 | K     |
| Total Initial Flow Rate       | 1      | mol/s |
| Inner Fiber Diameter          | 400    | Å     |
| Outer Fiber Diameter          | 1000   | Å     |
| Number of Fiber               | 99472  | -     |
| Module Diameter               | 1      | m     |

Medi et al. [12] and Khalilpour et al. [13].

**Table 2.** Initial Conditions of Chemical Species

| Parameter                     | Mole Fraction | Permeance ( $P_{m,i}$ ) [ $10^{10} \text{ mol}/(\text{m}^2 \cdot \text{Pa} \cdot \text{s})$ ] |
|-------------------------------|---------------|-----------------------------------------------------------------------------------------------|
| CH <sub>4</sub>               | 0.6           | 3.72                                                                                          |
| CO <sub>2</sub>               | 0.2           | 134                                                                                           |
| C <sub>2</sub> H <sub>6</sub> | 0.15          | 1.02                                                                                          |
| C <sub>3</sub> H <sub>8</sub> | 0.05          | 0.2                                                                                           |

Medi et al. [12] and Khalilpour et al. [13].

The dynamic viscosity of a gas  $\mu_i$  is calculated using the kinetic theory of gases, which relates this property to the temperature  $T$ , the molar mass  $M$ , the collision diameter  $\sigma$ , and the collision integral  $\Omega_\mu$ .

$$\mu_i = 2.669 \times 10^{-5} \frac{\sqrt{T \cdot M}}{\sigma^2 \cdot \Omega_\mu} \quad (5)$$

The reduced collision integral is calculated by considering the possible trajectories of particles during their approach. An empirical correlation relates  $\Omega_\mu$  to temperature.

$$\Omega_\mu = \frac{1.16145}{T^{*-0.14874}} + \frac{0.52487}{\exp(0.77320T^*)} + \frac{2.16178}{\exp(2.43787T^*)} \quad (6)$$

The viscosity of a diluted gas is related to the mole fraction  $x_i$  and the viscosity of the diluted gas component  $i$ , following Wilke's equation.

$$\mu_{mix} = \sum_i \frac{x_i \mu_i}{\sum_j x_j \varphi_{ij}} \quad (7)$$

The binary weighting factor  $\varphi_{ij}$  expressed as a function of the gas viscosity and the molecular weight of the component as follows.

$$\varphi_{ij} = \frac{\left[ 1 + \left( \frac{\mu_i}{\mu_j} \right)^{0.5} \left( \frac{M_i}{M_j} \right)^{0.25} \right]^2}{\left[ 8 \left( 1 + M_i/M_j \right) \right]^{0.5}} \quad (8)$$

### Sensitivity Analysis in Permeation

Permeation is one of the most relevant parameters in membrane separation, as it determines the process's permeability and selectivity. Previous studies indicate that when the CO<sub>2</sub> concentration in the feed is below 20%, and the pressure is below 14.8 atm, the plasticization effect becomes negligible. For this reason, these values are often assumed to remain constant [14].

Although this work does not develop an explicit model for permeability variation a simulations were carried out in which the permeation of CH<sub>4</sub> was modified. This approach accounts for the fact that operating conditions—at least in wells located in the "Golfo de México"—exceed the referenced pressures, and these changes can influence the final gas volume required. This provides insight into the process sensitivity to potential variations in permeation.

## 2.2 Statistical Method

Correlation analysis is one of the most commonly used and reported statistical methods in scientific and medical research. Its visual representation is known as a scatter plot. It is used to confirm or refute the existence of a relationship between two variables based on the Pearson correlation coefficient described in Equation (9), [15].

$$\rho(a, b) = \frac{E(ab)}{\sigma_a \sigma_b} \quad (9)$$

Where  $E(ab)$  represents the cross-correlation between  $a$  and  $b$ , and where  $\sigma_a^2 = E(a^2)$  and  $\sigma_b^2 = E(b^2)$  correspond to the variances of the variables.

When considering variables  $a$  and  $b$ , a scatter plot is a powerful tool that visually represents their ordered pairs within a coordinate system. It's not just a graph but a visual representation of the relationship between the two variables. When most points align closely with a straight line, the correlation is classified as linear. Conversely, the correlation is considered nonlinear if the points follow a curved pattern. However, if no discernible pattern is observed among the ordered pairs, it indicates the absence of a relationship between the two variables. To depict the curve or regression line that best fits the distribution of the ordered pairs, Equation (10) is applied.

$$y = a_0 + a_1x_1 + a_2x_2 + \dots + a_mx_m \quad (10)$$



The correlation coefficient, or  $R$ , is a fundamental measure for assessing relationships between variables within a system. In the context of gas volume prediction, it helps us understand how changes in one variable, such as pressure or permeation, might affect the volume of separated gas in a hollow fiber membrane. The magnitude and direction of the correlation coefficient can be either positive (from 0 to 1) or negative (from -1 to 0). A value of  $R$  close to  $\pm 1$  indicates a stronger correlation.

The determination coefficient  $R^2$  is a crucial factor in predicting the volume of separated gas in hollow fiber membranes. It indicates the percentage of variability in the dependent variable that the independent variables can explain. This correlation analysis is instrumental in selecting representative variables for the ANFIS model, a process that significantly reduces model dimensionality and enhances predictive performance. The importance of this proper variable selection cannot be overstated, as it ensures the reliability and accuracy of our research.

To minimize model error, our study employs Gradient Descent Optimization (GDO) using the Least Squares Regression (LSR) method, as described in [15]. This strategic use of GDO allows us to identify the most influential variables in gas volume prediction, ensuring that only the most relevant variables are incorporated into the ANFIS model. This approach minimizes error and enhances our model's precision, providing a deeper understanding of the gas volume prediction process.

In addition to GDO, we calculated the Mean Absolute Error (MAE) and the Mean Absolute Percentage Error (MAPE) to evaluate the model's performance, following the methodology outlined in [15]. These error metrics help us assess the accuracy and reliability of our predictions. The rigorous validation of the model's performance ensures that our research is reliable and instills confidence in the accuracy of our predictions.

$$x = \begin{bmatrix} x_{11} & x_{12} & x_{13} & \cdots & x_{1k} \\ x_{21} & x_{22} & x_{23} & \cdots & x_{2k} \\ x_{31} & x_{32} & x_{33} & \cdots & x_{3k} \\ \vdots & \vdots & \vdots & & \vdots \\ x_{n1} & x_{n2} & x_{n3} & \cdots & x_{nk} \end{bmatrix} \quad y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \quad (11)$$

The matrix "x" and the vector "y" from Equation (11) are shown in Equation (12).

$$x = [v_i^p \quad Pm_i \quad \mu_m \quad P] \quad y = [v_i^p] \quad (12)$$

Therefore, we can denote  $x_1$  as  $v_i^p$ , which in this case refers to the volume fo  $\text{CH}_4$ ,  $x_2$  as  $Pm_i$  representing the permeance in the retentate,  $x_3$  as the viscosity in the permeate  $\mu_m$  and  $x_4$  a  $P$ , which corresponds to the pressure in the permeate.

### 2.3 Intelligent Modeling with ANFIS

The technique to be implemented is an ANFIS, which combines two intelligent techniques, ANNs, and fuzzy logic, to leverage their strengths and overcome each



technique's weaknesses. Layer 2 consists of round nodes or fixed operations. Equation 1 represents the output obtained between each pair of membership functions, where  $\hat{\mu}$  is the membership function,  $A_i$  is the linguistic label, and  $w_i$  is the output or firing strength of each fuzzy rule [16 and 17].

$$w_i = \hat{\mu}_{A_i}(x_1) \times \hat{\mu}_{B_i}, \quad i = 1, 2. \quad (13)$$

Layer 3 consists of normalizing the firing strengths. Layer 4 involves specific parameters known as "consequents," which allow for "defuzzification" to generate results within the original output range. Finally, Layer 5 concludes with an average of all outputs from Layer 4 to determine a single output result, as described by Equation E.C., where  $f_i$  corresponds to the combination of input values with the consequent parameters from Layer 4.

$$\text{Total Output} = \frac{\sum_i w_i f_i}{\sum_i w_i} \quad (14)$$

The neural network component allows the weights and parameters to be continuously adjusted through the learning process. The learning or training used in this work is called hybrid, as it combines least squares to estimate the output from one layer to the subsequent and gradient descent to propagate the error from one layer back to the previous one, minimizing it by adjusting the parameters.

For gradient descent, Equation E.C. shows the so-called cost function, described by the difference between the estimated and actual values, also known as the error  $E_p$  between the two signals. Gradient descent involves partial derivatives concerning  $\alpha$  (a generic system parameter), as demonstrated in Equation E.C., which is based on Equation 5, applying the learning rate represented by  $\eta$ .

$$\text{Total Output} = \frac{\sum_i w_i f_i}{\sum_i w_i} \quad (15)$$

$$\frac{\partial E_p}{\partial \alpha} = \sum_{m=1}^L \frac{\partial E_p}{\partial \alpha} \quad (16)$$

$$\Delta \alpha = -\eta \frac{\partial E_p}{\partial \alpha} \quad (17)$$

### Selection of Input Variables

To determine the best model configuration, three options for input data delays were evaluated:

$$\text{Case 1} \quad \hat{v}_i^R(k) = f[v_i^R(k-1) \quad Pm_i(k-1) \quad \mu_m(k-1) \quad P(k-1)] \quad (17)$$

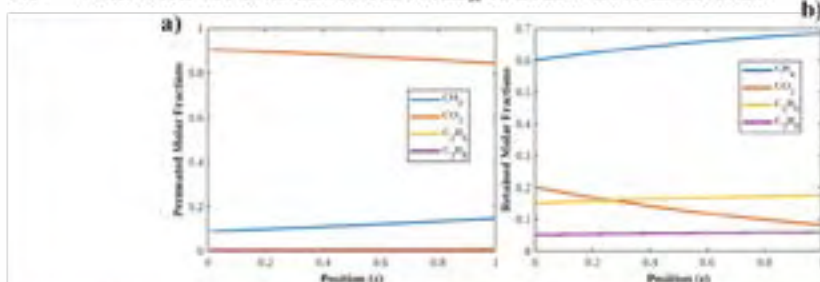
$$\text{Case 2} \quad \hat{v}_i^R(k) = f[v_i^R(k-2) \quad Pm_i(k-2) \quad \mu_m(k-2) \quad P(k-2)] \quad (18)$$

$$\text{Case 3} \quad \hat{v}_i^R(k) = f[v_i^R(k-3) \quad Pm_i(k-3) \quad \mu_m(k-3) \quad P(k-3)] \quad (19)$$

The data were generated by the white-box model and subsequently loaded for analysis. The selection of input variables was guided by the methodology described previously, particularly correlation analysis.

### 3 Results and Discussion

#### 3.1 Validation of Mathematical modeling of hollow fiber membrane



**Fig. 1.** a) Molar flow profiles of the retentate for four species ( $\text{CH}_4$ ,  $\text{CO}_2$ ,  $\text{C}_2\text{H}_6$ ,  $\text{C}_3\text{H}_8$ ) along the hollow fiber. b) Molar flow profiles of the permeate, showing the distribution of the same species in the permeate stream. The x-axis represents the axial length of the membrane, from the inlet to the outlet of the module.

In Figure 1(a), it can be observed that as the gas advances through the membrane module, the fraction of  $\text{CH}_4$  in the retentate gradually increases, while the  $\text{CO}_2$  fraction decreases steadily. This behavior aligns with the membrane's higher affinity for carbon dioxide, which tends to permeate more easily into the low-pressure stream. Consequently,  $\text{CH}_4$  becomes "enriched" on the retentate side.

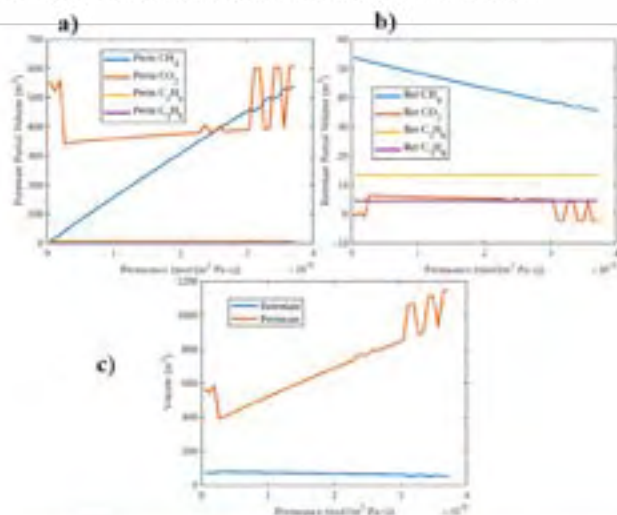
In Figure 1(b), the permeate stream initially exhibits a very high  $\text{CO}_2$  content, confirming its high permeability. However, methane is not completely absent in the permeate but slightly increases along the module. This relative increase in  $\text{CH}_4$  suggests that while  $\text{CO}_2$  is the dominant species, the driving force (pressure and concentration gradients) allows some methane to pass through the membrane, particularly during the initial stages of the process or when the  $\text{CO}_2$  concentration decreases.

For  $\text{C}_2\text{H}_6$  and  $\text{C}_3\text{H}_8$ , their fractions in both streams are significantly lower than those of  $\text{CH}_4$  and  $\text{CO}_2$ . Nevertheless, the observed trend aligns with the lower permeability of heavier hydrocarbons, maintaining slightly higher concentrations in the retentate.

These results highlight the importance of membrane selectivity and the driving force in the separation efficiency. The reduction of  $\text{CO}_2$  in the retentate and its majority presence in the permeate suggest that the process is well-suited for applications aimed at  $\text{CO}_2$  removal. On the other hand, the residual presence of  $\text{CH}_4$  in the permeate indicates the need to optimize operational variables (e.g., operating pressure, module length, or feed velocity) to minimize methane losses and maximize the purity of the retentate gas. This model has been validated according to bibliographical data [12, 13].

According to Fig 2, the sensitivity analysis studied volumetric flow instead of molar flow to provide a more practical perspective for designing membrane separation processes. Increasing the permeance of a component significantly raises the partial volume of that component in the permeate. This phenomenon is particularly noticeable with methane ( $\text{CH}_4$ ), whose partial volume increases substantially as  $\text{CH}_4$  permeance rises. On the other hand, the presence of  $\text{CO}_2$  and the hydrocarbons  $\text{C}_2\text{H}_6$  and  $\text{C}_3\text{H}_8$  may

show more moderate variations, also depending on their respective permeances and affinities with the membrane. The combined effect of these changes is reflected in the final composition of the streams, highlighting that permeance is a key parameter for optimizing both the recovery and selectivity of each component.



**Fig. 2.** Influence of CH<sub>4</sub> permeance on partial and total volumes in the permeate and retentate streams. a) Partial volumes of CH<sub>4</sub>, CO<sub>2</sub>, C<sub>2</sub>H<sub>6</sub>, and C<sub>3</sub>H<sub>8</sub> in the permeate. b) Partial volumes of CH<sub>4</sub>, CO<sub>2</sub>, C<sub>2</sub>H<sub>6</sub>, and C<sub>3</sub>H<sub>8</sub> in the retentate. c) Total volumes of the permeate and retentate as a function of permeance.

### 3.2 Results Statistical Method

This section presents and analyzes the results obtained from the multiple linear regression model and the corresponding evaluation metrics. The results are summarized in Tables 3, 4, and Fig. 3, which detail the model parameters and performance metrics. These results were obtained to predict the volume of gas separated in a hollow fiber membrane.

The proximity of the points to the diagonal line strongly indicates the model's ability to predict dependent variable values with exceptional accuracy. This is further reinforced by the quantitative results in Tables 3 and 4, where a coefficient of determination ( $R^2$ ) is close to 1, and minimal errors (MAE and MAPE) are observed. The graph also allows for identifying potential outliers or regions where the model could improve its accuracy, providing a comprehensive view of the model's performance.

The intercept  $a_0$  is extremely close to zero, suggesting that, within the context of the model, the value of the dependent variable  $y$  is practically null when all independent variables ( $x_1, x_2, x_3, x_4$ ) are zero. This result is consistent with the normalization applied to the data during the modeling process. The negative coefficients of  $a_1, a_2$ , and  $a_3$  indicate an inverse relationship between the independent and dependent variables.

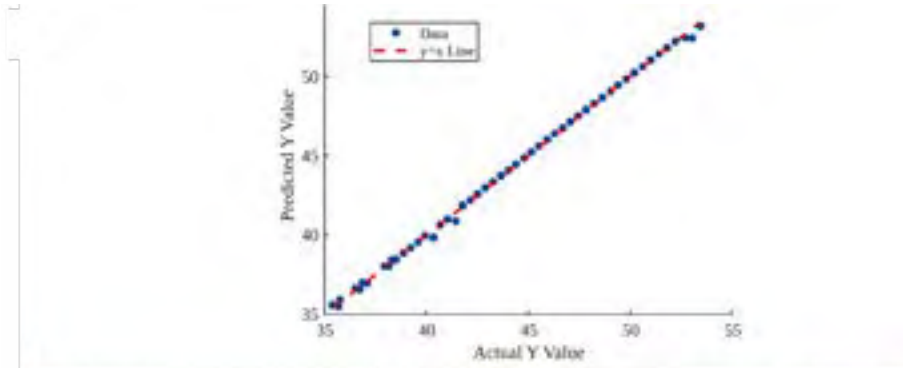


Fig. 3. Actual vs. predicted values of "y" for a multiple linear regression model. The blue dots represent the actual data points, while the red dashed line represents the ideal.

$$y = 1.606e^{-12} - 0.6610x_1 - 0.4351x_2 - 0.2000x_3 \quad (12)$$

Table 3. The values of  $a_k$

| Parameter | MCS            |
|-----------|----------------|
| $a_0$     | $1.606e^{-12}$ |
| $a_1$     | -0.6610        |
| $a_2$     | -0.4351        |
| $a_3$     | -0.2000        |

The coefficient of determination  $R^2$  of 0.9990 indicates that the model explains 99.90% of the variability in the dependent variable, suggesting an almost perfect fit to the data. This high  $R^2$  value is supported by the model's predictions, which have minimal error in absolute and percentage terms, with low MAE (0.1180) and MAPE (0.27%) values. These results demonstrate the model's precision and trustworthiness in predicting the volume of gas separated in the hollow fiber.

Table 4. Comparison of Regression Model Performance Metrics.

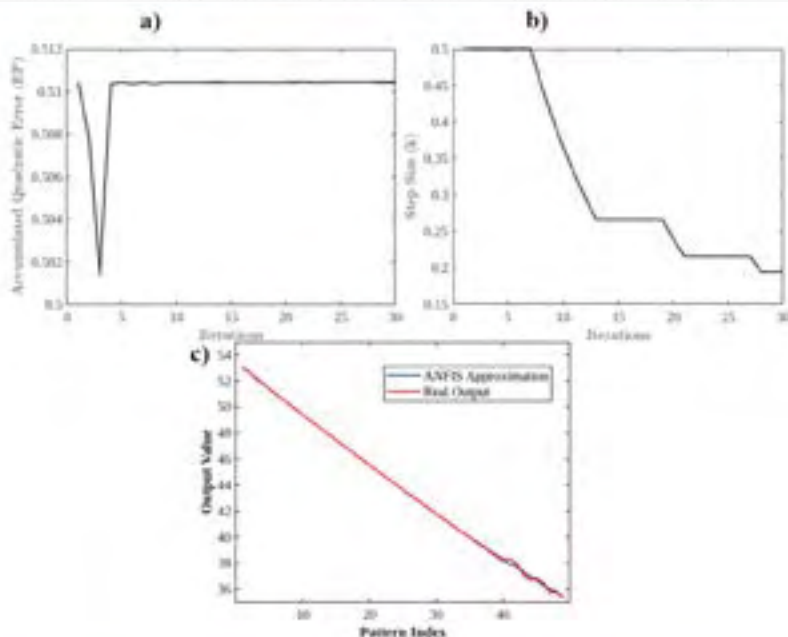
| Metric | Value  |
|--------|--------|
| $R^2$  | 0.9990 |
| MAE    | 0.1180 |
| MAPE   | 0.27%  |

### 3.3 Results of Intelligent Modeling with ANFIS

Integrating the ANFIS with the white-box model significantly improved predictive accuracy and adaptability. Figures 4, 5, and 6 illustrate the training performance of the



ANFIS for Cases 1, 2, and 3, respectively, highlighting the evolution of error metrics, step size adjustments, and the alignment between predicted and actual outputs.

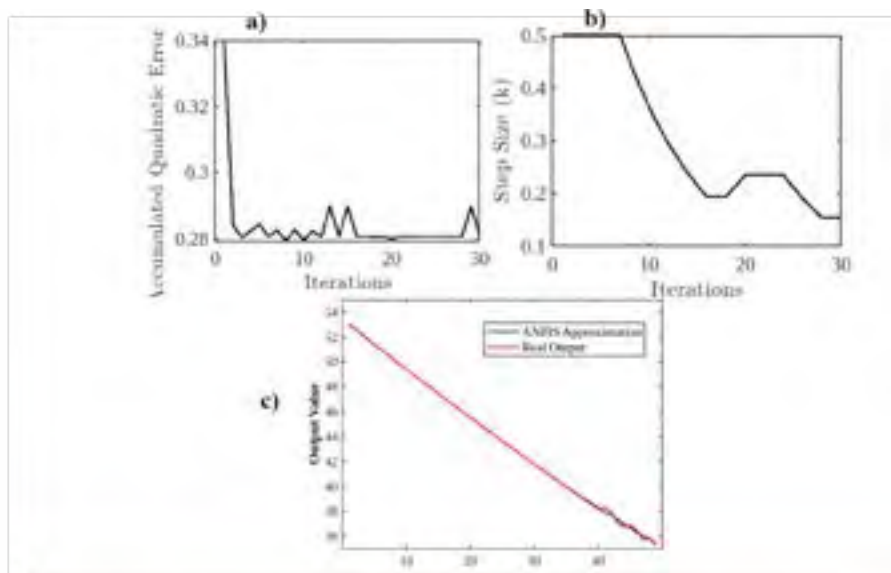


**Fig. 4.** Evolution of error and step size during the ANFIS training process and comparison between the approximated and real output. a) Accumulated Quadratic Error (EP) as a function of iterations. b) Step size  $\alpha_k$  as a function of iterations. c) Comparison between the approximated output obtained by ANFIS and the real output. The results correspond to Case 1.

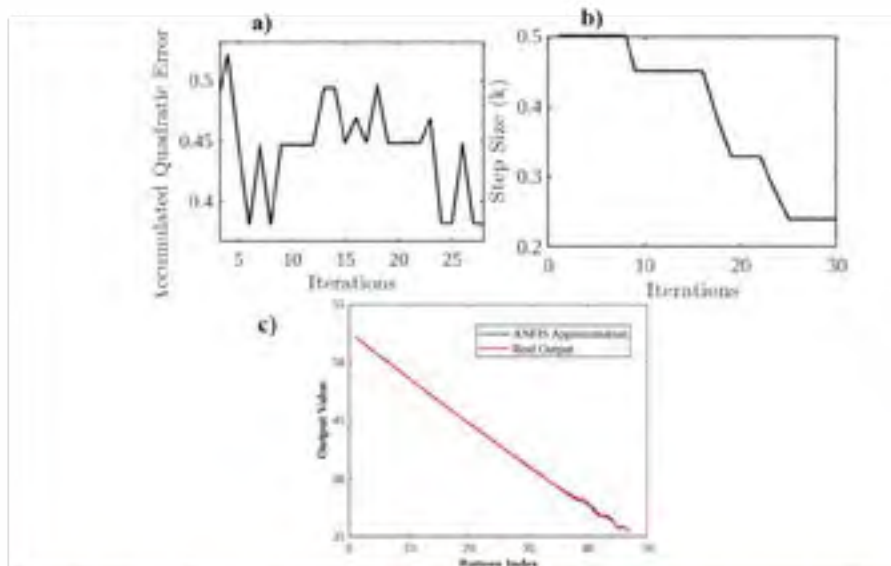
In Figure 4(a), the Accumulated Quadratic Error (EP) for Case 1 decreases sharply within the first 50 iterations, followed by a gradual stabilization. This rapid reduction indicates effective learning during the initial training phase, while the plateau suggests convergence toward an optimal solution. A similar trend is observed in Figures 5(a) and 7(a) for Cases 2 and 3. However, Case 3 exhibits a marginally slower convergence rate, likely due to the increased complexity introduced by delayed input variables. The final EP values for all cases remain below  $1 \times 10^{-3}$ , demonstrating the model's capability to minimize prediction errors effectively.

The step size ( $\alpha_k$ ), depicted in Figures 4(b), 5(b), and 6(b), reflects the adaptive nature of the hybrid learning algorithm. Initially, larger step sizes facilitate rapid parameter adjustments, accelerating error minimization. As training progresses, the step size decreases, ensuring finer tuning of the ANFIS parameters to avoid overshooting local minima. Case 3 (Figure 6(b)) maintains a slightly higher step size throughout training, which may enhance exploration in a more complex input space. This adaptability underscores ANFIS's robustness in balancing exploration and exploitation during optimization.





**Fig. 5.** Evolution of error and step size during the ANFIS training process and comparison between the approximated and real output. a) Accumulated Quadratic Error (EP) as a function of iterations. b) Step size  $\alpha_k$  as a function of iterations. c) Comparison between the approximated output obtained by ANFIS and the real output. The results correspond to Case 2.



**Fig. 6.** Evolution of error and step size during the ANFIS training process and comparison between the approximated and real output. a) Accumulated Quadratic Error (EP) as a function of iterations. b) Step size  $\alpha_k$  as a function of iterations. c) Comparison between the approximated output obtained by ANFIS and the real output. The results correspond to Case 3.

## 4 Conclusion

This study introduces a hybrid "gray-box" model combining physico-mathematical frameworks and neuro-fuzzy systems (ANFIS) to optimize hollow fiber membranes for multicomponent gas separation. The integration balances accuracy, interpretability, and adaptability, achieving exceptional predictive performance ( $R^2 = 0.9990$ , MAE = 0.1180). Sensitivity analysis confirmed permeance's pivotal role in selectivity, especially under varying  $\text{CO}_2/\text{Gas Natural}$  ratios. ANFIS enabled dynamic adaptation to complex scenarios, ensuring robustness in real-world environments.

To advance the model, future research will focus on three axes: improving physical models, enhancing ANFIS, and integrating control systems. Physical model refinements include iterative subroutines for gas solubility/diffusivity (addressing non-ideal effects like plasticization), turbulent flow pressure-drop equations for high-pressure operations, and cubic equations of state (e.g., Peng-Robinson) for accurate gas behavior. For ANFIS, autoregressive/parallel configurations could capture spatiotemporal dependencies, while deep learning integration would handle complex datasets. Lastly, embedding bio-inspired algorithms (e.g., ant particle swarm optimization) into predictive control scheme. These enhancements aim to broaden the model's applicability to diverse separation systems, driving scalability and sustainability in the energy sector.

All the methodologies presented in this study will be applied to a  $\text{N}_2/\text{O}_2$  separation process to optimize nitrogen injection in reservoirs. This injection is a key process, the main objective is for optimization and control in a hydrocarbon production system using ANNs and bioinspired system [18].

### Acknowledgments

The first author thanks to CONAHCYT by its support via a scholar grant for Ph. D. studies. Likewise, the authors thank Universidad Autonoma del Carmen by allowing the facilities to develop this research project.

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# Identification of agricultural irrigation model via differential neural networks

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<https://www.cucei.udg.mx/es/investigacion/cuerpos-academicos/sistemas-inteligentes-0>

**Abstract.** Continuous monitoring of agricultural crops has traditionally been carried out through direct human supervision, either empirically or through instrumentation, this way in which agricultural workers monitor states of their production. This activity is very laborious since it involves constantly taking measurements and visual verifications during practically the entire evolutionary period within the crop to have certainty in the production yields for each established agricultural cycle. This article describes a method that uses a differential neural network that identifies the stages dynamic evolution; available water resource, amount used by plant and amount of material that fulfilled its life cycle, biomass, and that with accurate data it is possible to have better crop performance in each agricultural cycle as well as the care of the inputs and resources related to this important human activity.

**Keywords:** identification, differential neural network, evapotranspiration, algorithm, irrigation, agriculture

## 1 Introduction

Currently there are numerous strategies and ways to carry out control, identification, estimation and monitoring, all with applications to physical measurements of known signals, obtaining a permanent reading of the controlled variables, and through the execution of an algorithm or mathematical method. In this document it is based on the identification part that is fundamental for the success of a good control implementation and is carried out using a differential neural network [1][2][3]. Here this differential neural network DNN method is applied to a dynamic model of agricultural crop growth [9] which identifies parameters for their biological development through its variables, such as the amount of water needed and the amount of biomass developed [8]. Constant monitoring of an agricultural crop traditionally carried out by a human here is assisted by DNN, a computational that integrates calculation and simulation tools, capable of identifying the system parameters in detail [11]. MATLAB® and Python are software that, among their multiple functionalities, contain modules that could

<https://doi.org/10.61728/AE20255015>





estimate the parameters of a plant[17][18]. It would also allow calculating its response to different input signals or physical variables to be measured, and thus determine the intelligent models that best fit the reality of a given system in the agricultural sector. Information on the status of crops is a growing demand from both farmers (to support precision farming methods) and institutions at different levels (to improve yield forecasts or ensure environmentally friendly practices)[12]. Agricultural management by growth stage is essential to optimize the yields of inputs such as nitrogen , plant growth regulator (PGR), fungicides and water [9].

## 2 Methodology

Identification is a method of collecting data to model the behavior of a given system [1][3]. In this paper, this identification incorporates a DNN differential neural network structure. These have the potential to model nonlinear systems that take into account the input/output relationship of a dynamic differential network. Therefore, with the purpose of carrying out the process of identifying the parameters of the system itself for state variables in the first instance for the agricultural sector, the dedicated structure to carry out this process is shown, Fig.1. Effectiveness has been recognized through the use of artificial neural networks for solving problems in reality that are based on an intelligent approach that is based on mathematical theorems that approximate for the identification of nonlinear systems [1] [13].

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### Algorithm 1 algorithm DNN

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1.  $(x_n, y_n^*)$ , Data Set  $A, W_j$  initialize
  2. for each  $x \leftarrow \hat{x}$
  3. for each layer  $\sigma_i(x) = a_i \left(1 + e^{-b_i x_i}\right)^{-1} - c_i \phi_{i,j}(x) = \hat{a}_{i,j} \left(1 + e^{-\sum_p b_{ij}^p x_p}\right)^{-1} - \hat{c}_{i,j}$
  4. compute  $(x_n, y_n^*)W_j = -s_i [K_1 P \Delta_t \sigma(\hat{x}_t)^T] W_j = -s_i [K_2 P \Delta_t \gamma(u_t)^T \phi(\hat{x}_t)^T]$
  5. for each weight  $W_t \leftarrow$  update
  6.  $\dot{V}_t \leq s_i [\Delta_t^T Q_0 \Delta_t + \eta]$  is obtained  $V_t$  bounded
  7.  $(x_n, y_n^*)$ , update parameters  $\theta$
  8. while  $\Delta_t, W_{1,t} + W_{2,t} \in L^\infty$  condition not satisfied
  9. Repeat
- 

where  $W_j$  refers to the weights in node  $i_j$ .

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Algorithm 1 shown in the pseudocode can be seen that learning law (12) of multilayer dynamic neural network (7) has a structure similar to the back propagation of multilayer perceptrons. Because it is derived using the Lyapunov approach, the stability of the global asymptotic error is guaranteed. Hence, the local minimum convergence problem.

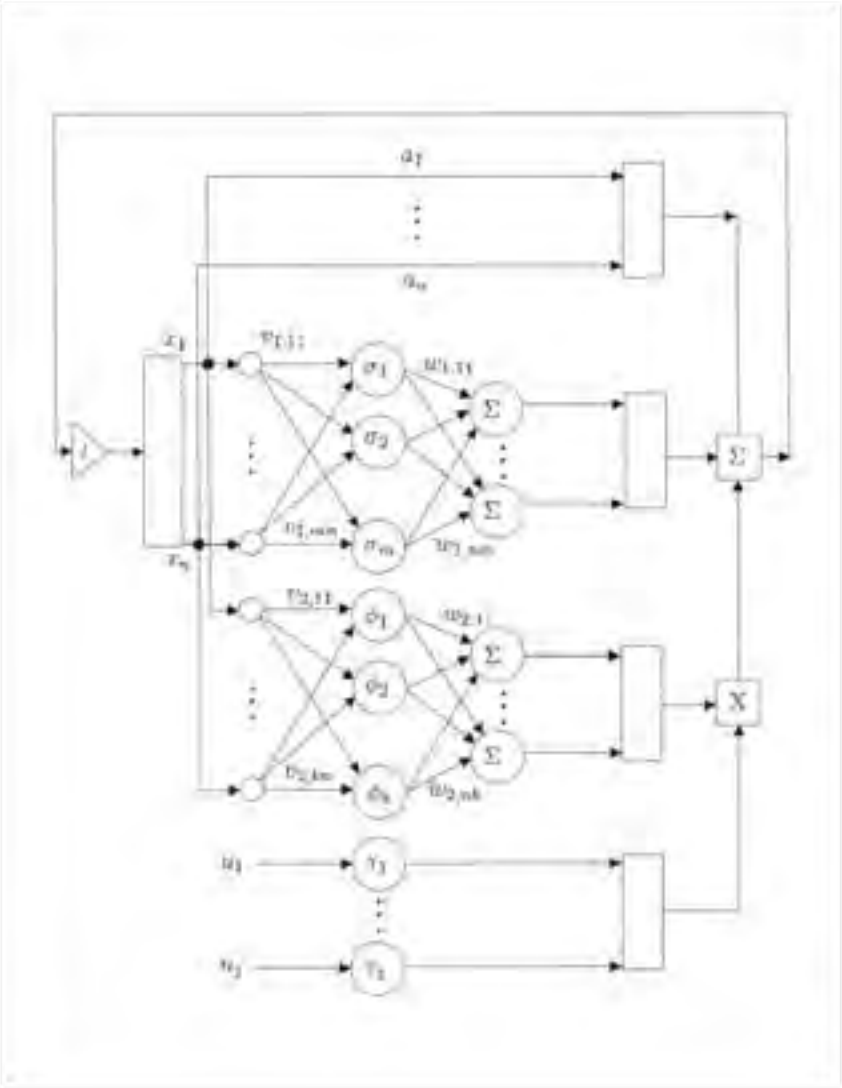


Fig.1. neuro-dynamic network structure

### 3 Crop model formulation

It is well known that variations in water content affect plant growth, the water flow process forms a soil-plant system, where water variations directly affect the roots of the plant [7][8]. Description is represented by the following:

1. Soil water availability.
2. Water is available for growth.
3. dry biomass number.

Process is the movement of molecules, water that enters is equal to that which is not used by transpiration and the stored :

$$\frac{dW}{dt} = \{W_{absorption}\} - \{W_{removed}\} \quad (1)$$

$$\{W_{absorption}\} = \xi_4 \left( \frac{x_2}{1 + \xi_5} \right) r_t \quad (2)$$

$$\{W_{removed}\} = \mu \rho(x) \xi_2 + x_2 \xi_6 \quad (3)$$

in (3) the term  $G(x)$  is considered by transpiration and  $\mu$  is the plant growth rate

$$\dot{x}_3 = -\alpha_9 x_{3,t} - \frac{\sigma x_t}{1 + g x_t^\psi} \quad (4)$$

For plant growth [5], the variation in dry matter is considered,  $x_t$  number of biomass processed in time,  $\alpha_9$  correspond to the degradation rate of plant,  $\sigma$  reason of essential intent and element  $\psi$  drives speed growth, classification according to  $\psi$ :

- (a) the dry mass cannot grow; If  $\psi < 0$ , then  $\rho(x) = \frac{\theta x}{1 + \theta^{1-\psi}}$ ,  $x \gg 1$  tends  $\theta x$ .
- (b)  $\psi = 0$ , presents  $\rho(x) = (\frac{\theta}{1+\theta})x$ , biomass increases as area.
- (c)  $\psi > 1$ , if  $x \gg 1$  then  $\rho(x) = \frac{1}{x^{(\psi-1)}} \frac{\theta}{\psi}$ , this case is unusual since it quickly goes to zero.

below dynamic system, which represents the relationships given in equations (1) to (4).

$$\begin{cases} \dot{x}_1 = -\alpha_1 \frac{x_{1,t} x_{2,t}}{1 + \alpha_3 x_{2,t}} - \alpha_1 x_{1,t} + r_t \\ \dot{x}_2 = \alpha_4 \frac{x_{1,t} x_{2,t}}{1 + \alpha_3 x_{2,t}} - \alpha_5 x_{2,t} - \frac{\alpha_6 x_{3,t} x_{2,t}}{1 + \alpha_7 x_{3,t}} \\ \dot{x}_3 = -\alpha_9 x_{3,t} + \frac{\alpha_8 x_{2,t} x_{3,t}}{1 + \alpha_7 x_{3,t}} \end{cases} \quad (5)$$

Plant of the previous system (5) is defined  $\Omega = (x_1, x_2, x_3) \in R^3 | \Omega \geq 0$ .

Climatic parameters ultimately influence dynamic evolution of agricultural crops, solar irradiation, humidity, air, and also elemental inputs for their development, as those described in Table 1. [9]

**Table 1.** Parameters description

| Parameters | description                                    | units                                   |
|------------|------------------------------------------------|-----------------------------------------|
| $\alpha_1$ | Reason for pond water decrease.                | $[\text{time}]^{-1}$                    |
| $\alpha_2$ | Water consumed by plant                        | $[\text{time} \times \text{mass}]^{-1}$ |
| $\alpha_3$ | Limiting parameter of $x_{2,t}$                | $[\text{mass}^{-1}]$                    |
| $\alpha_4$ | Intrinsic increase of water within the plant   | $[\text{time} \times \text{mass}]^{-1}$ |
| $\alpha_5$ | Reason for water decrease within the plant.    | $[\text{time}]^{-1}$                    |
| $\alpha_6$ | Intrinsic decrease in water by photosynthesis. | $[\text{time} \times \text{mass}]^{-1}$ |
| $\alpha_7$ | Limiting parameter of $x_{3,t}$                | $[\text{mass}]^{-1}$                    |
| $\alpha_8$ | Characteristic ratio water within the plant.   | $[\text{time} \times \text{mass}]^{-1}$ |
| $\alpha_9$ | Plant degradation                              | $[\text{time}]^{-1}$                    |
| $x_{1,t}$  | Water available in the delimited area          | $[\text{time}]^{-1}$                    |
| $x_{2,t}$  | Quantity of internal water                     | $[\text{time} \times \text{mass}]^{-1}$ |
| $x_{3,t}$  | Biomass completed process                      | $[\text{time} \times \text{mass}]^{-1}$ |
| $r_t$      | Irrigation action                              | $[\text{time} \times \text{mass}]^{-1}$ |

A dynamic model system approach to agricultural systems markedly improves production in each cycle, which although this is outside the scope of this document, It has a great economic and labor impact environmental impact, in addition to the social components .

#### 4 Differential neural network structure

Nonlinear system (5) and the DNN (7) are considered. If the assumptions are met [1][2][3]:

$$\begin{aligned} x_t &= f(x_t, u_t, t) \\ x_t &\in \mathbb{R}^n, u_t \in \mathbb{R}^m, n \geq m \end{aligned} \quad (6)$$

which analyzes following neuronal structure:

$$\begin{aligned} \frac{d\hat{x}}{dt} &= A\hat{x}_t + W_{1,t}\sigma(\hat{x}) + W_{2,t}\phi(\hat{x})u_t \\ A &\in R^{n \times n}, W_{1,t} \in R^{n \times n}, W_{2,t} \in R^{n \times n}, \sigma(\cdot) \in R^n \end{aligned} \quad (7)$$

and with sigmoidal activation functions that satisfy Lipschitz condition based on Lemma 1:

$$\begin{aligned}\sigma_i(x) &= a_i \left( 1 + e^{-b_i x_i} \right)^{-1} - c_i \\ \phi_{ij}(x) &= \bar{a}_{ij} \left( 1 + e^{-\sum_p \bar{b}_{ij}^p x_p} \right)^{-1} - \bar{c}_{ij}\end{aligned}\quad (8)$$

$$\begin{aligned}\|\sigma(x_t) - \sigma(x'_t)\|_{A_\sigma}^2 &\leq I_\sigma \|x_t - x'_t\|_{A_\sigma}^2 \\ \|\varphi(x_t) - \varphi(x'_t)\|_{A_\varphi}^2 &\leq I_\varphi \|x_t - x'_t\|_{A_\varphi}^2,\end{aligned}\quad (9)$$

where  $A_\varphi, A_\sigma$  are positive definite matrices.

Input signal is defined as:

$$r_t \leq \bar{r}_t$$

A strictly positive matrix  $\Theta$  given that a matrix  $A$  is stable, then the Riccati equation positive

$$A^T P + P A + P \Gamma P + \Theta = 0 \quad (10)$$

$$\begin{aligned}\gamma &= 2\bar{W}_1 + 2\bar{W}_2 + A_f^{-1} \\ W_1 &:= W_1^*{}^T A_1^{-1} W_1^* \\ \bar{W}_1 &:= W_2^*{}^T A_1^{-1} W_2^* \\ \Theta &= \Theta_1 + A_\sigma + \mu^2 A_\phi\end{aligned}\quad (11)$$

Weight updating rule contained in the differential neuronal structure shown in Fig.1 is shown.

$$\begin{aligned}W_1 &= -s_t [K_1 P \Delta_t \sigma(\hat{x}_t)^T] \\ W_2 &= -s_t [K_2 P \Delta_t \gamma(u_t)^T \phi(\hat{x}_t)^T]\end{aligned}\quad (12)$$

where dead zone is defined by:

$$s_t := 1 - \frac{\mu}{\|P^{\frac{1}{2}} \Delta\|} \quad (13)$$

$$\mu(t) = \frac{\bar{\eta}}{\lambda_{\min} \frac{P}{Q_1 P^{-\frac{1}{2}}}}, \quad (14)$$

**Lemma 1.** *if differentiable vector given  $\vartheta(x) \in \mathbb{R}^n, (x \in \mathbb{R}^m)$  satisfies the Lipschitz condition globally, presents the constant  $I$*

$$\|f(x_1) - f(x_2)\| \leq I \|x_1 - x_2\|, I > 0 \quad (15)$$

for any  $x_1, x_2 \in \mathbb{R}^n$ , property for  $x, \Delta x \in \mathbb{R}^n$  :



$$\|f(x + \Delta x) - \theta(x) + \nabla^T g(x) \Delta x + v_\theta\| \quad (16)$$

where the vector  $v_\theta$  meets  $\|v_\theta\| \leq 2L_g \|\Delta x\|$

**Lemma 2.** A positive function  $V(x) \in \mathbb{R}^n$

$$V(x) := \|\|x - x^*\| - \mu\|_+^2 \quad (17)$$

$[\bullet]_+^2 := ([\bullet]_+^2)[\bullet]_+$  defined :

$$[\kappa]_+ = \begin{cases} \kappa, & \kappa \geq 0 \\ 0, & \kappa < 0 \end{cases} \quad (18)$$

and  $V(x)$  is differentiable:

$$\nabla V(x_t) := 2[\|x_t - x_t^*\| - \mu]_+ \frac{x_t - x_t^*}{\|x_t - x_t^*\|} \quad (19)$$

the Lipschitz constant = 1.

**Theorem 1.** For a system of equations form (6) in conjunction with neural network (7), it is true that:

$$\Delta_t, W_{1,t} + W_{2,t} \in I^\infty \quad (20)$$

where identification error  $\Delta_t$  meets following equation:

$$\limsup_{t \rightarrow \infty} \frac{1}{T} \int_{t=0}^T (\Theta_1 \Delta_t^T \Delta_t s_t dt \leq \bar{\eta}. \quad (21)$$

be candidate Lyapunov function and its derivative:

$$V_t := \Delta_t^T P \Delta_t + tr \left[ \bar{W}_{1,t}^T K_1^{-1} \bar{W}_{1,t} \right] + tr \left[ \bar{W}_{2,t}^T K_2^{-1} \bar{W}_{2,t} \right] \quad (22)$$

$$\begin{aligned} \dot{V}_t = & \frac{d}{dt} (\Delta_t^T P \Delta_t) + \frac{d}{dt} tr \left[ \bar{W}_{1,t}^T K_1^{-1} \bar{W}_{1,t} \right] \\ & + \frac{d}{dt} tr \left[ \bar{W}_{2,t}^T K_2^{-1} \bar{W}_{2,t} \right] \end{aligned} \quad (23)$$

Given that  $s_t \geq 0$

$$\dot{V}_t \leq s_t \Delta_t^T I \Delta_t + I_{w1} + I_{w2} - \Delta_t^T \Theta_1 s_t + \bar{\eta} s_t \quad (24)$$

where:

$$\begin{aligned}
I &= A^T P + P A + P Y P + \Theta \\
2tr I_{w1} &= \left[ \hat{W}_{1,t}^T K_1^{-1} \hat{W}_{1,t} \right] + 2 \Delta_t^T P \hat{W}_{1,t} \sigma s_t \\
2tr I_{w1} &= \left[ \hat{W}_{1,t}^T K_1^{-1} \hat{W}_{1,t} \right] + 2 \Delta_t^T P \hat{W}_{1,t} \mu s_t
\end{aligned}$$

equating learning matrices:

$$\hat{W}_{1,t} = \hat{W}_{1,t}, \hat{W}_{2,t} = \hat{W}_{2,t} \quad (25)$$

is obtained

$$I_{w1} = 0, I_{w2} = 0 \quad (26)$$

is obtained  $V_t$  bounded

$$\dot{V}_t \leq s_t [\Delta_t^T \Theta_0 \Delta_t + \bar{\eta}] \quad (27)$$

Right side of this inequality can be estimated as follows:

$$\dot{V}_t \leq s_t \lambda_{\min} \left[ P^{\frac{1}{2}} \Theta_1 P^{-\frac{1}{2}} \right] \left[ \|P^{\frac{1}{2}} \Delta\|^2 - \mu \right] \leq 0 \quad (28)$$

Since  $0 \leq s_t \leq 1$ , produces:

$$\dot{V}_t \leq -\Delta_t^T \Theta_0 \Delta_t \bar{\eta} s_t \leq -\Delta_t^T \Theta_0 \Delta_t s_t + \bar{\eta} \quad (29)$$

Integrating (27) from 0 to  $T$ :

$$V_T - V_0 \leq - \int_{t=0}^T (\Theta_1 \Delta_t^T \Delta_t s_t dt) \leq \bar{\eta} \quad (30)$$

Since  $W_{1,0} = W_{1,0}^*$  and  $W_{2,0} = W_{2,0}^*$ ,  $V_0$  are bounded

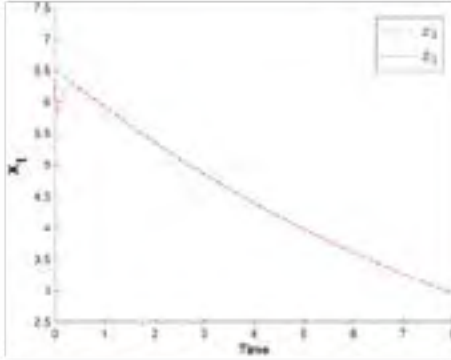
$$\int_{t=0}^T (\Theta_1 \Delta_t^T \Delta_t s_t dt) \leq V_0 - V_T \bar{\eta} \leq V_0 + \bar{\eta} T \quad (31)$$

## 5 Simulation results

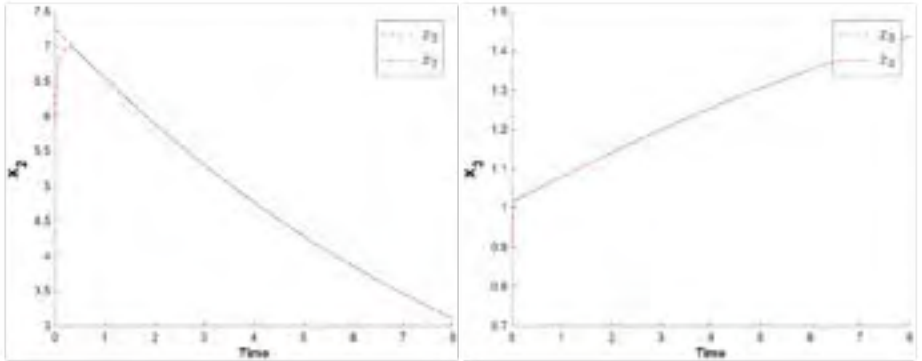
DNN constants initialization:

$$A_0 = \begin{pmatrix} -8 & 0 & 0 \\ 0 & -8 & 0 \\ 0 & 0 & -8 \end{pmatrix} \hat{x}_0 = (7.5 \ 0 \ 0)$$

$$W_1 = W_2 = \begin{pmatrix} 2 & 2 & -2 \\ 2 & 5 & -4 \\ 7 & -4 & 6 \end{pmatrix} P = \begin{pmatrix} 0.15 & 0.08 & -0.1 \\ 0.08 & 0.32 & -0.22 \\ -0.1 & 0.22 & 0.36 \end{pmatrix}$$



**Fig. 2.** First state of identifier converging true system state;  $\alpha_2 = 2.0(\text{time} \times \text{mass})^{-1}$ ,  $\alpha_8 = 0.01(\text{time} \times \text{mass})^{-1}$ ,  $\alpha_3 = 0.0001(\text{time})^{-1}$



**Fig. 3.** Second and third states of identifier converging true system state;  $\alpha_1 = 0.0001(\text{time})^{-1}$ ,  $\alpha_3 = 20(\text{mass})^{-1}$ ,  $\alpha_4 = 0.1(\text{time} \times \text{mass})^{-1}$ ,  $\alpha_5 = 0.1(\text{time})^{-1}$ ,  $\alpha_6 = 0.1(\text{time} \times \text{mass})^{-1}$ ,  $\alpha_7 = 0.1(\text{mass})^{-1}$

Identification simulation shows characteristics achieved over time by dynamic system (5), which are shown by means of DNN initialization constants matrices  $A, W_1, W_2$ ; first in Fig. 2 the convergence of state  $x_1$  towards the natural evolution of the trajectory (available water) is observed with  $\alpha_2, \alpha_8$  and  $\alpha_9$  parameters arranged below this same graph, second in Fig. 3 dynamic evolutionary trajectories of states  $x_2$  and  $x_3$  are shown which in conjunction with the  $\alpha_1, \alpha_3, \alpha_4, \alpha_5, \alpha_6$  and  $\alpha_7$  parameters show the temporary consumption of water by the plant and reach of maturity of its biomass. Evolution of states are captured in these simulations which in applications of DNN proposal in this document give a very approximate graphic identification result as those shown above.

## 6 Conclusion

DNN is applied to identification dynamic agriculture growth (evapotranspiration). Through it, a numerical example was developed to show how proposed identifier will be used to approximate the dynamics of the system of equations and its states are shown in graphic form. Mathematical use from specific model result useful applied agriculture area with model every time better approximated by hand of artificial neurons which in document is applied through a specific structure that provides a high quality result and a well-supported numerical interpretation all this in company of computational numerical software.

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# Formation Control with Area Constraints for Omnidirectional Mobile Robots

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**Abstract.** A consensus-based formation control strategy with area constraints and collisions avoidance is used on omnidirectional mobile robots for testing flexibility and robustness. This control law integrates a vertex-tension function for collision avoidance problem. Simulations are presented using CoppeliaSim<sup>®</sup> from Coppelia Robotics AG, 8049 Zurich, Switzerland and the default omnidirectional model included.

**Keywords:** Signed area constraints · Omnidirectional-drive robots · Multi-robot systems · Collision avoidance · Formation control.

## 1 Introduction

Collaborative and cooperative task are one of most popular advantages for multi-agent systems, such applications can be cooperative transportation, search-and-rescue, collaborative exploration along with others [1, 2]. More precisely a multi-robot system can be described as a group of robots with the capabilities of communication, sensing and actuation, which can work together to solve a problem and archive a common goal. Formation control aim to drive a multi-robot system to archive certain patterns, most of the time formation control can be solved as a consensus problem, but there are many other ways to solve the formation problem [3, 4]. A consensus-based formation control aims to converge all agents into a common value which defines pattern centroid [5].

Collision among agents are common when working with formation tasks of multiple agents, to solve this problem the most common approach is use of artificial potential field [6, 7], this method is unstable in presence of communication delays. Moreover, edge-weighted consensus-based formation control strategy can overcome these drawbacks by guaranteeing collision avoidance among agents by employing weighted graphs properties, allowing to adapt shape of formation to avoid collisions among robots. This work extends results presented in [8], where an edge-weighted formation control for differential mobile robots is presented, in which length of edges of the  $i$ th robot and  $j$ th robot are given by edge-tension function for collision avoidance and a signed area term to mitigate ambiguities in robot formation, the main focus is to implement the control law on different type of robots and a different environment to prove the robustness and flexibility

<https://doi.org/10.61728/AE20255022>



of the controller and its many advantages on multi-robot systems. In addition, inspiring to work with a wider variety of robots is another goal of this work and how they can be used to solve formation control problem.

This work addresses vertex-weighted consensus-based formation control with a control law that incorporates a vertex-tension function with a signed area term to consider constraints for omnidirectional robots, in past works edge-weighted consensus-based formation control with collision avoidance has been explored [12]. Vertex-tension functions aim to maintain agents of formation from colliding each other [10], by controlling the sign of the area of a triangle and the length of the sides we can add a constraint that mitigate ambiguities and avoid local minimum stagnation as well as helping with the desired formation shape, a desired shape can be constructed by using a variety of triangles to form it. Another advantage of the signed area is the capability of performing formation control in a decentralized manner archiving the desired formation pattern in any initial position [11], we call this the sign area constraints. For the multi-robot system, omnidirectional mobile robots from simulation software CoppeliaSim® are used.

Omnidirectional mobile robots have non-conventional wheels allowing them to move along any direction in plane  $X$  and  $Y$  because of this, they have a good maneuverability. Furthermore, lineal velocities  $v_x$   $y$   $v_y$  and angular velocity  $\omega_z$  are control variables. In this paper, main focus are four wheeled configuration.

Main contributions of this paper can be summarized below: Given the vertex-weighted consensus-based formation control with area constraints and collision avoidance strategy and a desired formation, test proposed approach for an omnidirectional type of robot and prove the flexibility and robustness of this strategy. Test the efficiency under a different simulated environment.

This paper is organized as follows: Section 2, presents the kinematic model formulation of a holonomic omnidirectional mobile robot. Then, vertex-weighted consensus-based control design is included at Section 3. In Section 4, the experimental results are presented in CoppeliaSim® with graphics for the velocities and lengths of the edges. An analysis of the reported results are given in Section 5. Lastly, conclusions are presented in Section 6.

## 2 Kinematics Model Formulation

Case of study considers a set of  $N$  omnidirectional four wheeled drive robots, they are holonomic allowing all three degrees of freedom (DOF) to be controlled without restriction. A omnidirectional four wheeled drive robot model is illustrated in Fig. 1. For each mobile platform  $i$ , the robot pose is given by position  $(v_x, v_y)$  and orientation  $(\omega_z)$ , is a local framework  $Fo_i$ , with respect to a world frame  $FG$ .

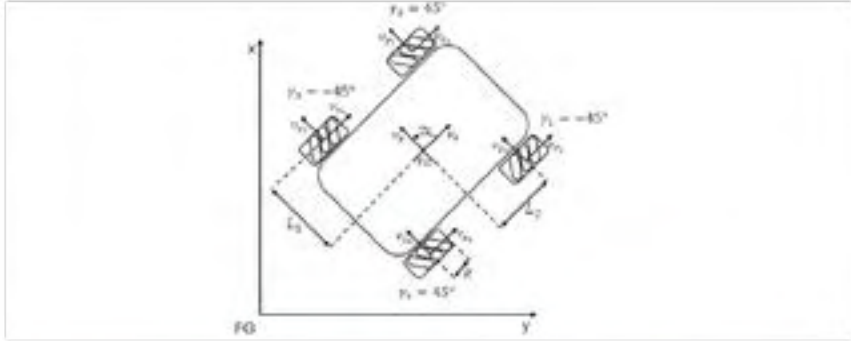


Fig. 1. Omnidirectional wheeled driven robot model.

each wheel  $i$  has a velocity  $v_{x_i}$  and  $v_{y_i}$ , rollers at an angle represented by  $\gamma_i$ ,  $R$  which denotes radius of wheels,  $L_1$  and  $L_2$  represent the distance between wheel axis and body center. Using the framework of each wheel, velocities of each component can be obtain and are represented in Eq. 1.

$$\begin{aligned} v_{x_1} &= v_1 + v_{r_1} \cos(45^\circ) & v_{x_2} &= v_2 + v_{r_2} \cos(45^\circ) \\ v_{y_1} &= v_{r_1} \sin(45^\circ) & v_{y_2} &= -v_{r_2} \sin(45^\circ) \\ v_{x_3} &= v_3 + v_{r_3} \cos(45^\circ) & v_{x_4} &= v_4 + v_{r_4} \cos(45^\circ) \\ v_{y_3} &= -v_{r_3} \sin(45^\circ) & v_{y_4} &= v_{r_4} \sin(45^\circ) \end{aligned} \quad (1)$$

where  $v_i$  and  $v_{r_i}$  represents linear velocity of wheel  $i$  and rollers respectively. Based on local framework, the equations obtain for each wheel velocity are given by

$$\begin{aligned} v_{x_1} &= v_x - L_1 \omega_z & v_{x_2} &= v_x - L_1 \omega_z \\ v_{y_1} &= v_y + L_2 \omega_z & v_{y_2} &= v_y - L_2 \omega_z \\ v_{x_3} &= v_x + L_1 \omega_z & v_{x_4} &= v_x + L_1 \omega_z \\ v_{y_3} &= v_y - L_2 \omega_z & v_{y_4} &= v_y - L_2 \omega_z \end{aligned} \quad (2)$$

based on Eq. 1 and Eq. 2 linear velocities can be expressed for each wheel  $v_i$  as a function of base frame as:

$$\begin{aligned} v_1 &= v_x - v_y - (L_1 + L_2) \omega_z \\ v_2 &= v_x + v_y + (L_1 + L_2) \omega_z \\ v_3 &= v_x - v_y - (L_1 + L_2) \omega_z \\ v_4 &= v_x + v_y + (L_1 + L_2) \omega_z \end{aligned} \quad (3)$$

this is the inverse kinematic of a omnidirectional mobile robot with four wheels or inverse velocity solution [9] which can also be represented in matrix form as:

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} 1 & -1 & -(L_1 + L_2) \\ 1 & 1 & (L_1 + L_2) \\ 1 & 1 & -(L_1 + L_2) \\ 1 & -1 & (L_1 + L_2) \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix} \quad (4)$$

Therefore, the local kinematic of the four-wheeled omnidirectional model is given by Eq. 5.

$$\begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix} = \frac{R}{4} \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & 1 & 1 & -1 \\ 1 & 1 & 1 & 1 \\ -\frac{1}{L_1 + L_2} & \frac{1}{L_1 + L_2} & -\frac{1}{L_1 + L_2} & \frac{1}{L_1 + L_2} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} \quad (5)$$

A transformation matrix show in Eq.6 is used to map velocities from local frame to global frame.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix} \quad (6)$$

Replacing Eq. 5 in Eq. 6, inverse kinematic of the global frame is obtain, this is the kinematic of each omnidirectional robot

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} \sqrt{2}\sin(\alpha) & -\sqrt{2}\cos(\alpha) & -(L_1 + L_2) \\ \sqrt{2}\cos(\alpha) & \sqrt{2}\sin(\alpha) & (L_1 + L_2) \\ \sqrt{2}\cos(\alpha) & \sqrt{2}\sin(\alpha) & -(L_1 + L_2) \\ \sqrt{2}\sin(\alpha) & -\sqrt{2}\cos(\alpha) & (L_1 + L_2) \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \quad (7)$$

where  $\alpha = \theta + \frac{\pi}{4}$ .

### 3 Edge-Weighted Formation Control

First, some concepts of graph theory are explain next to better comprehend robot undirected graph used for control law. An undirected graph with  $N$  elements is defined as  $G = (V, \mathcal{E})$ , where  $\mathcal{E} \subseteq V \times V$  is the edge set and  $V = \{v_i, i = 1, 2, \dots, N\}$  is the vertex set of cardinality  $N$ ,  $\mathcal{E}_k = (v_i, v_j)$  is the  $k$ th edge of  $G$  and represents bidirectional edge communication between agent  $i$  and  $j$ .

Then, vertex-tension function is define for every vertex  $v_i \in V$ , as proposed in [10] vertex-tension function is defined as

$$V_i = \sum_{j \in N_i} \alpha_{ij} \left( \coth \left( \frac{\|l_{ij}\| - \delta}{k_{ij}} \right) + \frac{1}{2} \|l_{ij}\|^2 - V_{ij}^{min} \right) \quad (8)$$



where  $N_i = \{\forall v_j \in V \mid (i, j) \in \mathcal{E}\}$  is a subset of neighbors of the  $i$ th robot, and  $K_{ij}$  is a constant that defines a related position of the minimum, for example, desired length between each couple of agents,  $\alpha_{ij}$  defines inter-robot influence,  $\delta$  is a safe distance parameter for collision avoidance,  $l_{ij} = p_i - p_j$  is an edge vector, where  $p_i$  and  $p_j$  are the state of the  $i$ th and  $j$ th agents respectively,  $V_{ij}^{min} > 0$  is defined as

$$\min_{\|l_{ij}\| > \delta} V_i = 0 \quad (9)$$

As proposed in [8] a connected graph is created in such way that each vertex  $v_i \in V$  is connected to, at least, one triplet  $(i, j, k)$ , where  $\{(i, j), (j, k), (k, i)\} \in \mathcal{E}$  and a signed area function is used for every triplet to avoid ambiguities and local minima. The set of all triplets  $(i, j, k)$  is denoted by  $T$ , if this set  $T$  is permuted in a cyclical manner, triangle form by the triplet is the same, the subsets of  $T_i$  can be defined as  $\{(i, j) \mid (i, j, k) \in T\}$  those are all triplets where the vertex  $v_i$  is involved. The triplet-tension function used for every vertex is defined in Eq. 10.

$$V_{T_i} = \sum_{(j,k) \in T_i} \frac{1}{2} K_{T_{ijk}} (S_{ijk} - S_{ijk}^*)^2 \quad (10)$$

where  $K_{T_{ijk}} \in \mathbb{R}$  and  $K_{T_{ijk}} > 0$  this gain allows for avoiding ambiguities and local minima, desired signed area is represented by  $S_{ijk}^*$  and current signed area is  $S_{ijk}$  which is defined as:

$$S_{ijk} := \frac{1}{2} \det \begin{bmatrix} 1 & 1 & 1 \\ p_i & p_j & p_k \end{bmatrix} \quad (11)$$

which denotes a triangle who is either positive or negative according to the ordering of  $p_i, p_j, p_k$  around the boundary of the triangle is counterclockwise, or clockwise [11].

A total potential function is defined based on Eq. 8 and Eq. 10.

$$V = \sum_{i=1}^N (V_i + V_{T_i}) \quad (12)$$

The total potential function  $V$  obtain before is the edge-weight function which is designed to ensure collision avoidance between agents  $i$  and  $j$ , if the  $\delta$  parameter is strictly greater than the distance  $\|l_{ij}\|$ . The distance between robots  $i$  and  $j$  is given by

$$\|l_{ij}\| = \delta + K_{ij} \operatorname{acsch} \left( \sqrt{K_{ij}} \right) \quad (13)$$

when this function reaches its minimum the magnitude of the edge vector becomes the specified as desired.

A gradient descent control law for every robot is defined so that the  $i$ th agent moves according to  $\dot{P} = -\frac{\partial V}{\partial P_i}$  which can be translate to Eq. 14

$$\dot{P}_i = U_{N_i} + U_{T_i} \quad (14)$$

where

$$U_{N_i} = - \sum_{j \in N_i} \alpha_{ij} \left( -\frac{1}{k_{ij} \|l_{ij}\|} \operatorname{csch}^2 \left( \frac{\|l_{ij}\| - \delta}{k_{ij}} \right) + 1 \right) (P_i - P_j) \quad (15)$$

$$U_{T_i} = - \sum_{(i,j) \in T_i} K_{T_{ijk}} (S_{ijk} - S_{ijk}^*) \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} (P_j - P_k) \quad (16)$$

The Control Law in Eq. 14 is designed for holonomic robots. For a decentralized control, it is important to ensure that the information used is not accessible to a central unit, but to the robots and every vertex in the graph is part of at least one triplet. Since, signed area function described in Eq. 11 requires the global positions of  $P_i$ ,  $P_j$  and  $P_k$  for control. For decentralized control purposes this function can be expanded and express in relative position terms:

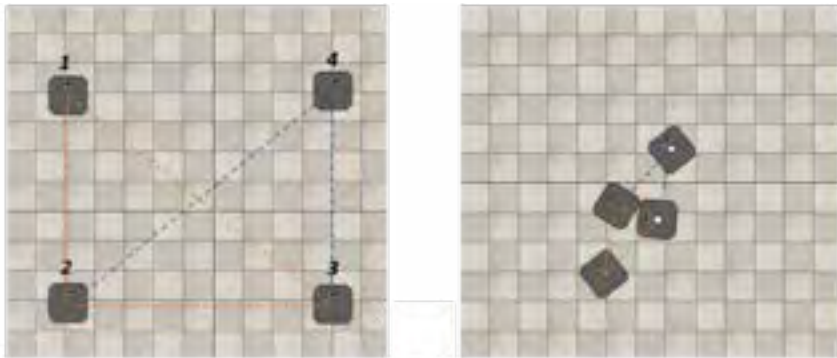
$$S_{ijk} = \frac{1}{2} (P_i - P_j)^T \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} (P_i - P_k) \quad (17)$$

## 4 Experimental Results

The performance and flexibility of the formation control strategy design in [8] is verified with the use of four omnidirectional mobile robots simulated using CoppeliaSim® and four of preset omnidirectional robot model included in this software. Since omnidirectional robots are holonomic unlike differential robots we can use the conventional  $\dot{P}_i = [x_i, y_i]^T$ .

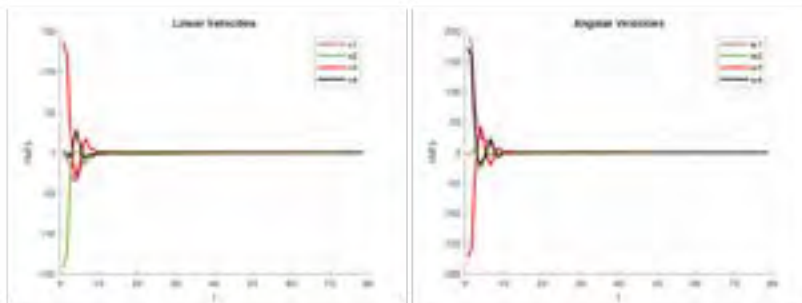
The desired formation aim in this paper is a rhombus shape, the parameters to form this shape are  $k_{ij}$  and  $S_{ijk}^*$ , where  $K_{ij}$  defines the distance between agents  $P_i$  and  $P_j$ , while  $S_{ijk}^*$  is the desired signed area. Formation control settings are briefly described,  $\delta$  which is the safety distance,  $\alpha$  which is the inner-robot influence and  $K_{T_{ijk}}$  which is signed area control gain for triplets. Parameters for each experiment are presented later for different distances of this shape.

First, a rhombus shape with edge distance  $\|L_{ij}\| = 1$ , the distance values to get that magnitude are defined as  $k_{ij} = 0.85175781$  and  $S_{ijk}^* = -0.43301$ , formation control parameters are  $\delta = 0.5$ ,  $\alpha = 1.0$  and  $K_{T_{ijk}} = 5.0$ . In Fig. 3. linear and angular velocities can be observed and how they converge, based on Fig. 4. we can observed the edge distances close to 1 with a small error between the different edges, while the formation is archive as shown in Fig. 2. the error, although small, is significant and can be improved.

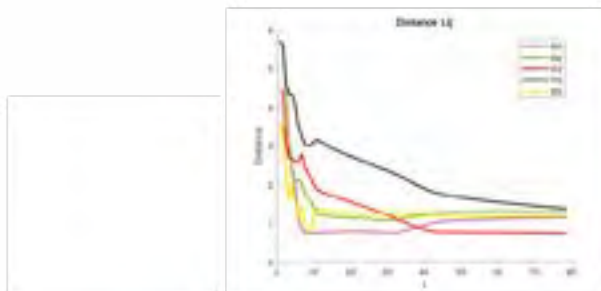


**Fig. 2.** Initial and final position of four omnidirectional robots for distance of 1.

In fig 2, we can see the arrange of the robots in their initial position an the connections between them, as well as the final rhombus shape and how the graph moved.



**Fig. 3.** Linear and angular velocities of each robot.



**Fig. 4.** Edge distance of each connection  $l_{ij}$  with a distance of 1.

In the next figures an increase on the distance was implemented for this the parameters used were  $k_{ij} = 8.5175781$  and  $S_{ijk}^* = -4.3301$ , for the formation control settings the parameters were  $\delta = 1.0$ ,  $\alpha = 1.0$  and  $K_{T_{ijk}} = 1.5$ , the results are shown in Fig. 2 where a clear bigger rhombus shape was archive.

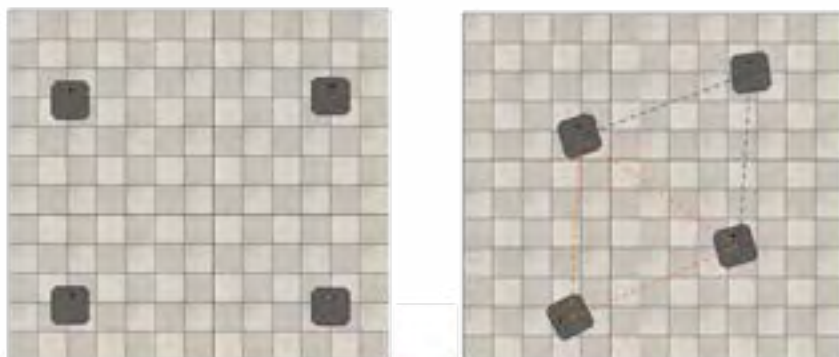


Fig. 5. Initial and final position of four omnidirectional robots with a bigger distance.

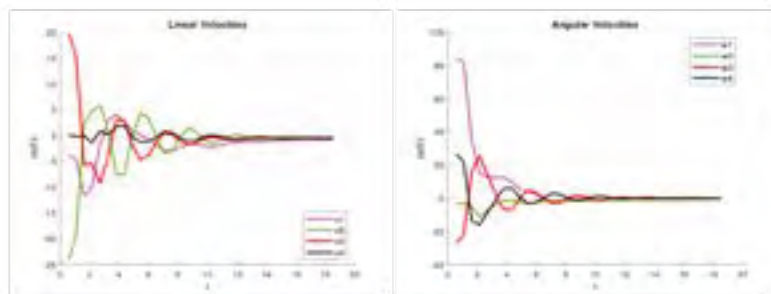


Fig. 6. Linear and angular velocities of each robot.

As expected the formation shape is archive with a better result than the obtain in Fig. 4, the distance between each edge converge with less error than the first example meaning it can be improve with a good selection of parameters, since this experiment was made in CoppeliaSim<sup>30</sup> another factor can be added since the experiment runs on a continuous timer this can be consider as an online experiment.

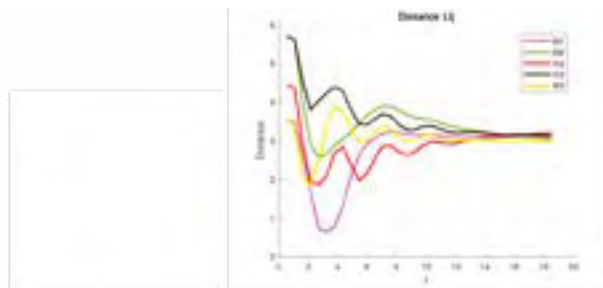


Fig. 7. Edge distance of the increased formation.

## 5 Discussion

The results obtained here prove the flexibility of the control law seen in [8] where the desired shape was achieved with a minimal error, while the results obtained here have been shown to contain an error the proposed approach has many advantages in formation control with a variety of robots, with this paper we add the flexibility and robustness to that control law and how it works under an online simulation, also the capabilities of a holonomic robot using this method can be seen, since the controller shown in Eq. 14 is holonomic. The performance seen here was good achieving the correct formation in under 15 seconds. A next step for this type of controller could be the experimentation of different types of robots like a three wheeled omnidirectional robot or legged ones, also formation control mixing different types to solve this problem, the use of aerial mobile robots on a third-dimensional environment is another possible step in which they could incorporate use of signed volume or use of robots with control law on a real world task.

## 6 Conclusions

This paper addressed the implementation of an edge-weighted consensus-based formation control for omnidirectional four wheeled driven robots in which robustness and flexibility are the objective of this work for a different mobile robot since some works in the past use this type of controller on a differential mobile robot, by achieving the desired formation with a small error in an environment close to real world physics we can prove the efficiency of this type of controller for formation problems, since the controller is design based on a graph topology and the use of signed area makes it so not all of the vertices are required to be connected, the results obtained here are satisfactory proving the efficiency, robustness and flexibility of this type of controller and how it can be used on different type of robots and different environments.



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# Expert PID Algorithm for Autonomous Navigation of an Octocopter UAV

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**Abstract.** In this research work, the design of a PID flight controller with the rules of an expert system was applied to the navigation of an octocopter UAV. The Newton-Euler mathematical formulation is used to calculate the dynamic model of the octocopter UAV. The proposed set of decision rules for the Expert PID flight controller design allows the moment controllers to increase their response capability versus error variations. The simulation results of the navigation algorithm implemented in the octocopter UAV demonstrate that the translation Expert PID controller in interconnection with the attitude Expert PID controller can track a helical trajectory, fulfilling the objective of trajectory tracking as a validation for the proposed navigation algorithm.

**Keywords:** Expert PID · UAV · Octocopter.

## 1 Introduction

In recent years, applications such as agriculture, construction, civil operations, surveillance, and rescue missions have seen increasing demand, presenting new challenges. UAVs have proven to be highly useful in these areas; however, adapting to these evolving needs has led to the emergence of new challenges and requirements for UAV applications. New UAV configurations, such as the eight-rotor design, have been introduced, demonstrating greater stability and robustness against faults compared to the classic four-rotor configuration. For this reason, new controller techniques for octocopter UAVs have been proposed, seeking better response times when addressing faults.

There are some ways to set the configuration of an octocopter UAV. One combines a “+” way where the rotors turn counterclockwise; in the “x” way, the rotors are clockwise. With this configuration, the octocopter UAV has four rotors turning in one way and the other four rotors turning in the other way to stabilize the octocopter UAV when

<https://doi.org/10.61728/AE20255039>



all rotors are in optimal condition [1]. The authors of this work employed a PD control technique to manage attitude and altitude, utilizing a linearized dynamic model. For rotor control, they implemented a robust multicopter motor control approach that accounts for variations in battery voltage. The results were validated through simulations using the parameters of a quadrotor UAV. Additionally, a linear-quadratic regulator (LQR) was specifically designed for 3D trajectory tracking in the octocopter UAV, and the simulation was carried out by studying the altitude, attitude, and navigation controller for tracking position. The results were compared with the previous works mentioned above using the PD controller, concluding that the PD controller presents a fast response [2]. The octocopter is a UAV that presents the capability of playing with the general shape of the aircraft; the classic shape is symmetrical, but other authors, as in [3], changed the UAV to create a "V" shape where four motors are in the left side and other four motors are in the right side. The authors of this octocopter UAV named it a V8 configuration that used a Linear Quadratic Gaussian with an integral (LQG-I) control to stabilize the UAV attitude; this control was compared with a PID and an LQR controller to see the efficiency of energy usage. The authors in [4] presented an octocopter UAV with an asymmetric configuration, where two different arm distances were selected for the rotor in each arm; this design intends to improve the solution using multiple sensors or cameras. The authors used a PID controller with a Grey Wolf Optimizer (GWO) for parameters. They concluded that this octocopter UAV has room to improve due to the experiment not being better than a symmetric octocopter UAV for specific tasks. In [5], an attitude estimation algorithm was designed and implemented on an IMU hardware board. Two attitude controllers were developed and analyzed. The first controller employed a PID approach, which is commonly used for maintaining stable flight conditions in multicopter UAVs. The second control method employed utilized an L1 adaptive control framework. Simulation results suggest that this approach delivers excellent performance, particularly in handling modeling errors and rejecting disturbances, when compared to the PID controller. However, the L1 adaptive controller, being more complex, was more challenging to implement and showed limited noise attenuation. In contrast, the PID controller was successfully deployed on real-time hardware, where experimental flight tests delivered positive outcomes.

A star-shaped octocopter UAV configuration is considered in [6], where an active fault tolerant controller was implemented on such UAV using dynamic control allocation performing a 3-D path. Control allocation intends to use the available UAV actuators to achieve the controls. In [7], the application of fault-tolerant control strategies for an octocopter UAV was discussed. Specifically, it focuses on passive and active fault-tolerant control methods using Second Order Sliding Mode Control (SOSMC). Passive fault tolerance involves designing the system to inherently tolerate faults, while active fault tolerance involves using control strategies to mitigate the effects of faults. A nonlinear optimal control approach for the model of an octocopter UAV was proposed in [8]. They designed a control system that optimally manages the octocopter UAV dynamics in a nonlinear environment. Nonlinear optimal control typically involves sophisticated mathematical techniques to find the best control inputs that optimize a specific performance criterion.



In this work, an Expert PID flight navigation controller that designates the PID strength according to the octocopter UAV error value, each axis and angle is presented. Five main rules are designed by analyzing the actual and previous error values. Simulation results are presented, illustrating the behavior of each axis and angle of the octocopter UAV.

To facilitate a better understanding of this research, the paper has been organized as follows: The equations of motion for the octocopter UAV are presented in Section 2. The proposed Expert PID controller is introduced in Section 3. The control system architecture is described in Section 4, and the simulation results are discussed in Section 5. Finally, a summary of the conclusions and key findings is provided in Section 6.

## 2 Equations of motion for an octocopter UAV

The mathematical representation of the octocopter UAV dynamics utilizes two reference frames. The first is the body frame, which is attached to the structure of the octocopter UAV and aligned with its center of mass, represented as  $B=\{x_b, y_b, z_b\}$ . The second is the inertial frame, fixed to the ground, represented as  $I=\{x_i, y_i, z_i\}$ , as illustrated in Fig. 1. The equations of motion are derived using the Newton-Euler formulation, which serves as a compact mathematical framework for describing the dynamics of the octocopter UAV [10], [11]. Definitions of parameters are shown as follows:

- $\xi$ : Vector coordinate position relative to the inertial frame,  $[x \ y \ z]^T$ .
- $V$ : Translational velocity vector expressed in the inertial reference frame,  $[v_x \ v_y \ v_z]^T$ .
- $R$ : Orthogonal rotation matrix in  $SO(3)$ .
- $T_F$ : Total force vector that contains the total thrust in the direction of gravity  $[0 \ 0 \ f_T]^T$ .
- $f_T$ : Summatory of actuated forces produce by each rotor  $f_k$  of the octocopter UAV.
- $\omega_k$ : Rotation speed of the  $k$ -th rotor in  $rad/s$ .
- $m$ : Total mass of the octocopter UAV.
- $g$ : Gravity force in the inertial frame.
- $e_3$ : Aligned in the direction of the center of Earth.
- $\eta$ : Vector that describes the rotation coordinates for the octocopter in the inertial frame,  $[\phi \ \theta \ \psi]^T$ .
- $E$ : Euler matrix to convert angular velocity in the body frame to the inertial frame.
- $\Omega$ : Angular velocity vector defined in the body-fixed reference frame,  $[p \ q \ r]^T$ .
- $J$ : Matrix  $3 \times 3$  that contain the inertial moments in diagonal form  $J_{xx}$ ,  $J_{yy}$ , and  $J_{zz}$ .
- $\tau_a$ : Moment vector due the actuators,  $[\tau_\phi \ \tau_\theta \ \tau_\psi]^T$ .
- $\tau_\phi$ : Roll moment affected by the rotors  $\omega_1$ ,  $\omega_2$ ,  $\omega_7$ , and  $\omega_8$ .
- $\tau_\theta$ : Pitch moment affected by the rotors  $\omega_1$ ,  $\omega_2$ ,  $\omega_5$ , and  $\omega_6$ .
- $\tau_\psi$ : Yaw moment affected by the drag of all rotors and their direction of rotation.
- $d$ : Distance of each arm from the center of mass to the rotation axis of the rotor.
- $c_T$ : Constant value representing the propeller thrust factor.
- $c_D$ : Constant value representing the drag coefficient of the propeller.

$$\dot{\xi} = V \quad (1)$$

$$m\dot{V} = R(-T_F) + mge_3 \quad (2)$$

$$\dot{\eta} = E\Omega \quad (3)$$

$$J\dot{\Omega} = -\Omega \times J\Omega + \tau_a \quad (4)$$

$$R = \begin{bmatrix} c_\theta c_\psi & s_\theta c_\psi & -c_\phi s_\psi & c_\phi s_\theta c_\psi + s_\phi s_\psi \\ c_\theta s_\psi & s_\theta s_\psi & c_\phi c_\psi & c_\phi s_\theta s_\psi - s_\phi c_\psi \\ -s_\theta & s_\phi c_\theta & c_\phi c_\theta & \end{bmatrix} \quad (5)$$

$$E = \begin{bmatrix} 1 & s_\phi c_\theta & c_\phi c_\theta \\ 0 & c_\phi & -s_\phi \\ 0 & \frac{s_\theta}{c_\phi} & \frac{c_\theta}{c_\phi} \end{bmatrix} \quad (6)$$

The complete dynamic model of the UAV is represented as follows, where  $c_a, s_a, t_a$  with  $a = \phi, \theta, \psi$  denote the cosine, sine, and tangent functions of the Euler angles, respectively.

$$\begin{aligned} \dot{x} &= v_x & \dot{\phi} &= \frac{c_\theta p + s_\theta s_\psi q + c_\phi s_\psi r}{c_\phi} \\ \dot{y} &= v_y & \dot{\theta} &= c_\phi q - s_\phi r \\ \dot{z} &= v_z & \dot{\psi} &= \frac{s_\theta q + c_\theta r}{c_\phi} \\ \dot{v}_x &= -\frac{f_T(s_\theta s_\psi + c_\phi s_\psi c_\psi)}{m} & \dot{p} &= \frac{(J_{xx} - J_{yy})q + J_{xz}r}{J_{xx}} \\ \dot{v}_y &= -\frac{f_T(c_\theta s_\psi - s_\phi c_\psi)}{m} & \dot{q} &= \frac{(J_{xx} - J_{zz})p + J_{xy}r}{J_{yy}} \\ \dot{v}_z &= -\frac{f_T c_\phi c_\psi + mg}{m} & \dot{r} &= \frac{(J_{zz} - J_{yy})p + J_{yz}q}{J_{zz}} \end{aligned} \quad (7)$$

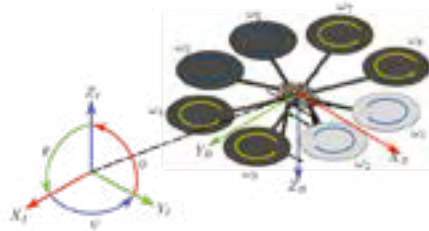


Fig. 1: Coordinate systems and rotational directions of each rotor in the octocopter UAV.

The total thrust force vector of the octocopter UAV propulsion ( $f_T$ ) is calculated by summing all the individual thrust forces produced by the eight rotors ( $f_1, \dots, f_8$ ) of the octocopter UAV, as shown below.

$$f_T = \sum_{k=1}^8 f_k = c_T \sum_{k=1}^8 \omega_k^2, \quad \text{with } f_k = c_T \omega_k^2 \quad (8)$$

The total thrust force vector  $T_T$  is described in the body frame of the octocopter UAV as:

$$T_T = \begin{bmatrix} 0 \\ 0 \\ f_T \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \sum_{k=1}^8 f_k \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ c_T \sum_{k=1}^8 \omega_k^2 \end{bmatrix} \quad (9)$$



The variables  $\omega_1, \dots, \omega_8$  represent the rotor speeds, and variables  $f_1 = c_T \omega_1^2, f_2 = c_T \omega_2^2, \dots, f_8 = c_T \omega_8^2$  represent the lift forces of each one of the eight rotors.

The moments acting in the octocopter UAV are strictly related to the rotor speeds; depending on which rotors perform more speed than the other rotors, the octocopter UAV performs the moments that are indicated in the definitions at the beginning of the section 2 in which rotors move each moment. The roll moment is influenced by rotors  $\omega_7$  and  $\omega_8$  operating at high speed, while rotors  $\omega_3$  and  $\omega_4$  perform with low speed, operate at low speed; this action produces a positive moment. To generate a negative moment, the speed of rotors  $\omega_3$  and  $\omega_4$  must be increased, and the speed of rotors  $\omega_7$  and  $\omega_8$  must be reduced. The positive pitch moment is actuated with the high speed of rotors  $\omega_1$  and  $\omega_2$  and the lower speed of rotors  $\omega_5$  and  $\omega_6$ . The case of the positive yaw moment uses the direction of rotation speed; in this case, rotors  $\omega_1, \omega_2, \omega_5$ , and  $\omega_6$  rotate in the clockwise direction, these rotors rotate with high speed in comparison of the other rotors that rotate in counterclockwise and with lower speed.

$$\begin{bmatrix} f_T \\ \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} c_T & c_T & c_T & c_T & c_T & c_T & c_T & c_T \\ 0 & 0 & -c_T P & -c_T P & 0 & 0 & c_T P & c_T P \\ c_T P & c_T P & 0 & 0 & -c_T P & -c_T P & 0 & 0 \\ c_Q & c_Q & -c_Q & -c_Q & c_Q & c_Q & -c_Q & -c_Q \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \\ \omega_5^2 \\ \omega_6^2 \\ \omega_7^2 \\ \omega_8^2 \end{bmatrix} \quad (10)$$

### 3 Expert PID controller design

The Expert PID control is to design PID parameters with plant characteristics and the control expert experience, with no need for modeling information. The experience is mainly based on the system error response. At time  $t$ , the desired value is considered as  $r_d(t)$ , the measurement value as  $y_o(t)$ , and then the tracking error is  $e_c(t) = r_d(t) - y_o(t)$  at time  $t$ , and  $e_c(t-1)$  and  $e_c(t-2)$ , represent the error at time  $t-1$  and  $t-2$ , respectively [9]. The parameters definitions for the Expert PID controller are shown as follows:

- $u_c$ : Input control that change depending of the specific rule with  $c = \phi, \theta, \psi, x, y, z$  referring to whose control is applied.
- $M_{1c}, M_{2c}$ : Setting the limit values of the errors in rules.
- $C_{nc}$ : Constant value to increase the PID controller to a maximum value where  $n$  is a designed number.
- $k_{pc}, k_{ic}, k_{dc}$ : Gains of the PID controller for the corresponding  $c$  parameter.
- $e_c(t)$ : Proportional error at time  $t$  and  $t-1$ , respectively.
- $\Delta e_c(t), \Delta e_c(t-1)$ : Differential error at time  $t$  and  $t-1$ , respectively.
- $ts$ : Time sample.
- $e_{ic}$ : Integrative error.
- $k_{1c}, \dots, k_{5c}$ : Gains setting the strength of the PID controller.

### 3.1 Rules for Expert PID controller

The Expert PID rules are designed for each controller of the octocopter UAV. These rules are given as follows:

**Rule 1** When  $|e_c(t)| > M_{1c}$ , the strongest PID controller is used to minimize error quickly.

$$u_c(t) = C_{nc}(k_{pc}e_c(t) + k_{dc}\frac{\Delta e_c(t)}{ts} + k_{ic}e_{ic}(t)) \quad (11)$$

**Rule 2** When  $e_c(t)\Delta e_c(t) > 0$  or  $\Delta e_c(t) = 0$ , two conditions are considered as follow:  
A stronger PID controller is used if  $|e_c(t)| \geq M_{2c}$ .

$$u_c(t) = u_c(t-1) + k_{1c}(k_{pc}e_c(t) + k_{dc}\frac{\Delta e_c(t)}{ts} + k_{ic}e_{ic}(t)) \quad (12)$$

A weak PID controller is used if  $|e_c(t)| < M_{2c}$ .

$$u_c(t) = u_c(t-1) + k_{2c}(k_{pc}e_c(t) + k_{dc}\frac{\Delta e_c(t)}{ts} + k_{ic}e_{ic}(t)) \quad (13)$$

**Rule 3** When  $e_c(t)\Delta e_c(t) < 0$ ,  $\Delta e_c(t)\Delta e_c(t-1) > 0$ , or  $e_c(t) = 0$ , which indicates the absolute of error value tends to smaller or constant value, the control input can hold.

$$u_c(t) = u_c(t) \quad (14)$$

**Rule 4** When  $e_c(t)\Delta e_c(t) < 0$ , and  $\Delta e_c(t)\Delta e_c(t-1) < 0$ , which indicates the error value is in extremism state. Two conditions are considered as follows:

A strong PID controller is used if the absolute error value is big,  $|e_c(t)| \geq M_{2c}$ .

$$u_c(t) = u_c(t-1) + k_{3c}(k_{pc}e_c(t) + k_{dc}\frac{\Delta e_c(t)}{ts} + k_{ic}e_{ic}(t)) \quad (15)$$

A weaker PID controller is used if the absolute error value is small,  $|e_c(t)| < M_{2c}$ .

$$u_c(t) = u_c(t-1) + k_{4c}(k_{pc}e_c(t) + k_{dc}\frac{\Delta e_c(t)}{ts} + k_{ic}e_{ic}(t)) \quad (16)$$

**Rule 5** When  $|e(t)| \leq e_c$  indicates that the error magnitude approaches a very small value, a significantly weaker PID control strategy is used for reducing the static error.

$$u_c(t) = k_{5c}(k_{pc}e_c(t) + k_{dc}\frac{\Delta e_c(t)}{ts} + k_{ic}e_{ic}(t)) \quad (17)$$

Where  $\Delta e_c(t) = e_c(t) - e_c(t-1)$ ,  $\Delta e_c(t-1) = e_c(t-1) - e_c(t-2)$ , and  $e_{ic}(t) = e_{ic}(t) + e_c(t)ts$ . Also,  $k_{1c} > k_{3c} > k_{2c} > k_{4c} > k_{5c}$  are the gains that set the strength of the PID controller depending on the rule.

## 4 Flight controller design

### 4.1 Mixer rotor controller

The control vector  $U = [u_1, \dots, u_8]^T = [\omega_1^2, \dots, \omega_8^2]^T$  is utilized to generate the velocity, which depends on the total thrust force and the aerodynamic moments acting on the octocopter UAV. Also, the parameters definitions of the flight controller are shown as follows:

- $U$ : Input controller vector containing each rotor quadratic speed of the octocopter UAV.
- $C_A$ : aerodynamic thrust and drag coefficients matrix of the octocopter UAV.
- $\Gamma$ : vector containing the total thrust and momentos  $[f_T, \tau_\phi, \tau_\theta, \tau_\psi]^T$ .
- $u_k^{Sat}$ : input controller of the quadratic  $k$ th rotor speed saturated.
- $u_{k_{max}}$ : maximum quadratic  $k$ th rotor speed saturated.
- $u_{k_{min}}$ : minimum quadratic  $k$ th rotor speed saturated.
- $\bar{F}_{T_c}$ : Total thrust control associated with the altitude PID controller.
- $\phi_d^{Sat}, \theta_d^{Sat}$ : roll and pitch angles constrained in the range between  $-\pi/2 \text{ rad}$  and  $\pi/2 \text{ rad}$ .
- $u_z$ : altitude PID controller.
- $u_x, u_y$ : navigation PID controller.
- $u_a$ : moment PID controllers,  $[u_\phi, u_\theta, u_\psi]^T$ .

The simplified form of equation (10) is expressed as:

$$\Gamma = C_A U \quad (18)$$

Due to the fact that the  $C_A$  matrix is not square, a pseudo-inverse equation is used to obtain the inverse matrix, as shown below.

$$C_A^{-1} = C_A^T (C_A C_A^T)^{-1} \quad (19)$$

This allows for obtaining the vector of the desired control variables corresponding to each rotor. The developed matrix expression is provided as follows:

$$U = C_A^{-1} \Gamma \quad (20)$$

Obtaining the vector of the desired controller variables corresponds to each rotor. Below is such a developed matrix expression:

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \\ u_6 \\ u_7 \\ u_8 \end{bmatrix} = \begin{bmatrix} \frac{1}{8c_T P} & 0 & \frac{1}{4c_T P} & \frac{1}{8c_Q} \\ \frac{1}{8c_T P} & 0 & \frac{1}{4c_T P} & \frac{1}{8c_Q} \\ \frac{1}{8c_T P} & \frac{-1}{4c_T P} & 0 & \frac{-1}{8c_Q} \\ \frac{1}{8c_T P} & \frac{-1}{4c_T P} & 0 & \frac{-1}{8c_Q} \\ \frac{1}{8c_T P} & 0 & \frac{-1}{4c_T P} & \frac{1}{8c_Q} \\ \frac{1}{8c_T P} & 0 & \frac{-1}{4c_T P} & \frac{1}{8c_Q} \\ \frac{1}{8c_T P} & \frac{1}{4c_T P} & 0 & \frac{-1}{8c_Q} \\ \frac{1}{8c_T P} & \frac{1}{4c_T P} & 0 & \frac{-1}{8c_Q} \end{bmatrix} \begin{bmatrix} f_T \\ \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} \quad (21)$$

Thus, the required control strategies are determined for the individual rotors in the octocopter UAV. A saturation function will be introduced to establish the operational limits

of the rotors, including their minimum and maximum rotation speeds. The saturation functions consider the practical limits of the motor angular velocity. This specific saturation function is defined as:

$$u_k^{\text{Sat}} = \text{Sat}(u_k) = \begin{cases} u_{k_{\max}} & \text{if } u_k \geq u_{k_{\max}} \\ u_k & \text{if } u_{k_{\min}} < u_k < u_{k_{\max}} \\ u_{k_{\min}} & \text{if } u_k \leq u_{k_{\min}} \end{cases} \quad (22)$$

#### 4.2 Altitude controller

The total thrust aligned with  $Z_B$ , is not necessarily directed along the inertial frame  $e_3$ . The thrust control is connected to the altitude controller and is calculated based on the roll and pitch angles. The dynamics of the desired thrust force  $f_T$  is proposed as  $F_{Tc}$  by the actuators, with the aim of ensuring that the stationary or ascending flight regime is maintained, leading to the following formulation:

$$F_{Tc} = \frac{1}{\cos(\theta_d^{\text{Sat}})\cos(\phi_d^{\text{Sat}})}(mg - m\ddot{z}) \quad (23)$$

where  $\phi_d^{\text{Sat}}$  and  $\theta_d^{\text{Sat}}$  are constrained to avoid the singularity presented at  $\pm 90(\text{deg})$ , and the thrust control  $F_{Tc}$  is reached by an altitude Expert PID controller, such that this controller is defined as

$$\ddot{z} = k_{pz}e_z(t) + k_{dz}\frac{\Delta e_z(t)}{ts} + k_{iz}e_{iz}(t) \quad (24)$$

where  $e_z = z_d - z$   $z$  is defined as the altitude error,  $z_d$  is identified as the desired altitude, and  $z$  is referred to as the current altitude. To enhance trajectory tracking, a saturation function is applied to the desired thrust force. The saturated thrust controller is formulated as follows:

$$F_{Tc}^{\text{Sat}} = \text{Sat}(F_{Tc}) = \begin{cases} F_{T_{\max}} & \text{if } F_{Tc} \geq F_{T_{\max}} \\ F_{Tc} & \text{if } F_{T_{\min}} < F_{Tc} < F_{T_{\max}} \\ F_{T_{\min}} & \text{if } z \leq F_{T_{\min}} \end{cases} \quad (25)$$

#### 4.3 Attitude controller

Defining a controller vector  $u_a = [u_\phi, u_\theta, u_\psi]^T$  is the main focus of the control problem. To manage the octocopter UAV attitude, a specialized PID control strategy is implemented. Based on the definition established in vector (10), the external moments are reformulated and expressed according to the proposed control law, as detailed here:

$$\begin{bmatrix} u_\phi \\ u_\theta \\ u_\psi \end{bmatrix} = \begin{bmatrix} k_{p\phi}e_\phi(t) + k_{d\phi}\frac{\Delta e_\phi(t)}{ts} + k_{i\phi}e_{i\phi}(t) \\ k_{p\theta}e_\theta(t) + k_{d\theta}\frac{\Delta e_\theta(t)}{ts} + k_{i\theta}e_{i\theta}(t) \\ k_{p\psi}e_\psi(t) + k_{d\psi}\frac{\Delta e_\psi(t)}{ts} + k_{i\psi}e_{i\psi}(t) \end{bmatrix} \quad (26)$$

Then  $u_\phi$ ,  $u_\theta$ , and  $u_\psi$  represent the Expert PID controller law for managing the octocopter UAV attitude. The trajectory tracking of the attitude control system is enhanced



by introducing saturation to the desired moments. The expression for the saturated moment controllers is presented below.

$$u_{\eta}^{\text{Sat}} = \text{Sat}(u_{\eta}) = \begin{cases} u_{\eta_{\max}} & \text{if } u_{\eta} \geq u_{\eta_{\max}} \\ u_{\eta} & \text{if } u_{\eta_{\min}} < u_{\eta} < u_{\eta_{\max}} \\ u_{\eta_{\min}} & \text{if } u_{\eta} \leq u_{\eta_{\min}} \end{cases} \quad (27)$$

where  $u_{\eta}^{\text{Sat}} = [u_{\theta}^{\text{Sat}}, u_{\phi}^{\text{Sat}}, u_{\psi}^{\text{Sat}}]^T$ . With attitude and altitude controllers, the next step is to define the navigation controller.

#### 4.4 Navigation controller

To achieve effective flight control, the attitude control system is incorporated within the octocopter UAV, ensuring that the desired setpoints of the attitude vector  $\eta_d$  are calculated based on the translational position controller functioning over the  $X-Y$  plane, while utilizing the reference rotation matrix  $R(\psi) \in SO(2)$ . An Expert PID control strategy is proposed to compute the desired forces for the translational position controller in the  $X-Y$  plane.

$$\begin{bmatrix} u_x \\ u_y \end{bmatrix} = \begin{bmatrix} k_{px}e_x(t) + k_{dx}\frac{\Delta e_x(t)}{\Delta t} + k_{ix}e_{ix}(t) \\ k_{py}e_y(t) + k_{dy}\frac{\Delta e_y(t)}{\Delta t} + k_{iy}e_{iy}(t) \end{bmatrix} \quad (28)$$

Position errors are defined as  $e_x = x_d - x$  and  $e_y = y_d - y$  corresponding to  $e_1$  and  $e_2$ , respectively, with  $x_d$  and  $y_d$  representing the target positions along these directions. The proposed Expert PID-type navigation controller is connected to the external control layer through the rotation matrix  $R(\psi) \in SO(2)$ , aiming to generate the desired reference angles  $\theta_d$  and  $\phi_d$  for the attitude controller. This setup establishes the relationship between the attitude and translational controllers, as detailed below.

$$\begin{bmatrix} \phi_d^{\text{Sat}} \\ \theta_d^{\text{Sat}} \end{bmatrix} = \begin{bmatrix} \sin(\psi) & -\cos(\psi) \\ \cos(\psi) & \sin(\psi) \end{bmatrix} \begin{bmatrix} u_x \\ u_y \end{bmatrix} \quad (29)$$

Equation (29) outlines the proposed navigation controller for the octocopter UAV. The trajectories are tracked within the plane defined by the  $X$  and  $Y$  axes, and the complete control scheme and system dynamics are shown in Fig. 2.



Fig. 2: Diagram of controller and dynamics interactions.



## 5 Simulation of Flight Control Systems

The rules of the Expert PID are used as follows to define which strength PID controller is being used according to the condition of the rules.

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### Algorithm 1 Expert PID algorithm

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1: Rule 1
2: if  $|e_c(t)| > M_{1c}$  then
3:    $u_c(t) = C_{1c}(k_{pc}e_c(t) + \frac{k_{dc}\Delta e_c(t)}{ts} + k_{ic}e_{ic}(t))$ 
4: else
5:   if  $|e_c(t)| > 0.7M_{1c}$  then
6:      $u_c(t) = C_{2c}(k_{pc}e_c(t) + \frac{k_{dc}\Delta e_c(t)}{ts} + k_{ic}e_{ic}(t))$ 
7:   end if
8: else
9:   if  $|e_c(t)| > 0.5M_{1c}$  then
10:     $u_c(t) = C_{3c}(k_{pc}e_c(t) + \frac{k_{dc}\Delta e_c(t)}{ts} + k_{ic}e_{ic}(t))$ 
11:   end if
12: else
13:   if  $|e_c(t)| > 0.2M_{1c}$  then
14:     $u_c(t) = C_{4c}(k_{pc}e_c(t) + \frac{k_{dc}\Delta e_c(t)}{ts} + k_{ic}e_{ic}(t))$ 
15:   end if
16: end if
17: Rule 2
18: if  $e_c(t)\Delta e_c(t) > 0$  or  $\Delta e_c(t) = 0$  then
19:   if  $|e_c(t)| \geq M_{2c}$  then
20:      $u_c(t) = u_c(t-1) + k_{1c}(k_{pc}e_c(t) + \frac{k_{dc}\Delta e_c(t)}{ts} + k_{ic}e_{ic}(t))$ 
21:   else
22:      $u_c(t) = u_c(t-1) + k_{2c}(k_{pc}e_c(t) + \frac{k_{dc}\Delta e_c(t)}{ts} + k_{ic}e_{ic}(t))$ 
23:   end if
24: end if
25: Rule 3
26: if  $e_c(t)\Delta e_c(t) < 0$  and  $\Delta e_c(t)\Delta e_c(t-1) > 0$  or  $e_c(t) = 0$  then
27:    $u_c(t) = u_c(t)$ 
28: end if
29: Rule 4
30: if  $e_c(t)\Delta e_c(t) < 0$  and  $\Delta e_c(t)\Delta e_c(t-1) < 0$  then
31:   if  $|e_c(t)| \geq M_{2c}$  then
32:      $u_c(t) = u_c(t-1) + k_{3c}(k_{pc}e_c(t) + \frac{k_{dc}\Delta e_c(t)}{ts} + k_{ic}e_{ic}(t))$ 
33:   else
34:      $u_c(t) = u_c(t-1) + k_{4c}(k_{pc}e_c(t) + \frac{k_{dc}\Delta e_c(t)}{ts} + k_{ic}e_{ic}(t))$ 
35:   end if
36: end if
37: Rule 5
38: if  $|e_c(t)| \leq e_c$  then
39:    $u_c(t) = k_{5c}(k_{pc}e_c(t) + \frac{k_{dc}\Delta e_c(t)}{ts} + k_{ic}e_{ic}(t))$ 
40: end if

```

---

### 5.1 Parameters of the octocopter UAV controller

Numerical simulations utilize parameters obtained from the octocopter UAV model developed in SolidWorks. Table 1 lists the numerical values associated with the model parameters. To enable trajectory tracking, the gains of the saturated Expert PID controller in the attitude control layer are tuned to match the desired sinusoidal inputs for each input of the octocopter UAV. The adjusted gains for the saturated Expert PID controller in the inner attitude layer are presented in Table 2.

To tune the parameters of the navigation controller, the altitude controller is implemented as the initial step in the tuning process. The position control in the X-Y plane is then adjusted, applying setpoint references to manage the translational movement along

Table 1: Newton-Euler aircraft model parameters.

| Parameter | Value                           | Parameter | Value                         | Parameter | Value            |
|-----------|---------------------------------|-----------|-------------------------------|-----------|------------------|
| $c_T$     | $8.33 \times 10^{-5} (N-s^2)$   | $J_{xx}$  | $83 \times 10^{-2} (kg-m^2)$  | $m$       | 8 (kg)           |
| $c_Q$     | $2.42 \times 10^{-6} (N-m-s^2)$ | $J_{yy}$  | $83 \times 10^{-2} (kg-m^2)$  | $g$       | 9.81 ( $m/s^2$ ) |
| $d$       | 0.721 (m)                       | $J_{zz}$  | $165 \times 10^{-2} (kg-m^2)$ |           |                  |

Table 2: Attitude controller gains for Expert PID.

| Gain               | Value | Gain               | Value                   | Gain               | Value                   | Gain             | Value | Gain           | Value |
|--------------------|-------|--------------------|-------------------------|--------------------|-------------------------|------------------|-------|----------------|-------|
| $k_{\phi\phi}$     | 80    | $k_{\psi\psi}$     | 6                       | $e_\theta$         | $\frac{\pi}{600}$ (rad) | $C_{\phi\phi}$   | 60    | $k_{\chi\chi}$ | 30    |
| $k_{\phi\psi}$     | 4     | $k_{\psi\phi}$     | 6                       | $C_{\psi\psi}$     | 120                     | $C_{\psi\phi}$   | 60    | $k_{\chi\phi}$ | 8     |
| $k_{\phi\theta}$   | 20    | $M_{\phi\theta}$   | $\frac{\pi}{120}$ (rad) | $C_{\phi\theta}$   | 120                     | $k_{\phi\chi}$   | 50    | $k_{\chi\psi}$ | 8     |
| $k_{\psi\theta}$   | 80    | $M_{\psi\theta}$   | $\frac{\pi}{120}$ (rad) | $C_{\psi\theta}$   | 100                     | $k_{\psi\chi}$   | 50    | $k_{\chi\phi}$ | 7     |
| $k_{\psi\psi}$     | 4     | $M_{\psi\psi}$     | $\frac{\pi}{120}$ (rad) | $C_{\psi\psi}$     | 100                     | $k_{\psi\phi}$   | 10    | $k_{\phi\psi}$ | 7     |
| $k_{\theta\theta}$ | 20    | $M_{\theta\theta}$ | $\frac{\pi}{120}$ (rad) | $C_{\theta\theta}$ | 80                      | $k_{\theta\chi}$ | 10    |                |       |
| $k_{\theta\psi}$   | 7     | $e_\psi$           | $\frac{\pi}{600}$ (rad) | $C_{\theta\psi}$   | 80                      | $k_{\theta\phi}$ | 30    |                |       |

the X and Y axes. Table 3. presents the adjusted gains for the Expert PID navigation controller. Circular trajectory tracking is achieved by defining the position references  $x_d$  and  $y_d$  through the following equations.

Table 3: Navigation controller gains for Expert PID.

| Gain     | Value | Gain           | Value   | Gain     | Value | Gain     | Value | Gain     | Value |
|----------|-------|----------------|---------|----------|-------|----------|-------|----------|-------|
| $k_{px}$ | 10    | $M_{\delta x}$ | 1 (m)   | $C_{1x}$ | 12    | $C_{2x}$ | 100   | $k_{zy}$ | 1     |
| $k_{dx}$ | 0.2   | $M_{\delta y}$ | 0.4 (m) | $C_{2y}$ | 10    | $C_{3y}$ | 80    | $k_{zy}$ | 3     |
| $k_{ix}$ | 100   | $M_{\delta z}$ | 1 (m)   | $C_{3x}$ | 8     | $C_{4z}$ | 60    | $k_{dy}$ | 0.8   |
| $k_{py}$ | 10    | $M_{\delta x}$ | 0.4 (m) | $C_{4x}$ | 6     | $k_{1x}$ | 5     | $k_{zy}$ | 0.7   |
| $k_{dy}$ | 0.2   | $M_{\delta z}$ | 10 (m)  | $C_{1y}$ | 12    | $k_{2x}$ | 1     | $k_{1z}$ | 50    |
| $k_{iy}$ | 100   | $M_{\delta y}$ | 1 (m)   | $C_{2y}$ | 10    | $C_{3x}$ | 3     | $k_{2z}$ | 10    |
| $k_{pz}$ | 60    | $e_x$          | 0.2 (m) | $C_{3y}$ | 8     | $k_{4x}$ | 0.8   | $k_{3z}$ | 30    |
| $k_{dz}$ | 3     | $e_y$          | 0.2 (m) | $C_{4y}$ | 6     | $k_{5x}$ | 0.7   | $k_{4z}$ | 8     |
| $k_{iz}$ | 10    | $e_z$          | 0.3 (m) | $C_{1z}$ | 120   | $k_{1y}$ | 5     | $k_{5z}$ | 7     |

$$\begin{aligned} x_d &= A_x \sin(2\pi f t) \\ y_d &= A_y \cos(2\pi f t) \end{aligned} \quad (30)$$

where  $A_x$  and  $A_y$  represent the radius of the cylinder,  $f$  is the frequency, and  $t$  is the time. For the cylindrical trajectory,  $A_x$  and  $A_y$  were set to 3 meters. The saturation values are provided in the table below.

Table 4: Saturator values.

| Parameter                    | Value      | Parameter                    | Value                   | Parameter                 | Value       | Parameter               | Value       |
|------------------------------|------------|------------------------------|-------------------------|---------------------------|-------------|-------------------------|-------------|
| $\omega_{\phi_{\text{min}}}$ | 100 (RPM)  | $\phi_{\phi_{\text{min}}}$   | $-\frac{\pi}{10}$ (rad) | $u_{\phi_{\text{min}}}$   | -20 (N · m) | $u_{\psi_{\text{min}}}$ | -13 (N · m) |
| $\omega_{\phi_{\text{max}}}$ | 3700 (RPM) | $\phi_{\phi_{\text{max}}}$   | $\frac{\pi}{10}$ (rad)  | $u_{\phi_{\text{max}}}$   | 20 (N · m)  | $u_{\psi_{\text{max}}}$ | 13 (N · m)  |
| $\bar{F}_{r_{\text{min}}}$   | 0 (N)      | $\theta_{\phi_{\text{min}}}$ | $-\frac{\pi}{10}$ (rad) | $u_{\theta_{\text{min}}}$ | -20 (N · m) |                         |             |
| $\bar{F}_{r_{\text{max}}}$   | 156 (N)    | $\theta_{\phi_{\text{max}}}$ | $\frac{\pi}{10}$ (rad)  | $u_{\theta_{\text{max}}}$ | 20 (N · m)  |                         |             |

## 5.2 Navigation and Trajectory Tracking

MATLAB/Simulink was used to generate the simulation results. At first, the signals corresponding to the navigation trajectory are presented. The octocopter UAV ascends while following a circular path, creating a helical pattern. Figure 3 illustrates the desired and actual trajectory tracking of the octocopter UAV, forming a geometrically helical trajectory. Additionally, the total thrust compensation is depicted. Finally, the control moments of the octocopter UAV are shown.

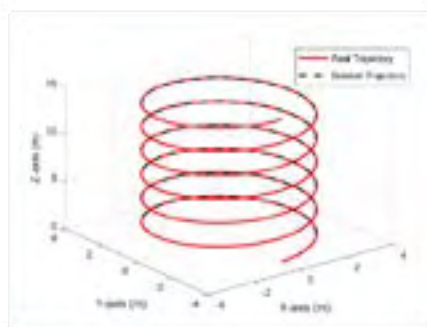
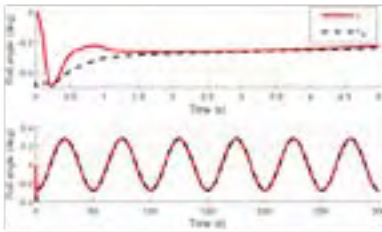
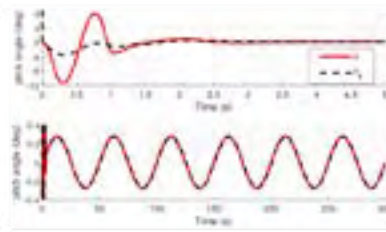


Fig. 3: Trajectory tracking of the octocopter UAV.

Figure 4 presents the response to a sinusoidal wave due to the circling behavior of the helical trajectory of the octocopter UAV; a negative peak of  $-0.49$  (deg) is presented at  $0.2$  (s) where the amplitude of the cosine is  $\pm 0.2$  (deg). Figure 5 shows a sinusoidal behavior. The action of the saturators  $\phi_{\phi}^{\text{Sat}}$  and  $\theta_{\phi}^{\text{Sat}}$  are not presented because the helical trajectory is defined to make a slow motion, a negative peak of  $-11$  (deg) and a positive peak of  $8$  (deg) are presented, while the amplitude of angles is  $\pm 0.27$  (deg).

Fig. 4: Response of  $\phi$  angle.Fig. 5: Response of  $\theta$  angle.

A regulation in yaw angle is shown in Figure 6. At a time of 0.6 (s) a negative peak of  $-0.7$  (deg) is presented. The reason for  $\psi_d = 0$  resides in the idea of always looking in the north direction. Meanwhile, this controller is set as a classic PID due to the response behavior as a regulation that never goes to zero, so the rules of the Expert PID are not an option for this case.

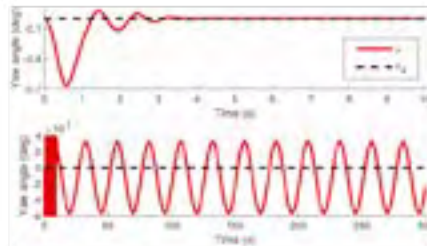
Fig. 6: Response of  $\psi$  angle.

Figure 7 shows the altitude response where the response is constantly ascending, which means the total of the octocopter UAV is stabilized.

Figures 8 and 9 show the navigation performing without problems. Due to the response in the Euler angles, there is a minimal deviation unnoticed in the trajectory tracking that performs an outside cylinder from the desired helical trajectory.

In Figure 10, the total thrust compensation is shown. The maximum total thrust that can be performed in the octocopter UAV is  $156\text{ N}$ , which is the double force required to maintain the equilibrium of the octocopter UAV. The total thrust goes to  $102\text{ N}$  at the beginning of the response; after the stabilization, the total thrust is  $78.5\text{ N}$ , which is the necessary force to maintain the flight of the octocopter UAV during navigation.

## 6 Conclusions

In this research work, we have designed a navigation algorithm for an octocopter UAV using a PID flight controller, which implements expert decision rules. It has been named

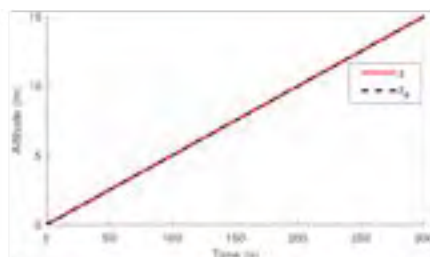


Fig. 7: Response of Z axis position.

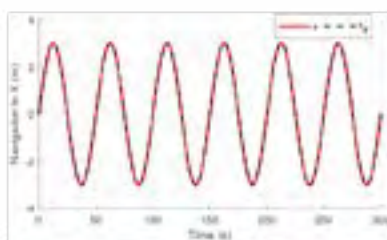


Fig. 8: Response of X axis position.

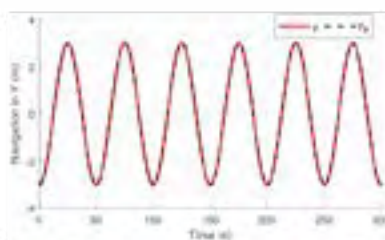


Fig. 9: Response of Y axis position.

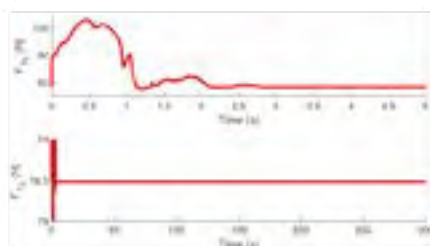


Fig. 10: Total thrust response.

“Expert PID Flight Controller.” The navigation algorithm used by the Expert PID flight controller is subjected to simulation tests to fulfill the tracking of a time-varying trajectory, which has a helical geometric shape. The set of expert rules that are part of the “Expert PID Flight Controller” has the ability to reassign the values of the PID controller parameters for a small region of the error of pitch and roll angles, as well as the translation positions in the X, Y, Z axes, the controller keeps the gains in a low profile to implement a weak, very weak and extremely weak controller, on the other hand for a large region of the error of the pitch and roll orientation angles, as well as the translation positions in the X, Y, Z axes, the controller keeps the gains in a high profile to implement a strong, very strong and extremely strong controller. The added capabilities



of the navigation algorithm to be able to change the gains of the "Expert PID Flight Controller" allow it to have an improved response to small and large variations of roll and pitch attitude error and translation error in X, Y, Z, versus variations in time of the desired trajectory that the octocopter UAV must follow.

**Acknowledgments.** The authors would like to thank the Autonomous University of Nuevo Leon (CINIA-FIME-UANL) and the Tecnológico Nacional de México/Instituto Tecnológico de La Laguna.

**Disclosure of Interests.** The authors declare no conflict of interest.

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# Classification of Surface Electromyography Recordings from Healthy and Peripheral Neuropathy Subjects

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**Abstract.** Peripheral Neuropathy are lesions of the peripheral nervous system, they could be caused by a wide variety of problems being the most common worldwide, diabetes mellitus. The most common methods of detection are a clinical diagnosis and an electromyography with invasive electrodes. Both of them represent a risk to the patient because they can cause lesions or infections, for these reasons, the objective of this work is to propose a non-invasive method, based on surface electromyography and that, supported by statistical analysis, may suggest the presence of Peripheral Neuropathies. Based on the literature, two muscles (flexor *digiti brevis* and abductor *digiti minimi*) responsible for the mobility of the cortex were identified as suitable for the study. Once the information was acquired, it was conditioned through digital filters, rectification and smoothing of the signal and later processed to extract the characteristics (in time and in frequency domain) of the signal which were the input to different classifiers in order to determine their performance in differentiating subjects with neuropathy from healthy subjects. The results indicate that it is possible to differentiate both groups with a percentage greater than 83% with at least 5 of the classification algorithms tested in this work: Weighted KNN (84%), RUSBoosted Trees (83.3%), Quadratic SVM (83.3%), Cubic KNN (83.3%) y Medium Gaussian SVM (83.3%). However, it is necessary to increase the sample size to corroborate the good performance of this methodology.

**Keywords:** Peripheral Neuropathies, Diabetes Mellitus, Electromyography, Decision Trees.

## 1 Introduction

Peripheral Neuropathy (PN) is a condition affecting the peripheral nervous system, primarily impacting the lower limbs, causing numbness in the affected area, tingling, sharp pain, hypersensitivity, burning sensations, muscle atrophy, and/or muscle weakness [1]. The causes of PN range from physical injuries, autoimmune diseases, tumors, and toxin exposure to metabolic disorders and hereditary factors. One of the most common causes is Diabetes Mellitus (DM), which, in Mexico alone, affected 12.8 million adults in 2019, with projections estimating 22.3 million cases by 2045 [1,2]. It is estimated that between 2.8 and 5.9 million Mexicans suffer from the disease but remain undiagnosed.

<https://doi.org/10.61728/AE20255046>



By 2030, the number of people with diabetes is expected to reach between 9.7 and 20.6 million, and by 2045, this number could rise to 26.8 million [2].

To provide context, it is important to examine the statistics surrounding this issue: approximately 70% of older adults experience some form of increased or decreased sensitivity in their feet, and in Mexico, 60% of adults with type 2 DM develop some form of PN as they live longer with the disease [3]. PN is characterized by infection, ulceration, and/or destruction of deep tissues, which progresses rapidly and increases the fragility of arteries in the extremities. When this condition affects the lower limb, specifically the foot, even minor trauma can lead to ulcers or infections [4,5].

The diagnosis of neuropathy-related infections is primarily clinical, based on the presence of suppuration or at least two inflammatory signs (erythema, induration, pain, tenderness, and/or warmth). According to a study published in 2016 by the Mexican Institute of Social Security (IMSS), approximately 100,000 Mexicans undergo some form of amputation annually due to this condition [6].

### 1.1 Classification of Peripheral Neuropathies

PN is classified based on three criteria: pathological findings, etiology, or clinical syndrome. A neurological examination typically reveals sensory loss, lower motor neuron weakness, atrophy, reduced tone, and decreased reflexes, depending on the affected nerves. Electromyography (EMG) and nerve conduction studies can be useful as extensions of the neurological exam.

**Peripheral neuropathies are categorized as follows:** **Polyneuropathies:** Distal, symmetrical abnormalities (often subacute, slow-progressing) affecting sensation, strength, or both. These are generally secondary to metabolic, toxic, or hereditary disorders. **Focal neuropathy:** Dysfunction affecting a single nerve (e.g., carpal tunnel syndrome), typically due to compression or focal nerve stretching. **Multiple mononeuritis:** Several individual nerves are affected asymmetrically, either simultaneously or progressively. This is usually secondary to inflammatory disorders and requires analysis for vasculitis [7,8].

**Symptoms and Diagnosis.** PN symptoms vary depending on the patient, affected area, and severity. A complete neurological examination is conducted to determine the cause, severity, and type of nerve damage. The medical evaluation considers social habits, work environment, family history, and disease risk factors. More specialized tests can clarify cardiovascular diseases, connective tissue disorders, and/or tumors. Additionally, genetic tests are available for certain hereditary neuropathies [1,4].

Physical examinations (strength tests, fasciculation/cramp assessments, and sensory evaluation) can reveal systemic disorders, nerve damage, and/or motor or sensory fiber impairments. Blood tests help detect diabetes, vitamin deficiencies, metabolic disorders, and abnormal immune system activity. A cerebrospinal fluid (CSF) test can reveal abnormal antibodies associated with certain immune-mediated neuropathies [1,4].



**Additional Diagnostic Tests for PN.** **Nerve conduction velocity tests:** Measure the degree of damage in large nerve fibers and determine whether PN is caused by myelin sheath degeneration or axonal damage. **Electromyography (EMG):** Involves inserting a thin needle into the muscle to record electrical activity at rest and during contraction. It detects abnormal electrical activity in motor neuropathies and helps determine whether the disorder originates from the muscle or nerve. **Magnetic resonance imaging (MRI):** Displays muscle size and condition, facilitating the detection of fatty tissue replacement, hernias, or tumors that could be causing PN. **Nerve biopsy:** A small nerve tissue sample is removed and examined. Although this test provides valuable information about nerve damage, it is an invasive procedure with potential neuropathic side effects. **Skin biopsy:** A small skin sample is extracted to examine the nerve fiber endings. This test determines damage in the smallest muscle fibers and is less invasive than a nerve biopsy, with fewer side effects [1].

**Need for Non-Invasive Diagnostic Methods.** Given the aforementioned challenges, it is crucial to develop or improve existing diagnostic mechanisms for PN by offering non-invasive, low-cost alternatives for patients. The diagnostic method must align with the current needs of individuals at risk of PN, enabling early detection.

Currently, the most medically accepted EMG recording method uses needle electrodes, as recommended by the National Institute of Neurological Disorders and Stroke (NINDS) and Mayo Clinic [1,4]. However, trauma can trigger PN [1,5], making invasive EMG electrodes a disadvantageous option.

**Development of Low-Cost, Non-Invasive EMG Detection.** This need has led to the development of non-invasive, low-cost EMG detection methods to identify tissue degradation and decreased foot sensitivity in diabetic individuals at different disease stages.

Yousaf et al. [9] studied the feasibility of using non-invasive EMG as a tool for detecting neuromuscular disorders, focusing on EMG signal acquisition and processing. Ullah et al. [10] conducted a study on detecting abnormal muscle contractions using non-invasive EMG, evaluating several lower limb muscles during walking—although they did not include foot muscles—demonstrating the applicability of their method.

This study explores the use of myoelectric signals through surface electrodes. The measurement area for these signals is the pretibial region of the patient. Measurements are taken immediately after repetitive toe flexion movements in three groups: Control subjects (healthy individuals), Subjects at risk of PN, and Subjects diagnosed with neuropathy. Since diabetes is the leading cause of PN, efforts should be focused on developing a low-cost, accessible detection method to improve the quality of life of affected individuals.



## 2 Materials and Methods

For this study, only the recordings obtained through a myoelectric signal amplifier built by the authors of this work were used.

## 2.1 Materials

**INA 128 Amplifier:** Myoelectric signals have an approximate amplitude of 250  $\mu\text{V}$  when the muscles contract; they are so small that any noise or interference can lead to misinterpretation. An instrumentation amplifier has the necessary characteristics to detect these small signals, amplify them, and reject part of the noise [9]. For this stage, an INA 128 amplifier was used, an integrated circuit with a low offset that commonly rejects noise in both electrodes using an external resistor ( $R_G$ ), providing a gain defined by the equation [11]:

$$G = 1 + \frac{50k\Omega}{RG} \quad (1)$$

**Analog Filters.** Analog filters are responsible for defining the parameters for the signal's cutoff frequencies. For our design, we will use two of them [12].

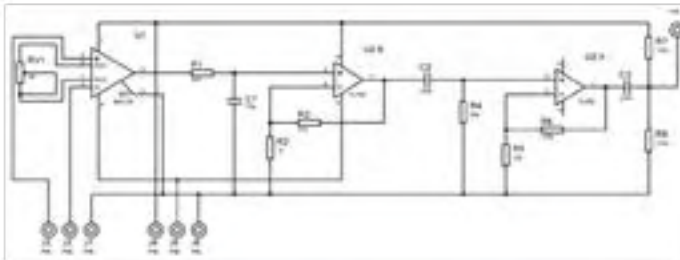
**Low-pass filter:** It is calculated using the following equation.

$$\omega_L = \frac{1}{R_f G} \quad (2)$$

High-pass filter: It is calculated using the following equation.

$$\omega_H = \frac{1}{2\pi RC} \quad (3)$$

Based on equations (1), (2), and (3), an EMG circuit was designed (Fig. 1), featuring a low-pass filter at 568 Hz with a gain of 27 and a high-pass filter at 23 Hz with a gain of 11.



**Fig. 1.** EMG Signal Amplifier Circuit.

With the circuit schematic, the design of the printed circuit board (PCB) was carried out.

**ARDUINO UNO Acquisition Board.** An ARDUINO UNO board was used to digitize the EMG signal, which was acquired at a sampling rate of 1000 samples/s on analog pin 2 and connected to the USB port of a laptop. The signal data captured by the ARDUINO was set to a DC value of 2.5V since the board does not detect negative voltages. The data was then processed in MATLAB® to obtain its value in millivolts after subtracting the 2.5V offset to account for the negative values of the signal.

**Acquisition Circuit Construction.** The construction of the EMG signal amplifier circuit consisted of six main steps, as illustrated in Fig. 2:

1. Printing the PCB on coated paper
2. Ironing the PCB onto a bakelite board
3. Immersing it in ferric chloride to remove excess copper
4. Drilling the bakelite board
5. Placing and soldering components
6. Placing the circuit inside a case with input and output connections

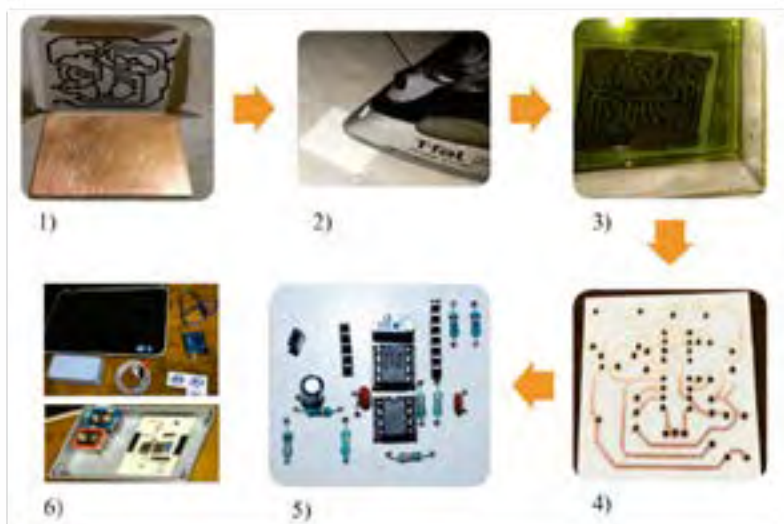


Fig. 2. EMG Circuit Fabrication.

**Electromyography.** EMG is responsible for detecting the electrical signals generated by muscle contraction. These signals are produced by the exchange of ions across the membranes of muscle fibers. The signal can be influenced by both muscle physiology and nervous system control [13].

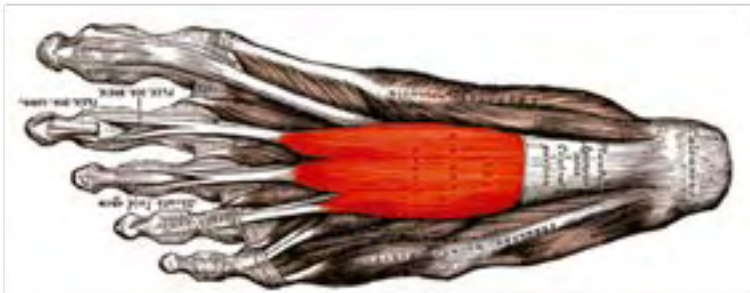
The electrical signal resulting from muscle activation anywhere in the body is known as the motor unit action potential (MUAP) [1], which typically has an amplitude ranging from 0 to 250  $\mu\text{V}$ , with a frequency content concentrated between 20 and 500 Hz [14].

To record these signals, invasive (needle) or non-invasive (surface or cutaneous) electrodes can be used. In this study, we focus on the latter, which use an electrolytic gel as a conductor between the skin and the metallic part of the electrode. When placed correctly, these electrodes reduce the risk of displacement during sudden movements. They are commonly used for physiological studies, human-machine interface applications, and superficial neurophysiological studies [13].

The main risk for patients when using EMG is electrical in nature, which occurs when the system lacks proper isolation [13].

**Studied Muscles.** The selection of muscles for this study was based on the fact that **Peripheral Neuropathy (PN) begins in the toes** [13]. Therefore, two muscles were chosen:

**Flexor digitorum brevis:** Originates in the **calcaneus process** and intermuscular septa, dividing into four tendons that insert into the base of the phalanges of the toes (excluding the big toe). This muscle is located on the **plantar surface of the foot** [15, 16], as illustrated in Fig. 3.



**Fig. 3.** Illustrative image of the flexor digitorum brevis muscle. Image retrieved from H. Gray, *Anatomy of the Human Body*. London, England, 2000 [17].

**Abductor hallucis:** It originates from the medial process of the calcaneus and inserts on the medial side of the big toe, at the base of the proximal phalanx of the hallux, located on the proximal dorsum of the foot [15, 16], as shown in Fig. 4.

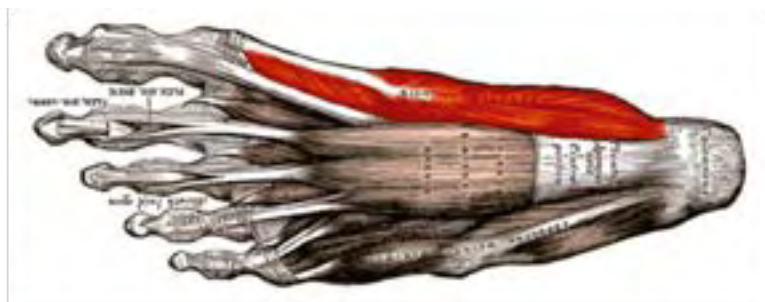


Fig. 4. Illustrative image of the Abductor Hallucis muscle. Image retrieved from H. Gray, *Anatomy of the Human Body*. London, England, 2000 [17].

## 2.2 Methods

**Selection of Study Subjects.** A study was conducted among healthy subjects (controls), subjects at risk of developing neuropathy, and a subject with a diagnosed neuropathy, using a surface electrode EMG recording. The subjects were grouped as shown in Table 1:

Table 1. Sample Characteristics.

| Groups                                                                                                                                                                     | Subject                   | Description                                                                                             |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|---------------------------------------------------------------------------------------------------------|
| <b>Healthy Group (Control):</b> considering the criteria of being individuals over 18 years old with no pathological history indicating any risk of developing neuropathy. | Healthy Subject 1 (HS1)   | 22-year-old woman with no previous pregnancies and no significant pathological history.                 |
|                                                                                                                                                                            | Healthy Subject 2 (HN2)   | 52-year-old man with no significant pathological history.                                               |
|                                                                                                                                                                            | Healthy Subject 3 (HN3)   | 19-year-old man with no significant pathological history.                                               |
| <b>At Risk Group for Neuropathy:</b> considering the criteria of being individuals over 18 years old who are at risk of developing neuropathy.                             | Subject at Risk 1 (SR1)   | 52-year-old woman with 4 previous pregnancies and vascular problems.                                    |
|                                                                                                                                                                            | Subject at Risk 2 (SR2)   | 78-year-old man with diabetes for 4 years, ex-smoker, with a history of alcoholism and strokes in 1999. |
|                                                                                                                                                                            | Subject at Risk 3 (SR3)   | 80-year-old woman with no previous pregnancies and vascular problems.                                   |
|                                                                                                                                                                            | Subject at Risk 4 (SR4)   | 53-year-old woman with 3 previous pregnancies and diabetes for 2 years.                                 |
| <b>Neuropathy Group:</b> considering the criteria of being individuals with a diagnosed neuropathy.                                                                        | Neuropathic Subject (NPS) | 52-year-old man with diabetes for 33 years, renal problems, and diabetic neuropathy for 5 years.        |



It should be mentioned that all subjects signed an informed consent form in which the purpose and procedure of the study were explained, and that there were no associated risks with the study. They were also informed about the study duration, confidentiality, data storage, and participants' rights. Due to the nature of the research, the number of subjects is limited, with a total of 8, and samples were taken from both the right foot (RF) and left foot (LF).

**Electromyographic Study.** To carry out the EMG recording, the guidelines from the SERMEF Rehabilitation and Physical Medicine Manual were followed, which states that for diagnostic recordings, repetitive movements of finger flexion and relaxation must be performed [18].

**Electromyographic Signal Conditioning.** Once all the recordings were obtained, rectification was applied to the EMG signal, followed by smoothing to select a threshold that would allow us to extract the segments of interest from the signal (activity parts), creating windows for each repetition of muscle activity (illustrative graphs are shown in Figure 5).

Each window had a feature vector extracted for later classification using different classification algorithms. The windows were obtained through a semi-automatic process in which data segments before and after segments with zero values (see Figure 5. d) were selected. These zero-value segments were previously obtained using a thresholding technique applied to the rectified and smoothed EMG signal. The threshold was chosen as a percentage of the maximum peak value recorded during the entire recording duration, which varied depending on the subject.

**Feature Extraction.** Twelve features were extracted from the conditioned signal, forming a feature vector [19, 20]:

1. Mean

$$\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i \quad (4)$$

2. Absolute mean

$$|\bar{x}| = \left| \frac{1}{N} \sum_{i=1}^N x_i \right| \quad (5)$$



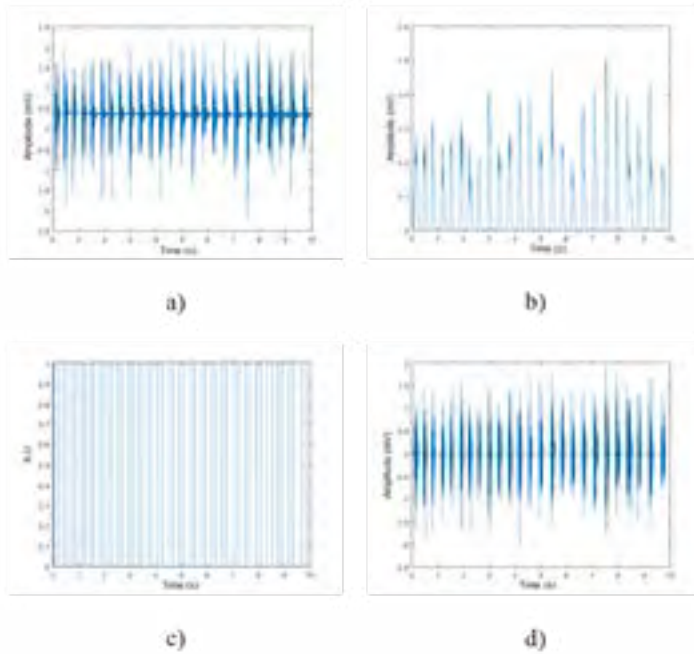


Fig. 5. Electromyographic Signal Conditioning. a) Signal acquired during the EMG recording. b) Rectification and smoothing of signal b. c) Thresholding of signal b. d) Study segments of the signal.

### 3. Standard Deviation

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \mu)^2} \quad (6)$$

### 4. Variance

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^N (x_i - \mu)^2 \quad (7)$$

### 5. RMS

$$RMS = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i)^2} \quad (8)$$

6. Maximum Amplitude, is the maximum value of the signal among all amplitude values of the signal.

$$Amp_{max} = \max(\mathbf{x}) \quad (9)$$

7. Minimum Amplitude, is the minimum value of the signal among all amplitude values of the signal.

$$Amp_{min} = \min(\mathbf{x}) \quad (10)$$

The following 5 features are frequency domain features and consist of the sum of the magnitude spectrum coefficients obtained through the Fourier Transform or the area under the curve for 5 frequency bands into which the EMG spectrum was divided (0-100, 101-200, 201-300, 301-400, 401-500 Hz), calculated as shown in equation (11).

$$A_{bf} = \sum_{i=1}^N |X(f)|_i \quad (11)$$

where  $A_{bf}$  is the area under the curve in the evaluated frequency band, and  $i$ , ranging from 1 to  $N$ , represents the spectrum coefficients in the studied frequency band.

Once the features were extracted from each signal, a data classification process was performed. This classification involved using the Matlab® app, Classification Learner, which allows us to input the features of each signal to identify and classify the data behavior. This app enables the use of different classification methods such as linear regression, quadratic regression, decision trees, support vector machines (SVM), etc. In this study, an 8-fold cross-validation was applied, and the features were subjected to each classifier to determine which one achieved the best performance.

### 3 Results and Discussion

The classification results obtained for the features in this study showed varying performances depending on the type of classifier used. Table 2 shows the performance in classifying EMG signals from three groups (Control, Risk, and Neuropathy) for the 5 classifiers that performed best using the 12 features presented in the previous section for the EMG signal.

**Table 2.** Performance of the top five classifiers for EMG signal classification in Control, Risk, and Neuropathy.

| Classifying algorithm | Performance |
|-----------------------|-------------|
| Weighted KNN          | 84.0 %      |
| RUSBoosted Trees      | 83.3 %      |
| Quadratic SVM         | 83.3 %      |
| Cubic KNN             | 83.3 %      |
| Medium Gaussian SVM   | 83.0 %      |

The results of this classification are favorable, as it is possible to separate the three groups (Control, Risk, and Neuropathy) with at least 84% accuracy. It is possible that the 16% uncertainty is due to the close similarity between the characteristics of the Risk group and the Neuropathic group, as well as with the Control group.

On the other hand, in Fig. 6, a visual separation between the groups can be observed by comparing the features of maximum amplitude (AmMax) and standard deviation. This shows that analyzing these features can be beneficial for separating and classifying the groups. Significant differences can also be observed between the Neuropathic group and the Control group.

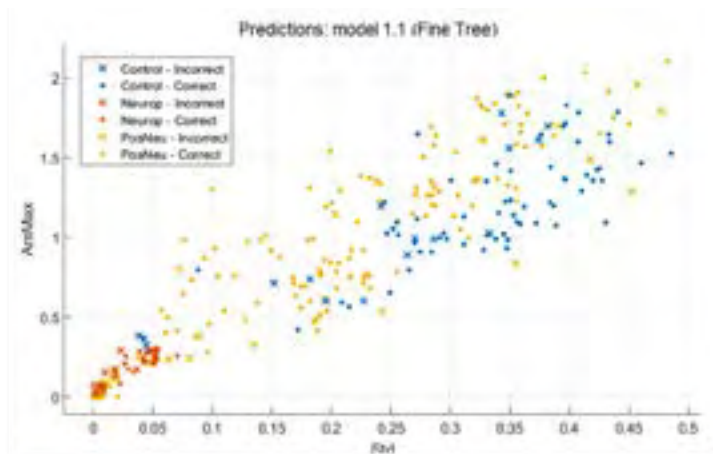


Fig. 6. Visualization of groups using the AmMax and Standard Deviation features. Three classes are distinguished: Control Subjects, Subjects with Neuropathy, and Subjects at Risk.

As can be observed, of the five best-performing algorithms presented in Table 2, the algorithm with the fifth-best performance (Medium Gaussian SVM, 83%) was not far from the algorithm in first place (Weighted KNN, 84%). Among these, there is also a decision tree-based algorithm (RUSBoostedTrees), which, along with Quadratic SVM and Cubic KNN, achieved a performance of 83.3%. Based on the above, we can say that it is possible to classify EMG signals from healthy subjects, subjects with possible neuropathy, and subjects with neuropathy with a percentage greater than 80% using the proposed signal features in this study across different classifiers. Taking into account that the Risk group (subjects at risk of developing neuropathy) shares characteristics with both the Control group (healthy subjects) and the Neuropathy group (subjects with neuropathy), we can understand why the algorithms tend to make more mistakes in correctly classifying this group, as seen in Figure 6. This study shows that it is possible to distinguish between subjects with and without neuropathy through non-invasive EMG analysis in diabetic subjects.

## 4 Conclusions

This work presents a methodology for detecting peripheral neuropathies using EMG, utilizing biosignal processing to characterize classification algorithms to determine the group membership of these signals. The groups are labeled, making it possible to assess the accuracy of the algorithms in determining the group to which the characterized EMG signals belong. The signals from Control (healthy), Risk (possible neuropathy), and Neuropathy subjects were classified with an accuracy of over 83% using at least five classification algorithms and 12 features. In this study, samples were only taken from 8 subjects, and the EMG activity recording was performed with a device made by

the authors. While it is possible to correctly record surface myoelectric activity with it, the methodology related to signal processing, feature extraction, and classification used in this work is the main contribution of this study. Based on this, the goal is to expand the number of subjects in the future and validate the results in neuropathy detection using EMG with low-cost equipment.

## Acknowledgments

The authors thank the subjects who participated in this study and also extend special thanks to the National Council of Science and Technology (CONACYT) for support No. CVU: 1000356.

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# Humanizing Fault Management: Implementing AI-Generated Avatars for Industrial Process Monitoring

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**Abstract.** Traditional fault notification systems in industrial environments depend on conventional technology like stack lights and auditory alarms. These systems provide limited contextual information and require prior operator training for accurate operation interpretation. This paper proposes an avatar-based fault management system that enhances human-machine interaction by replacing conventional alarm mechanisms with AI-generated avatars delivering structured, real-time notifications. The system is implemented on a Raspberry Pi that processes sensor inputs, classifies detected anomalies, and selects the appropriate pre-recorded video message stored on an SD card. These videos feature realistic avatars designed to avoid the uncanny valley effect, ensuring effective and intuitive communication. The system operates based on a state machine model, transitioning between normal operation, anomaly detection, video selection, playback, and daily summary reporting. The avatar indicates various fault levels, ranging from minor deviations to critical failures, and issues daily status reports when no faults are detected. A preliminary proof of concept confirms the feasibility of the proposed system, while future work will evaluate its effectiveness compared to conventional fault notification methods. By integrating human-like virtual assistants into industrial fault management, this system proposes a more intuitive and engaging alternative to traditional alert mechanisms. It improves situational awareness, decreases cognitive load, and can be seamlessly incorporated into IoT and Industry 4.0 ecosystems, paving the way for more human-centered automation in the industry.

**Keywords:** AI-Based-Avatar Fault Detection, Human-Machine Interaction, Industry 4.0 Automation.

## 1 Introduction

Industrial automation has traditionally relied on visual and auditory signals to alert operators, engineers, and managers about system anomalies and failures. Conventional warning systems, such as stack lights (red, yellow, and green) and alarm sounds, provide real-time status updates but lack human-like interaction, limiting their effectiveness in delivering contextualized and intuitive information. Additionally, these conventional systems are installed directly on the shop floor, meaning that failures or anomalies are often triggered—either intentionally or unintentionally—by operators or external events unrelated to the process itself, leading to unnecessary stoppages and potential

<https://doi.org/10.61728/AE20255053>



financial losses for the company. The proposed system would not only alert managers, supervisors, and administrative personnel but could also be seamlessly integrated into an IoT and AI ecosystem, making it a ubiquitous solution for a globally connected work environment.

This paper is a work in progress and proposes a novel approach to fault management by integrating AI-generated avatars as virtual assistants in an industrial monitoring interface. Using AI-generated video content, the system provides real-time narrated explanations of failures and operational conditions. These videos are saved on an SD card and shown on a small monitor connected to a Raspberry Pi, which receives input from physical buttons that simulate faults events. When activated, the avatar provides a structured explanation of the issue, facilitating a more humanized and informative interaction for the personnel in charge of monitoring and maintenance.

The proposed system bridges the gap between traditional indicator-based warning systems and more interactive digital interfaces. Replacing or enhancing conventional warning systems with an avatar-driven communication approach improves clarity, lowers the cognitive load on operators, and offers more detailed insights into failure conditions. This research explores the potential benefits of this implementation, including improved situational awareness, enhanced training possibilities, and better decision-making in industrial environments.

## 2 Related Work

Industrial fault detection and notification systems have significantly evolved over the past few decades, transitioning from basic mechanical indicators to digital and AI-driven solutions. Traditional methods, like stack lights and auditory alarms, have been widely used in manufacturing settings to indicate machine operating states, failures, or process anomalies. While these systems effectively convey immediate alerts, they lack contextual information, requiring operators to interpret signals based on prior training and experience.

Recent advancements in Human-Machine Interfaces (HMI) and Industry 4.0 technologies have resulted in more interactive, data-driven fault management systems. Research has demonstrated that digital dashboards, augmented reality (AR), and intelligent assistants can improve situational awareness and minimize downtime by giving operators more detailed insights into failure conditions. In [1], the authors provide a comprehensive review of methods and tools used in intelligent predictive maintenance in the context of Industry 4.0; they highlight how advanced technologies, including improved Human-Machine Interfaces (HMI) and data-driven solutions, contribute to fault detection and prevention, ultimately enhancing operational efficiency and reducing downtime in industrial settings. Furthermore, the paper examines key maintenance models, such as Condition-Based Maintenance (CBM) and Prognostics and Health Management (PHM), which leverage advanced interfaces and intelligent assistants to deliver detailed information on fault conditions. This approach enhances situational awareness among operators and facilitates more informed decision-making. However,



these systems often require complex integrations or real-time data processing capabilities that may not be feasible in all industrial settings.

AI-powered virtual assistants have recently gained attention in industrial applications. Studies indicate that AI-generated avatars and voice assistants can improve communication efficiency, particularly in environments where rapid decision-making is crucial. A study [2], related to AI-Powered Immersive Assistance for Industrial Environments, explores the application of AI-driven virtual assistants in industrial settings. The research demonstrates how AI-powered immersive assistance systems can support users in performing complex tasks, thereby enhancing communication efficiency and facilitating rapid decision-making in critical environments. These avatars provide a human-like interaction, making information delivery more intuitive for operators and managerial staff. For example, reference [3] introduces the *MetaStates* concept, a novel approach for integrating human workers' psychophysiological states into industrial simulations within the Industrial Metaverse. While digital avatars have become increasingly sophisticated in industrial applications, existing simulations primarily focus on physical attributes, neglecting critical human factors such as emotions, cognitive workload, and stress levels.

The proposed *MetaStates* framework aims to enhance the realism of industrial digital twins by incorporating real-time representations of workers' internal states.

The integration of IoT and avatars with advanced technologies to enhance human-computer interaction in smart environments is done in [4], where the study addresses key challenges in IoT systems, such as the need for sensory information representation and contextual awareness, proposing the use of mixed reality avatars as interactive agents that visualize IoT device states in a more intuitive and human-friendly manner.

Alternatively, people are increasingly accustomed to using avatars and virtual agents, integrating them organically into their daily lives, as demonstrated by the study reported in [5], authors investigate the acceptance of avatars in professional settings, particularly in remote work meetings. The researchers conducted a large-scale survey involving 2,509 knowledge workers across five countries to evaluate their preferences regarding avatar realism in workplace interactions. Participants evaluated five levels of avatar realism, determining their appropriateness for managers, familiar colleagues, and unfamiliar colleagues. The results show that higher realism is associated with greater acceptability; however, fully photorealistic avatars can occasionally trigger an uncanny valley effect; the uncanny valley effect refers to the unsettling or creepy feeling people experience when they encounter a human-like figure, such as a robot or computer-generated character, that looks almost entirely human but has slight imperfections. Less realistic avatars were generally rated as less acceptable, particularly in interactions with unknown colleagues or managers. Moreover, geographic differences impacted avatar preferences, with respondents from the United States and South Korea showing a higher willingness to use avatars in professional environments than their European counterparts.

Despite these advancements, there is limited research on the direct replacement of traditional visual indicators, such as stack lights, with avatar-based communication systems. This study aims to bridge that gap by proposing a novel, cost-effective, and easily

deployable system that leverages AI-generated video avatars for industrial fault management. Unlike existing solutions that require complex cloud-based processing, the proposed approach is lightweight, operates locally on a Raspberry Pi, and can be seamlessly integrated into existing industrial environments.

### 3 System Architecture and Implementation

The proposed system integrates AI-driven avatars into an industrial fault monitoring framework using a Raspberry Pi-based architecture. The system is designed to provide an intuitive and humanized fault-reporting mechanism, replacing traditional visual alarm systems such as stack lights. The system allows a virtual assistant to narrate various levels of anomalies identified in the industrial process by utilizing pre-recorded video messages saved on an SD card.

#### 3.1 Hardware Components

The system is built upon a **Raspberry Pi** as the central processing unit, which manages sensor inputs and video output. In Fig. 1 the hardware architecture is displayed

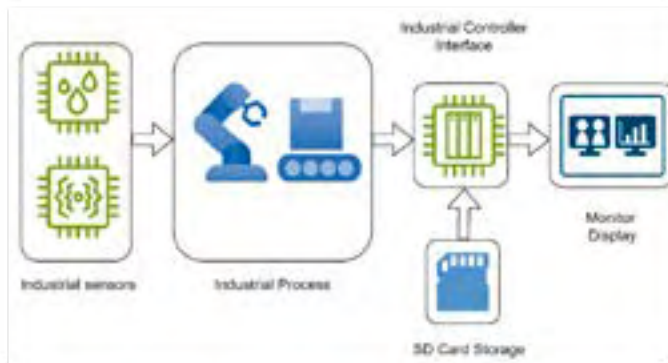


Fig. 1. System Components architecture.

**Industrial Sensors.** The system is equipped with multiple sensors that serve as inputs to detect process conditions. These sensors may include vibration, gyroscopic, and magnetic field sensors, capturing data related to operational anomalies.

**SD Card Storage.** All avatar videos are stored on an SD card and categorized based on the severity of the detected anomalies.

**Industrial Process.** The setup includes a servo-controlled linear guide that enables physical system movement, enhancing interaction and allowing the avatar to be displayed dynamically within the workspace.



**Industrial Controller Interface.** A programmable logic controller (PLC) manages sensor signals and communicates process states to the Raspberry Pi.

**Monitor Display.** A small industrial-grade display serves as the primary visual interface where the avatar presents real-time reports.

### 3.2 Software Architecture

The entire system is programmed in Python, providing flexibility in handling sensor inputs, executing decision algorithms, and managing video playback. At its core, the software processes real-time sensor data to determine the operational state of the industrial process. A decision model classifies faults into different levels, ranging from normal operation, where the avatar simply confirms that the system is functioning correctly, to minor and significant anomalies that may require monitoring or intervention. In cases of severe failures, the avatar issues urgent maintenance warnings, while catastrophic failures trigger immediate shutdown notifications. Additionally, a daily summary reporting module ensures continuity in system monitoring by generating an end-of-day video when no faults have been detected.

The system dynamically selects and plays the appropriate pre-recorded video from the SD card, ensuring the message accurately corresponds to the detected anomaly. The playback module is integrated with an actuation control system that interfaces with a servo-driven linear guide and an industrial controller, adjusting the avatar's display position based on the severity of the detected condition. This enhances the visibility and impact of the alerts, making them more intuitive for operators and supervisors. The architecture is designed to operate efficiently within an embedded industrial setup, minimizing latency while ensuring a reliable and context-aware fault notification system.

### 3.3 Avatar Design and Avoidance of the Uncanny Valley Effect

The avatars utilized in the system were created using a platform that generates hyper-realistic avatars from actual human images, ensuring natural facial expressions and gestures to prevent the uncanny valley effect. This approach enhances operator engagement and trust in the system, as the avatar delivers information in a serious and authoritative tone, appropriate for industrial fault communication.

### 3.4 System Evaluation Setup

The system was evaluated in a controlled industrial environment using a linear guide-driven testbed equipped with various sensors to simulate different fault conditions. The evaluation focused on assessing the accuracy of anomaly detection and classification, the effectiveness of avatar-based communication compared to traditional stack light signals, and user feedback on the clarity, engagement, and trustworthiness of the avatar reports. Throughout the testing phase, predefined scenarios representing normal operation, minor and major anomalies, severe failures, and catastrophic events were systematically triggered to observe the system's response. The ability of the avatar to deliver clear and contextually appropriate messages was analyzed based on response times and operator comprehension. Preliminary results indicate that the system

enhances fault communication by reducing cognitive load, providing richer contextual information, and improving reaction times for decision-making in industrial environments.

## 4 Results

### 4.1 Experimental Setup and Case Study

To assess the feasibility of the proposed system, an initial implementation and proof of concept were carried out in a controlled industrial environment. The system was deployed on a testbed featuring a Raspberry Pi, an array of industrial sensors, a servo-driven linear guide, and an industrial controller, simulating real-world conditions typically found in manufacturing settings (Figure 2).



Fig. 2. System testbed used.

The avatar-based fault reporting mechanism was tested using predefined scenarios, where the sensors captured operational data and triggered the corresponding pre-recorded video messages stored on an SD card. These messages were displayed on a monitor, allowing operators to visualize and interpret system conditions more intuitively. The proof of concept aimed to validate the system's capability to process sensor inputs, accurately classify anomalies, and generate real-time visual alerts via the avatar interface. Figure 3 depicts a Moore machine state to illustrate the system state transition

operation. Table 1 shows the transition conditions and the associated actions of the states.

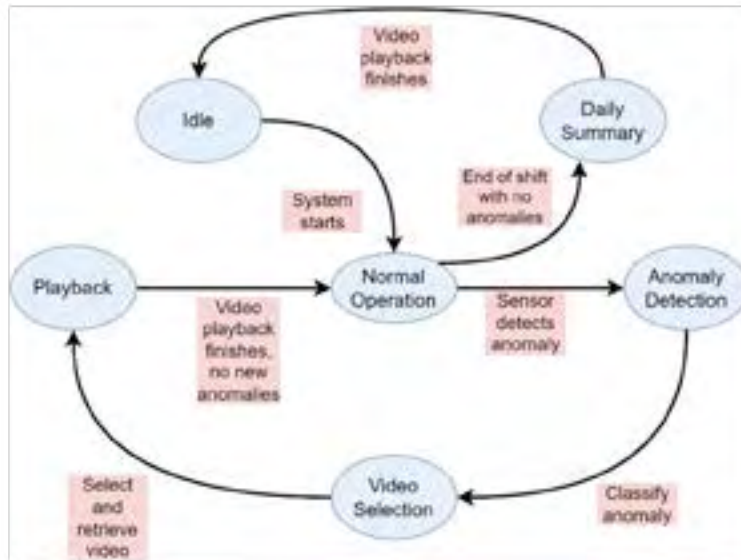


Fig. 3. State Machine for the Avatar-Based Fault Management System.

Table 1. State transition conditions description.

| Current State     | Transition Condition                      | Next State        | Associated Action            |
|-------------------|-------------------------------------------|-------------------|------------------------------|
| Idle              | System starts monitoring                  | Normal Operation  | Begin sensor data collection |
| Normal Operation  | An anomaly is detected                    | Anomaly Detection | Process sensor input         |
| Anomaly Detection | Classify the anomaly                      | Video Selection   | Identify severity level      |
| Video Selection   | Select the corresponding video            | Playback          | Load video from SD card      |
| Playback          | Video playback finishes, no new anomalies | Normal Operation  | Return to active monitoring  |
| Normal Operation  | End of shift with no anomalies            | Daily Summary     | Play daily summary video     |
| Daily Summary     |                                           | Idle              | System reset for next cycle  |

The initial testing phase confirmed that the avatar system operated as intended, with no significant sensor response or video playback delays. However, a comparison with conventional alarm systems (e.g., stack lights and acoustic alarms) was not conducted at this stage. Instead, the proof of concept results confirmed the system's potential for enhanced fault communication, setting the foundation for future studies. In upcoming



evaluations, a structured comparison will be performed to assess the system's effectiveness relative to traditional alarm mechanisms.

To illustrate the functioning of the proposed avatar-based fault management system, Figure 4 presents a set of representative screenshots from the video outputs generated in response to different operational conditions.



**Fig. 4.** Overview of the avatar-based fault reporting system. (a) A screenshot of the video corresponding to a daily summary report indicates that no failures occurred during the shift. (b) Screenshot reporting a fault event. (c) The screenshot indicates a normal operational state. (d) The screenshot reports an anomalous condition.

Figure 4 (a) shows a daily summary report, where the avatar confirms no anomalies occurred during the shift. This feature ensures continuous monitoring and reinforces confidence in the system's reliability. Figure 4 (b) displays a fault event report, where the avatar narrates the details of a detected issue, providing an immediate and human-like explanation of the problem. Figure 4 (c) corresponds to a normal operational state, indicating that all monitored parameters are within safe limits. In contrast, Figure 4 (d) illustrates an anomalous condition where the avatar warns about deviations from expected system behavior, prompting further inspection or corrective action.

## 4.2 Future Evaluation Metrics

A future study will include qualitative and quantitative indicators to systematically evaluate the impact of the avatar-based fault management system. Table 2 outlines the key performance metrics to consider in a future research phase.

**Table 2.** Key performance metrics to evaluate in the next phase of this research.

| Category           | Indicator                                         | Measurement Approach                                       |
|--------------------|---------------------------------------------------|------------------------------------------------------------|
| System Performance | - Response time to sensor triggers                | - The time delay between anomaly detection and alert       |
|                    | - Accuracy of anomaly classification              | - Correct classification vs. predefined conditions         |
|                    | - System stability and real-time performance      | - Latency analysis under varying load conditions           |
| User Experience    | * Clarity of avatar communication                 | * Operator surveys and comprehension tests                 |
|                    | * Perceived trustworthiness and engagement        | * User feedback on avatar realism and tone                 |
|                    | * Cognitive load reduction                        | * Comparison of operator response effort                   |
| Operational Impact | - Reaction time to alerts                         | - Time taken by operators to acknowledge alerts            |
|                    | - Decision-making efficiency                      | - Improvement in problem diagnosis and resolution          |
|                    | - Integration potential with existing IoT systems | - Evaluation of interoperability with industrial platforms |
|                    |                                                   |                                                            |

These metrics will offer a comprehensive framework for assessing the effectiveness of the avatar-based system in real-world industrial applications. The findings will aid in refining the system's design, optimizing its communication strategies, and ultimately determining its viability as a human-centered fault management solution in industrial environments.

## 5 Conclusion

The initial implementation and proof of concept of the avatar-based fault management system have demonstrated its feasibility as an alternative to conventional alarm mechanisms in industrial settings. The system successfully integrated sensor data processing, anomaly classification, and real-time avatar-based reporting, providing a structured method for communicating operational conditions. The ability to classify faults into different severity levels and deliver corresponding pre-recorded messages ensures that operators receive contextualized and intuitive alerts, potentially improving situational awareness and reducing the ambiguity often associated with traditional alarm systems.

One of the key advantages of this approach is the human-like interaction offered by the AI-generated system avatars. Unlike conventional alarms, which rely on color codes or tones that require prior training for correct interpretation, the avatar system delivers natural language explanations of anomalies, allowing operators, supervisors, and



engineers to quickly understand the nature and severity of the fault. Using realistic avatars based on actual human images helps avoid the uncanny valley effect, which can make users feel uncomfortable. This approach enhances user engagement and builds trust in the system, making alerts feel more relatable and impactful.

Despite these advantages, there are several challenges and areas for further exploration. The effectiveness of the avatar system compared to traditional fault indicators remains an open question, as no direct comparison has been conducted at this stage. Future studies should evaluate response times, comprehension accuracy, and operator trust when using avatar-based alerts compared to traditional alarm mechanisms. Furthermore, the system's scalability and integration with current IoT frameworks need to be assessed to guarantee its adaptability to various industrial environments. Integrating real-time analytics and machine learning could further improve anomaly detection capabilities, enabling the avatar system to report faults and forecast potential failures before they happen.

Another critical aspect to consider is user acceptance and adaptability. While early observations suggest that operators find avatar-based communication more engaging, a structured user experience study is required to determine if this approach reduces cognitive load and enhances decision-making efficiency in industrial settings. Factors such as perceived credibility, usability, and potential distractions must also be analyzed to optimize the system's implementation.

Overall, the proof of concept results provide a strong foundation for further development, emphasizing the potential of AI-driven avatars as a next-generation human-machine interface in industrial fault management. The planned future evaluation, incorporating qualitative and quantitative performance metrics, will help refine the system's effectiveness and assess its suitability for real-world deployment. If successful, this approach could significantly advance human-centered automation, bridging the gap between technical fault diagnostics and intuitive, accessible communication for industrial operators.

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# Evaluating the performance of a hybrid machine learning method for modeling evapotranspiration

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**Abstract.** Evapotranspiration (ET) is a hydrological variable that is very important in hydrology and agriculture. Traditionally, ET estimation process is based on empirical models and conducted over monthly and daily data. Technological developments have increased the collection of climate data related to ET. Commonly, processing data with a finer temporal resolution using classical methods is complex. However, artificial intelligence has become an alternative tool to model ET, when large datasets are available. One of the most used techniques to model ET is neural networks. Models developed using neural networks have shown good performance in ET estimation, mainly when a multilayer perceptron is employed. However, it is recognized that multilayer perceptron architectures could present difficulties related to their learning mechanisms. Thus, this paper presents the implementation of a hybrid machine learning method based on multilayer perceptron and metaheuristic algorithms. The experimental results show that hybridized methods can improve the ET estimation process. In this study, the performance comparison is based on several state-of-the-art metaheuristic methods including the Runge Kutta Optimization Algorithm, the Crow Search Algorithm, the Fuzzy Logic, and the Grey Wolf Optimizer Algorithm.

**Keywords:** Machine learning, Metaheuristic Algorithms, Multilayer Perceptron.

## 1 Introduction

Evapotranspiration refers to the quantity of water that returns to the atmosphere due to evaporation from water bodies and vegetation transpiration [1]. Estimating evapotranspiration is considered an essential task in hydrological studies and water resources management in agriculture [2]. Commonly, evapotranspiration estimation is based on the calculation of reference evapotranspiration, which is considered a climatic parameter that expresses the evaporating power of a specific location and time [3]. However, due to the complexity of their measurement, empirical methods were formulated through time mainly based on the relationship between evapotranspiration and climatological variables. Among these methods are Priestley-Taylor [4], Hargreaves [5] Penman [6], and the most used and recommended by the Food and Agriculture Organization (FAO), the FAO-56 Penman-Monteith method [3]. One feature of these methods

<https://doi.org/10.61728/AE20255060>



is that the calculations are performed commonly on a monthly and daily basis. This was due to the lack of information on the climatological variables used in the calculations in the past. Nonetheless, it is currently possible to use technological devices to collect meteorological data with a finer temporal resolution, but now, a task to solve consists of processing this information. In this sense, computational models derived from artificial intelligence have become a good option mainly due to their capacity to capture complex dynamics and non-linear patterns. Among these kinds of models, Neural Networks are one of the most used and tested to model evapotranspiration [7]. For example, Kumar et al. [8] use a Multilayer Perceptron to model reference evapotranspiration based on information on six meteorological variables, obtaining good results compared with the FAO 56 Penman-Monteith method and lysimeter measurements. Rahimikhoob [9] also uses a multilayer perceptron to model evapotranspiration but uses only information about maximum and minimum temperature and solar radiation. Their results show a good agreement with the reference evapotranspiration calculated based on FAO 56 Penman-Monteith method. Recently, Jain and Gupta [10] compared four different architectures to model evapotranspiration according to the climate conditions of India. Their results found that it is possible to model evapotranspiration with good results based only on temperature, solar radiation, and wind speed information. Nevertheless, the results recognized that the models based on multilayer perceptron could have problems with the global weight adjustment in their learning mechanisms. To solve this problem, new architecture has been proposed. The hybridization method has been recognized as a good option to improve the performance of the models because, in some research, precision improvement and a reduction in computing time have been observed. However, the need to study the behavior of these methods is recognized. Thus, this research aimed to implement a hybrid machine-learning method based on multilayer perceptron and metaheuristic algorithms and evaluate their performance to predict reference evapotranspiration.

## 2 Methodology

To analyze the performance of the optimization algorithm, a multi-layer perceptron was built based on a network architecture 5-6-1, which means the input layer is composed of five input variables, the hidden layer comprises six neurons, and an output layer which returns evapotranspiration predictions. The number of parameters or function weights according to the proposed architecture was 42. The iteration number to evaluate the performance of the optimization techniques was 1000. A schematic description of the multi-layer perceptron is shown in Figure 1. A list of the metaheuristic methods applied in the hybridization as well as their initial parameter configuration is shown in Table 1. The proposed algorithm was implemented using MATLAB software. The input data were obtained from a weather station located in Autlán, Jalisco, México. This weather station registers hourly data for temperature, solar radiation, wind velocity, relative humidity, and barometric pressure.



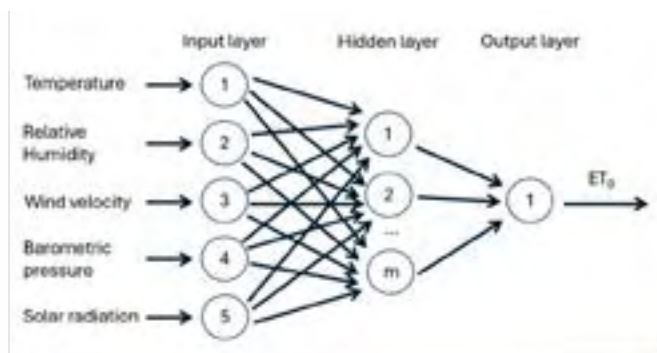


Fig. 1. Multi-layer perceptron architecture. The input layer uses the climatic variables commonly used to calculate evapotranspiration with traditional models.

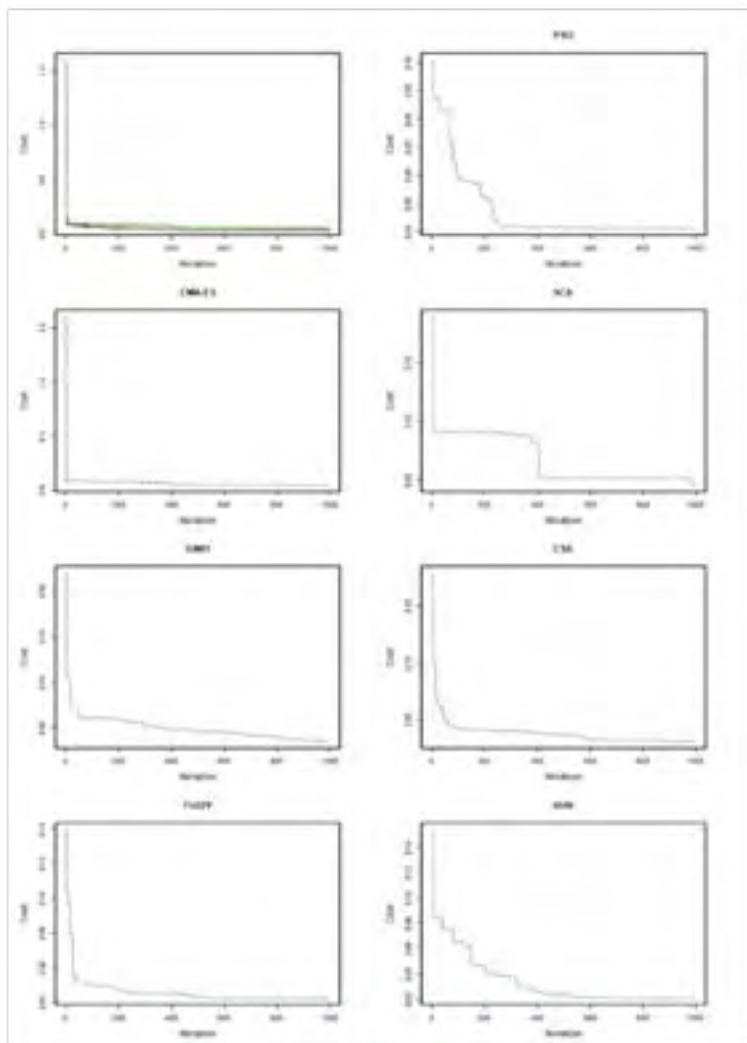
Table 1. Metaheuristic algorithms used for the hybridization.

| ID     | Name                                            | Parameters               |
|--------|-------------------------------------------------|--------------------------|
| PSO    | Particle Swarm Optimization                     | $C_1=2$                  |
|        |                                                 | $C_2=2$                  |
|        |                                                 | $Wdamp=0.99$             |
|        |                                                 | $W=1$                    |
| SCA    | Sine Cosine Algorithm                           | $r=2$                    |
| GWO    | Grey Wolf Optimizer                             | $r_1 = \text{rand}(0,1)$ |
|        |                                                 | $r_2 = \text{rand}(0,1)$ |
| CSA    | Crow Search Algorithm                           | $AP=0.1$                 |
|        |                                                 | $F1=2$                   |
| CMA-ES | Covariance Matrix Adaptation Evolution Strategy | $\sigma=0.3$             |
|        |                                                 | $a=2$                    |
|        |                                                 | $\beta=3.5$              |
| Fuzzy  | Fuzzy Logic                                     | $\beta_1=0.15$           |
|        |                                                 | $Per=1.5$                |
|        |                                                 | $Tam=0.75$               |
| RUN    | Runge Kutta Optimization Algorithm              | $h=2$                    |

### 3 Results and discussion

Figure 2 shows examples of the results obtained while running the seven metaheuristic algorithms used to optimize the model's parameters. The first subgraph shows the results for all the models tested. In this subgraph, apparently, all the models show similar behavior. However, when the results of each model were plotted individually, there was some interesting behavior. First, it is noticeable that almost all the models show rapid convergence, although the PSO, SCA, and RUN show better results after iteration number 400. According to the mean descriptive statistics (Table 2) calculated based on 30

runs of each algorithm, the Runge Kutta Optimization Algorithm performs better, followed by the Crow Search Algorithm, the Fuzzy Logic, and the Grey Wolf Optimizer.



**Fig. 2.** Convergence of the metaheuristic algorithms.

This behavior can also be observed in Figure 3. The asymptotic behavior of the Runge Kutta approaching the value of 0.02 is noticeable.

During the algorithms' running, the PSO algorithm's results fluctuated wildly, although their execution time can be considered low. On the other hand, the CMA-ES algorithm, which was expected to perform well, showed the highest variability between

runs, which can be confirmed through its standard deviation shown in Table 2. Although not designed with a focus on climatological data, the SCA algorithm shows a behavior similar to that observed with CMA-ES. Regarding the execution time, the Fuzzy Logic was the most time-consuming because it uses approximately six minutes per run compared to the two minutes of execution of the other algorithms. Nevertheless, this time of execution is considered as low because, in all the runs, the algorithms stopped until they reached 1000 iterations.

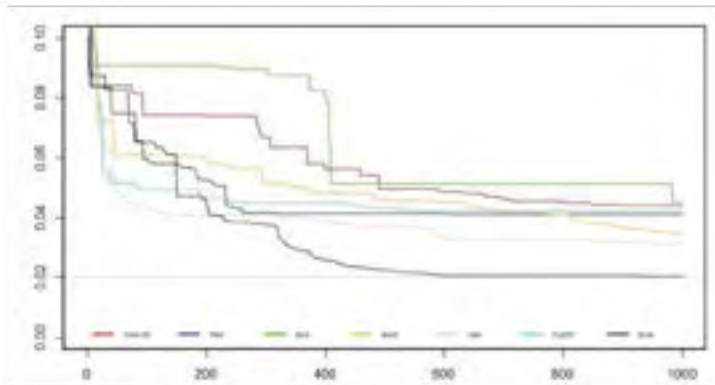


Fig. 3. Comparison of the convergence of the metaheuristic algorithms.

Table 2. Mean descriptive statistics of the running tests.

| Statistic | PSO   | SCA   | GWO   | CSA   | CMA-ES | FUZZY | RUN   |
|-----------|-------|-------|-------|-------|--------|-------|-------|
| Minimum   | 0.061 | 0.058 | 0.044 | 0.041 | 0.059  | 0.45  | 0.024 |
| Maximum   | 0.138 | 0.168 | 0.165 | 0.158 | 0.888  | 0.161 | 0.174 |
| Mean      | 0.067 | 0.072 | 0.051 | 0.047 | 0.068  | 0.050 | 0.041 |
| STD       | 0.012 | 0.015 | 0.010 | 0.011 | 0.029  | 0.011 | 0.021 |

## 4 Conclusion

In this research, machine learning techniques and metaheuristic algorithms were implemented to find models with better performance for the prediction of evapotranspiration. The algorithms selected for the study were the Particle Swarm Optimization (PSO), Crow Search Algorithm(CSA), Sine Cosine Algorithm (SCA), Grey Wolf Optimizer (GWO), Covariance Matrix Adaptation Evolution Strategy (CMA-ES), FUZZY LOGIC (FUZZY), and the Runge Kutta Optimizer (RUN) in conjunction with a multi-layer perceptron. The results show that hybridization can improve the performance of the models focused on the prediction of hourly evapotranspiration, mainly when it is used in the hybridization of the Runge Kutta Optimization Algorithm, the Crow Search Algorithm, the Fuzzy Logic, and the Grey Wolf Optimizer Algorithm. Nevertheless, it

is necessary to carry out more experiments to confirm and improve the performance of the models shown in this research.

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# A Review of Image Stitching Methods: From the Original Manual to the Modern Automatic Algorithms.

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**Abstract.** Image stitching is a fundamental image processing technique that combines multiple overlapping images into panoramic images while minimizing transitions and distortions. This paper explores the evolution of image stitching from its manual beginnings to contemporary automated systems driven by advances in AI. Traditional methods, including direct and feature-based approaches, are discussed, highlighting their strengths and limitations. Recent advancements in AI, particularly in deep learning techniques, have significantly improved the accuracy and robustness of image stitching in complex scenarios. The AutoStitch algorithm is also examined for its comprehensive approach to feature detection, homography estimation, and blending. Despite these advancements, challenges in handling large datasets and poor capture conditions remain. This paper concludes by discussing the potential of emerging techniques to further transform applications in photography, mapping, augmented reality, and beyond.

**Keywords:** Image Stitching, Panoramic Image Processing, Feature-based methods, Deep learning algorithms, AutoStitch, Computer vision, Image alignment, Optimization Techniques

## 1 Introduction

Image stitching is a fundamental technique in image processing that combines multiple overlapping images to create wide panoramic or higher-resolution images while minimizing transitions and distortions. This technique has transformed remarkably from its manual beginnings in the 19th century to contemporary automated systems, driven by advances in computer vision and artificial intelligence [1]. In its early days, this process was carried out manually by joining daguerrotypes, which, despite being innovative at the time, had significant limitations [2]: dependence on the operator's skill, lack of geometric precision,

<https://doi.org/10.61728/AE20255077>





and the inability to correct perspective differences. However, these rudimentary methods laid the groundwork for developing more sophisticated approaches, which we will explore in this article.

Image stitching methods are usually classified into two groups: *direct methods* and *feature-based methods*. While direct methods use pixel intensity-based alignment techniques to find correspondences between images, feature-based methods detect and match key points (features) between images, such as corners or edges, using algorithms like SIFT (Scale-Invariant Feature Transform) [3] and SURF (Speeded-Up Robust Features) [4]. Both approaches to image stitching have found their way to several applications, including panoramic photography, aerial mapping, virtual reality, specialized medical imaging, and remote sensing.

In recent years, advances in feature detection algorithms, geometric optimization, and artificial intelligence (AI) have expanded the scope of image stitching and improved its accuracy, especially in complex scenarios.

The remaining sections of this paper are organized as follows. Section II presents traditional techniques and their general methodology. New approaches to image stitching, which use AI techniques, are covered in Section III. The AutoStitch algorithm, a fully automated approach to image stitching proposed by Matthew Brown and David G. Lowe, is covered in section IV. Finally, Section V discusses the limitations and possibilities of the image stitching methodologies.

## 2 Image Stitching methods

Image stitching refers to merging multiple overlapping images into a unified panoramic image. Its main stages could be enumerated as follows: Feature Detection (identifying distinctive points in the images), Feature Matching (locating corresponding points across images), Alignment (applying transformations to align the images), and Blending (seamlessly combining the images).

Methods for image stitching are generally divided into two categories, depending on where the similarities between images are searched: direct methods and feature-based methods. Below, we outline a general algorithm that incorporates both methodologies.

### 1. Image Acquisition:

- Different types of sensors can be used for image capturing. For panoramic image stitching, images can be acquired by moving the camera in different sequential directions[5].

### 2. Image Registration:

#### – Direct Methods:

- Direct search for similarities between image regions using methods like cross-correlation or intensity difference minimization[6].
- Optimization of pixel-based alignment to improve registration accuracy[6].

#### – Feature-Based Methods:

- Detection of key features using algorithms like SIFT (Scale-Invariant Feature Transform)[7] or SURF (Speeded-Up Robust Features)[4].

- Matching features between images using techniques like k-nearest neighbors (k-NN)[8].
- Estimation of the homography or geometric transformation to align the images[8].

### 3. Image composition (Warping):

- Application of the estimated geometric transformation to align the images.
- Use of interpolation techniques, such as bilinear or bicubic, to smooth the transition between images[7].

### 4. Blending:

- Combination of the aligned images to create a seamless panoramic image.
- Common techniques include simple averaging, multi-band blending, or the use of transition masks[6].

### 5. Postprocessing:

- Removal of artifacts, such as ghosting edges, using smoothing techniques.
- Adjustment of color and brightness to ensure uniformity in the final image.

Direct methods, also called *pixel-based methods*, directly compare pixel intensity values, allowing for highly precise alignment in controlled conditions. However, they have a high computational cost and are highly sensitive to illumination variations and geometric transformations such as scale, rotation, and perspective changes. On the other hand, feature-based methods extract key points from images and use them for alignment, making them more robust and computationally efficient. These methods are instrumental in real-time applications. However, their performance depends on the quality of the detected key points and their descriptors. The table 1 offers a comparative of both approaches.

**Table 1.** General Differences Between Direct Methods and Feature-Based Methods

| Aspect                                   | Direct Methods                                                           | Feature-Based Methods                                                         |
|------------------------------------------|--------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| Working Principle                        | Compare pixel intensity values directly between images.                  | Detect and extract key features (points, edges, corners) for image alignment. |
| Robustness to Geometric Transformations  | Sensitive to scale, rotation, and perspective changes.                   | Invariant to rotation, scale, and perspective changes.                        |
| Tolerance to Illumination and Occlusions | Highly sensitive to illumination variations and occlusions.              | More robust to lighting variations and partial occlusions.                    |
| Computational Efficiency                 | Computationally expensive due to pixel-wise operations.                  | More efficient by reducing dimensionality using descriptors.                  |
| Precision                                | Can achieve highly accurate alignment for images with small variations.  | Accuracy depends on the quality of feature detection and matching.            |
| Real-Time Applicability                  | Less suitable for real-time applications due to high computational cost. | Optimized algorithms like ORB can run in real-time.                           |
| Example Algorithms                       | SAD, SSD, NCC, MI.                                                       | SIFT, SURF, ORB, BRISK, FREAK, KAZE, AKAZE.                                   |

## 2.1 Direct Methods

Direct methods include a variety of techniques designed to compare image regions directly. The most commonly used approaches are Sum of Squared Differences (SSD) and Sum of Absolute Differences (SAD), which measure similarity by computing pixel intensity differences. Additionally, correlation-based methods assess the degree of similarity between image patches, while Mutual Information is frequently employed in multimodal image registration to maximize shared information between images. These methods evaluate similarity measures between pixel values, making them particularly effective for processing well-aligned images with minimal distortions [5]. Further details about prominent direct methods are provided in the following paragraphs; their advantages and disadvantages are summarized in Table 2.

**Sum of Absolute Difference (SAD).** The SAD is a simple and effective method for image stitching, especially when motion estimation is required [9]. It calculates the absolute difference between pixel intensities of two images  $I_0$  and  $I_1$  at different displacements  $u$ :

$$\text{SAD}(I_1, I_2) = \sum_{x,y} |I_1(x, y) - I_2(x, y)| \quad (1)$$

A low SAD value indicates good alignment between the two images, helping determine the optimal transformation for stitching.

**Sum of Squared Difference (SSD).** The SSD is an alternative similarity metric used for alignment. By squaring the pixel intensity differences, SSD emphasizes larger discrepancies more than SAD:

$$\text{SSD}(u) = \sum_i [I_2(x_i + u) - I_1(x_i)]^2 \quad (2)$$

Minimizing SSD allows for locating overlapping regions between images, ensuring an accurate alignment [10].

**Cross-correlation** measures the intensity similarity between two images by computing their dot product:

$$C(I_1, I_2) = \sum_{x,y} I_1(x, y) \cdot I_2(x, y) \quad (3)$$

where  $C(m, n)$  represents the correlation value for a displacement  $(m, n)$ . This method is particularly useful for detecting patterns and aligning images with repetitive textures [10].

**Normalized Cross-Correlation (NCC).** When brightness variations exist between images, Normalized Cross-Correlation (NCC) provides a more robust

solution:

$$\text{NCC}(I_1, I_2) = \frac{\sum_{x,y} (I_1(x,y) - \mu_1)(I_2(x,y) - \mu_2)}{\sqrt{\sum_{x,y} (I_1(x,y) - \mu_1)^2 \sum_{x,y} (I_2(x,y) - \mu_2)^2}} \quad (4)$$

where  $\mu_1$  and  $\mu_2$  are the mean intensities of  $I_1$  and  $I_2$ , respectively. NCC is more robust to illumination changes and noise compared to SAD, SSD, and standard cross-correlation, making it a popular choice for image alignment tasks [10].

**Mutual Information (MI).** This method evaluates the statistical dependence between image intensities[11]. The MI between two images  $I_1$  and  $I_2$  is given by:

$$\text{MI}(I_1, I_2) = \sum_{i,j} p(i,j) \log \frac{p(i,j)}{p_1(i) \cdot p_2(j)} \quad (5)$$

where  $p(i,j)$  is the joint probability distribution of the intensities in  $I_1$  and  $I_2$ , and  $p_1(i)$  and  $p_2(j)$  are the marginal distributions. MI is highly effective for aligning images with different modalities or significant intensity variations, such as in medical imaging.

**Table 2.** Advantages and Disadvantages of Direct Methods

|                                       | Advantages(+) / Disadvantages(-)                                                                                                                                      |
|---------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Simplicity</b>                     | (+) Easy to implement.                                                                                                                                                |
| <b>Computational Cost</b>             | (-) High computational cost for high-resolution images.                                                                                                               |
| <b>Noise Robustness</b>               | (-) Highly sensitive to noise.                                                                                                                                        |
| <b>Illumination Invariance</b>        | (-) Sensitive to changes in lighting and contrast.                                                                                                                    |
| <b>Geometric robustness</b>           | (+) Effective for translations and simple affine transformations.<br>(-) Poor performance with rotations, scaling, or complex deformations.                           |
| <b>Efficiency in Complex Textures</b> | (+) Ideal for images with uniform textures or few distinctive features.<br>(-) Less effective in images with complex features.                                        |
| <b>Multimodal Image Alignment</b>     | (+) Methods such as Mutual Information (MI) are effective for images from different modalities.<br>(-) Requires precise estimation of probability distributions.      |
| <b>Accuracy in Similar Images</b>     | (+) High accuracy in images with strong similarity in intensity and structure.<br>(-) Struggles with images containing occlusions or significant perspective changes. |

## 2.2 Feature-Based Methods

With the advent of computer vision in the 1980s, algorithms emerged that could identify and match key features in images, such as corners, edges, and other key points that are invariant to changes in scale, rotation, and lighting conditions [3]. Some of the most notable examples are briefly described in the following paragraphs.



**Scale-Invariant Feature Transform (SIFT).** Introduced by Lowe [3], this algorithm identifies robust key points that are invariant to geometric transformations and illumination changes. It uses intensity gradients to create unique descriptors that enable precise matching between images.

**Speed-Up Robust Features (SURF).** Proposed as an improvement over SIFT by Herbert Bay [4], SURF employs Haar wavelet responses to accelerate the detection and description process. It is particularly effective in applications requiring real-time processing due to its lower computational complexity.

**Oriented FAST and Rotated BRIEF (ORB).** An efficient alternative to SIFT and SURF, ORB combines the FAST detector and the BRIEF descriptor, optimizing them for speed and robustness while also being invariant to rotation and scale [12].

**KAZE and AKAZE.** KAZE detects keypoints in nonlinear scale spaces using diffusion equations, which allows for better edge preservation compared to linear methods. AKAZE, on the other hand, is a faster version of KAZE, designed for real-time applications. Both algorithms are particularly useful in scenarios requiring high-precision feature detection [13].

**BRISK (Binary Robust Invariant Scalable Keypoints)** BRISK identifies keypoints using a circular sampling pattern and determines their orientation based on local gradients. It generates a binary descriptor by comparing intensity pairs within the sampling pattern [14]. This algorithm is well-suited for real-time applications and resource-constrained systems.

**FREAK (Fast Retina Keypoint)** FREAK employs a retina-inspired sampling pattern to detect keypoints and creates a binary descriptor by comparing pixel pairs within the pattern. This approach mimics the human visual system to enhance efficiency [15]. FREAK is highly efficient and is commonly used in mobile and low-power applications.

Once the features are detected, the next step is to find correspondences between the images. This is achieved by comparing the feature descriptors using distance metrics, such as the Euclidean distance. To improve accuracy, techniques like the following are applied:

1. **Lowe's ratio test:** Filters ambiguous matches by comparing the distance of the nearest neighbor with that of the second nearest neighbor [3].
2. **K-NN (k-Nearest Neighbors):** Finds the k closest matches for each feature [16].
3. **FLANN (Fast Library for Approximate Nearest Neighbors):** Designed to efficiently match large sets of descriptors, FLANN is particularly useful in projects involving high-resolution images.



With the correspondences between images having been found, it is time to estimate the homography, a projective transformation that maps points from one image to another. To estimate it, methods such as the following are used:

1. **RANSAC (Random Sample Consensus):** Fischler and Bolles [17] proposed RANSAC to eliminate outliers and robustly compute the homography. This method filters incorrect matches and randomly selects a subset of points, evaluating their consistency with the model.

The final step is image blending, where the images are projected onto a common plane and combined. The most common techniques include:

1. **Linear averaging:** Combines images by averaging pixel values in overlapping regions [9].
2. **Multi-band blending:** Szeliski [9] proposed this technique, which blends images at multiple frequency bands to avoid discontinuities.
3. **Poisson blending:** Uses differential equations to smooth transitions between images [18].

In addition to feature detection and matching, these techniques include optimization steps such as lens distortion correction and alignment based on homographies. This ensures that the images are assembled with minimal visual inconsistencies. The table 3 summarizes this approach's advantages and disadvantages.

**Table 3.** Advantages and Disadvantages of Feature-Based Methods

|                                | Advantages(+) / Disadvantages(-)                                                                                         |
|--------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| Computational Cost             | (+) Reduces dimensionality by working with descriptors.<br>(-) High computational cost for large images.                 |
| Real-Time Applicability        | (+) Algorithms like ORB are optimized for real-time processing.<br>(-) Higher implementation complexity.                 |
| Illumination Invariance        | (+) Robust to changes in lighting conditions.<br>(+) Sensitive to extreme illumination variations.                       |
| Geometric Robustness           | (+) Invariant to rotations, scaling, and perspective changes.<br>(-) Challenging under extreme scale variations.         |
| Efficiency in Complex Textures | (+) Ideal for images with rich textures and distinctive features.<br>(-) Less effective in images with uniform textures. |
| Handling of Occlusions         | (+) Can manage partial occlusions.<br>(-) Struggles with significant occlusions.                                         |

### 3 Emerging Techniques

Image stitching has significantly advanced through artificial intelligence (AI) techniques, mainly thanks to deep learning models that learn patterns directly from data, reducing reliance on manually crafted descriptors [19]. Beyond convolutional neural networks (CNNs), other AI approaches have been explored to enhance image stitching. For instance, Generative Adversarial Networks (GANs) have been employed to improve blending and artifact reduction, ensuring seamless transitions in stitched images [20]. Additionally, transformer-based models have been investigated for their ability to capture long-range dependencies, aiding in more accurate image alignment [21]. These advancements demonstrate how AI, beyond traditional CNNs, is revolutionizing image stitching by making it more robust, adaptive, and efficient across various applications, including medical imaging, satellite image mosaicking, and real-time panoramic video generation [19].

Among the different ways in which AI has enhanced the different stages of image stitching, we can highlight the following:

- **Feature Detection with CNNs:** They replace traditional methods like SIFT, generating more accurate keypoints. For example:
  - **SuperPoint:** It is a neural network that detects and describes keypoints in images. SuperPoint is trained in a self-supervised manner and outperforms traditional methods like SIFT in terms of accuracy and robustness. It was proposed by Detone in 2018 [22].
  - **LF-Net:** It is a neural network that jointly detects and describes features using a deep learning-based approach. Proposed by Ono et al. in 2018 [23].
- **Homography Estimation with Neural Networks:** Homography estimation has also benefited from deep learning. Some methods include:
  - **Unsupervised Homography Estimation:** Nguyen et al. (2018) [24], proposed an unsupervised method that trains a CNN using photometric consistency as the loss function. This eliminates the need for labeled homography data.
  - **DSAC (Differentiable Sample Consensus):** Proposed by Brachmann et al. (2017) [25], DSAC integrates RANSAC into a neural network, making the entire pipeline differentiable. This allows end-to-end training while maintaining the robustness of RANSAC.
- **Image Fusion with Deep Learning:**
  - **Deep Blending:** Uses a neural network to seamlessly blend images, minimizing discontinuities in overlapping regions [26].
  - **GAN-based Image Stitching:** Generative adversarial networks (GANs) have been used to generate realistic transitions between images. For example, Ma et al. [27] proposed a GAN-based method for medical image fusion, where the generator learns to produce fused images and the discriminator ensures their quality.

These modern techniques have significantly advanced the field of image fusion, offering improved quality, robustness, and adaptability compared to traditional methods. Techniques like CNN-based fusion and GANs have enabled new applications in medical imaging, remote sensing, and multi-modal fusion. However, challenges remain, particularly in terms of data requirements, generalization, and computational cost.

## 4 Automatic Panoramic Image Stitching

The AutoStitch algorithm [7], introduced by Matthew Brown and David G. Lowe in 2007, is one of the most influential methods in the field of panorama creation from multiple images. This algorithm relies on local feature detection using the SIFT (Scale-Invariant Feature Transform) descriptor and robust homography estimation through the RANSAC (Random Sample Consensus) algorithm. The overall operation of the algorithm could be summarized in the following steps:

1. **Feature Detection:** The algorithm employs the SIFT feature detector [3] to identify keypoints in each image. These keypoints are invariant to changes in scale and rotation, enabling the handling of images with varying orientations and zoom levels. Feature matching between image pairs is then performed using Lowe's ratio test, which eliminates false matches by comparing the distance between the two nearest neighbors in the feature space.
2. **Image Alignment and Homography Estimation:** A probabilistic model is used to estimate the geometric transformation (homography) between image pairs. RANSAC (Random Sample Consensus) is employed to robustly fit the homography and reject outliers.
3. **Bundle Adjustment:** Global alignment is achieved using bundle adjustment, which optimizes the camera parameters and image positions to minimize reprojection errors across all images.
4. **Blending and Compositing:** Multi-band blending is used to seamlessly merge images while minimizing ghosting and exposure differences. This technique blends images at multiple frequency bands, ensuring smooth transitions in both high-frequency details and low-frequency color gradients.

The AutoStitch approach combines robustness and efficiency, establishing itself as a comprehensive solution for image stitching. Its ability to handle complex transformations and produce seamless panoramas has made it a benchmark in the field.

## 5 Conclusion

Image stitching has evolved significantly from its manual origins to modern algorithms powered by deep learning. Traditional methods, such as direct and feature-based approaches, have laid the groundwork for more sophisticated techniques, enabling precise alignment and seamless blending of images. The introduction of deep learning, mainly through convolutional neural networks (CNNs)



and generative adversarial networks (GANs), has further enhanced the robustness, accuracy, and adaptability of image stitching, making it applicable to a wide range of scenarios, including medical imaging, remote sensing, and real-time panoramic video generation. The AutoStitch algorithm bridges traditional and advanced approaches, integrating feature detection, homography estimation, and blending to produce high-quality panoramas. However, challenges such as handling large datasets, adapting to adverse capture conditions, and reducing computational costs remain. Continued advancements in this field promise to further revolutionize applications in photography, mapping, augmented reality, and beyond, making image stitching an increasingly powerful tool in computer vision and image processing.

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# Heart Diseases Diagnosis Based on ECG Harmonic Analysis and Pattern Classification

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**Abstract.** Heart diseases have been a critical issue to deal with to improve people's health. Medical research and technology are being developed to obtain accurate diagnoses and treatments. This paper contributes to the design of an automated diagnosis system to classify electrocardiogram (ECG) signals to detect cardiac diseases. The proposed diagnosis system is based on the Fourier series analysis, which uses a dynamical state observer to instantaneously obtain salient features and patterns from the ECG harmonic content in real-time, whose information is classified through a K-Nearest neighbor algorithm (KNN), named as classifier, which determines the possible disease. The ECG signals used in this paper are obtained from the free online available PhysioNet databases, which contain information that can be used for the diagnosis and classification of healthy patients, arrhythmia cases, myocardial infarction, and heart failure. The proposed automated procedure is 93% effective in disease detection for the explored databases, highlighting its potential as a classification tool for ECG-based diagnosis.

**Keywords:** Heart diseases diagnosis · ECG · Fourier series · State observer · Harmonic content · Computational classifiers.

## 1 Introduction

Currently, derived from technological developments and electronic devices, different disciplines are improving their information analysis to make better decisions. It is even desirable to automate processes when possible. For instance, mechanisms in medicine are progressing to automate diagnosis, such as identifying cardiac pathologies from biomedical signals through electrocardiogram datasets, among other means. In 2021, around 220,000 people in Mexico died due to cardiovascular diseases, making it the leading cause of death in people over 55 years old [18]. The myocardial infarction was the primary cardiovascular disease and caused 177,000 deaths in 2021 [17]. Meanwhile, in the same year, 20.5 million deaths were recorded worldwide, according to reports from the World Heart Association [23].

Electrocardiograms are essential and non-invasive methods for diagnosing heart diseases. However, manual analysis based on human visualization/interpretation

<https://doi.org/10.61728/AE20255084>



of these ECG signals requires highly specialized knowledge, as they can be misinterpreted or misdiagnosed. Currently, an ECG is the result of electrocardiography, as the process of recording the electrical activity of the heart [22]. The obtained data can be displayed in an electrocardiograph for medical analysis, and additionally, the data can be digitally stored for computerized analysis purposes. In this sense, the importance of our proposed research is the faster and more automated analysis of ECG signals as a tool for detecting heart pathologies for adequate treatment by a specialist.

Techniques to automatically classify ECG signals and for detecting heart diseases have been developed. In the case of arrhythmias, for example, authors in [10] use Deep Separable Convolutional Neural Networks with Focal Loss (DSC-FL-CNN) to analyze and classify arrhythmias in ECG signals; in [24], authors use a Mixed-Kernel-based Extreme Learning Machine-based Random Forest binary classifier (MKELM-RF) with 98.1% accuracy in the classification. Also, in [3] employ a deep arrhythmia diagnosis method named Convolutional Neural Network-Bidirectional Long Short-Term Memory (CNN-BLSTM), with an accuracy of 96.59%. In [14], they employ a method to detect arrhythmias based on a combination of convolutional neural network and short-term memory. Another way to analyze the ECG signals is by preprocessing the information in the frequency domain. For instance, in [12], the data is preprocessed using the reduced-time Fourier transform and then image-focused neural networks are applied to classify the ECGs into two categories: healthy or presenting a heart anomaly. However, the method does not give a specific diagnosis the disease, that is, it only gives the result of whether the patient is healthy or has a heart disease. In this study, little real data is used, and therefore, artificial signals are used to simulate the ECGs. Another alternative is the usage of the Wavelet transform as done in [16], in which a model is developed, and use a support vector machine (SVM) classifier for the arrhythmias detection. In [9], a K-Nearest Neighbors algorithm is used to classify the ECG signals in the time domain, obtaining an accuracy of 80.9%. Additionally, the approaches above are focused only on binary classification, distinguishing only between healthy and arrhythmias, while our proposal tackles a wider problem by identifying between four specific heart conditions (i.e., heart failure, myocardial infarction, arrhythmia, and healthy). Apart from the fact that most studies focus on arrhythmias, there are also investigations dedicated to other diseases, such as in [11], where a system is proposed for detecting myocardial infarction. This model combines a convolutional neural network (CNN) with a long short-term memory model (LSTM), achieving an accuracy of 88.89%. However, in [25], a study is presented on a deep learning system that employs a classification CNN and a LSTM network to extract the spatial and temporal features of ECG signals.

This paper contributes by proposing a method for the automated diagnosis of heart diseases. The method uses the Fourier series and an optimal state observer (Kalman filter) to quickly obtain the harmonic content of ECG signals as a means of determining salient features of different heart pathologies, that a posteriori by employing a K-Nearest-Neighbors algorithm, the obtained harmonic

content features are classified to determine the possible pathologies. Unlike other studies, our method not only determines whether a patient is healthy but also classifies three different heart diseases: arrhythmia, myocardial infarction, and heart failure. The accuracy of the proposed diagnosis methodology is greater than 93%.

The organization of the paper is as follows. Section 2 describes the modeling of the periodic signals using the Fourier series and the design of the optimal observer. Section 3 presents the optimal estimator as a means of determining the ECG harmonic content quickly, which will be used for classification purposes. Section 4 describes the classification method used for heart disease detection and presents the metrics used to evaluate the performance of the proposed system. Finally, Section 5 presents the conclusions and future work.

## 2 ECG Modeling through a Fourier Harmonic Description

The heart is an organ that depends on coordinated electrical activity for its proper functioning [13]. The electrocardiogram is a fundamental tool for recording heart activity and reflects the electrical events that occur during each cardiac cycle [6]. The heart is an organ that works as a pump and is responsible for pumping blood through the body. The heart muscles carry out this pumping, which can work correctly thanks to electrical impulses [13]. One of the main tasks of the heart is to contract to generate enough pressure in its chambers to properly distribute oxygenated blood throughout the body [20]. Its ability to function as a pump depends on the pumping movements of the atria, ventricles, atrioventricular, and semilunar valves, which direct blood flow within the heart. As mentioned above, heart movements occur every certain period, known as the cardiac cycle. In more concrete words, the cardiac cycle refers to the events that occur between the start of one heartbeat and the start of the next.

### 2.1 The Electrocardiogram

One way to know the health state of the heart is through the ECG, which is a record of its electrical activity. The ECG represents the impulses generated during each cardiac cycle, which are graphically recorded and possibly digitally stored. ECG signals are composed of several wave-shaped features that represent the different events of the cardiac cycle, as depicted in Fig. 1, and described as [6, 8]: *P wave*: Represents the depolarization of the atria; *QRS complex*: It is the depolarization of the ventricles, which occurs just before ventricular repolarization; *T wave*: Corresponds to the repolarization of the ventricles, or in other words, the return to a resting state.

### 2.2 Fourier Harmonic Modeling

The Fourier transform and the Fourier series are widely used tools for analyzing biomedical signals. This proposal employs the latter. Fourier series allows



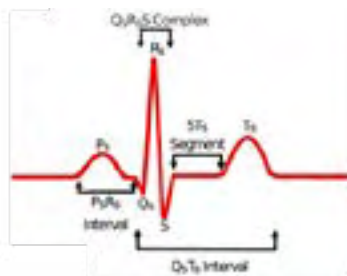


Fig. 1: ECG with their characteristics.

periodic functions/signals to be decomposed into an infinite sum of cosines and sines, which is mathematically described as

$$s(t) = \frac{a_0}{2} + \sum_{n=1}^N [a_n \cos(w_n t) + b_n \sin(w_n t)] \quad (1)$$

where  $s(t)$  is a periodic signal,  $\frac{a_0}{2}$  is the constant value (usually named DC component) of the signal,  $a_n, b_n$  are the Fourier coefficients,  $N \rightarrow \infty$  is the number of harmonics (for finite values of  $N$ , the series only approximates the signal), the angular frequency  $w_n = 2\pi n f$ , with  $f = \frac{1}{T}$  as the signal frequency of period  $T$ . For the purposes of modeling in this paper, it is convenient to present (1) as

$$s(t) = \frac{a_0}{2} + \sum_{n=1}^N A_n \sin(w_n t + \theta_n) \quad (2)$$

where  $A_n = \sqrt{a_n^2 + b_n^2}$  is the amplitude of the sinusoidal function, and  $\theta_n = \arctan\left(\frac{b_n}{a_n}\right)$  is the phase angle [15]. Hence, the harmonic content estimation of a signal consists in the determination of  $a_0$ ,  $A_n$ , and  $\theta_n$  in (2).

### 2.3 Periodic Signal Modeling in a State Space

Signal (2) can be presented in state space, such that a posteriori a state observer can be designed with the aim of determining the supposed unknown values of the parameters  $a_0$ ,  $A_n$  and  $\theta_n$ .

To this end, consider the basic case by taking  $a_0 = 0$ ,  $N = 1$ , the signal amplitude as  $Am$ , and employing the following trigonometric identity  $\sin(a+b) = \sin(a)\cos(b) + \sin(b)\cos(a)$  for (2), one obtains<sup>1</sup>:

$$s(t) = Am \cos \theta \sin(w t) + Am \sin \theta \cos(w t). \quad (3)$$

<sup>1</sup> The n-subscript notation is omitted for easy of notation.

By defining the following state space variables as

$$x_1 \triangleq \sin(wt); \quad x_2 \triangleq \cos(wt) \quad \text{and} \quad y = s(t)$$

the corresponding dynamical description in state space for (3) becomes

$$\begin{aligned} \dot{x}_1 &= w x_2 \\ \dot{x}_2 &= -w x_1 \\ y &= A m \cos \theta x_1 + A m \sin \theta x_2. \end{aligned} \quad (4)$$

Additionally, for the case when the signal  $s(t)$  contains a constant component, given in (2) as  $\frac{a_0}{2}$ , then the following state variable can be added to (4) as

$$\dot{x}_0 = 0 \quad (5)$$

with initial condition  $x(0) = a_0/2$ . Then, the complete signal model described by (4)–(5) can be presented in a matrix form as

$$\dot{x} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & w \\ 0 & -w & 0 \end{bmatrix} x \quad (6)$$

with  $x = [x_0 \ x_1 \ x_2]^T$  and corresponding output as

$$y = [1 \ A m \cos \theta \ A m \sin \theta] x. \quad (7)$$

Notice the previous analysis is for one harmonic, i.e.  $N = 1$ , where the definition of two state variables is needed. Now, the previous modeling procedure can be easily extended to finite values of  $N$ , and additionally, from practical considerations, signal  $s(t)$  is assumed to be affected by noise, resulting in a general system as

$$\dot{x} = A x + v_1 \quad (8)$$

and output

$$y = C x + v_2 \quad (9)$$

where the space state  $x \in \mathbb{R}^{2N}$  is defined as

$$x = [x_0 \ x_1 \ x_2 \ \cdots \ x_{2N-1} \ x_{2N}]^T$$

and matrices

$$A = \begin{bmatrix} 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & w & \cdots & 0 & 0 \\ 0 & -w & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 0 & w_N \\ 0 & 0 & 0 & \cdots & -w_N & 0 \end{bmatrix}$$

and

$$C = [1 \ A_1 \cos \theta_1 \ A_1 \sin \theta_1 \ \cdots \ A_N \cos \theta_N \ A_N \sin \theta_N]$$

while  $v_1 \in \mathbb{R}^{2N}$  and  $v_2 \in \mathbb{R}$  are the process noise and measurement noise, respectively. Noises  $v_1$  and  $v_2$  are considered Gaussian and zero-mean, with covariance given by  $E\{v_1(t) v_1^T(\tau)\} = Q_{v_1} \delta(t - \tau)$  and  $E\{v_2(t) v_2^T(\tau)\} = R_{v_2} \delta(t - \tau)$ , respectively, with matrices  $Q_{v_1}$  and  $R_{v_2}$  nonnegative. Model (8)–(9) will serve for the design of an optimal state estimator (known as Kalman filter), as follows.

## 2.4 Optimal Observer Design

State observers are algorithms used in dynamical systems to estimate variables (when possible) that are unmeasured or difficult to measure, which is achieved through the available measurements. Hence, considering system (8)–(9), the optimal state observer, based on the Kalman filter [2], is described as

$$\begin{aligned}\dot{\hat{x}} &= A \hat{x} + L(y - \hat{y}) \\ \hat{y} &= \bar{C} \hat{x}\end{aligned}\quad (10)$$

where the space state  $\hat{x} \in \mathbb{R}^{2N}$  is defined as

$$\hat{x} = [\hat{x}_0 \ \hat{x}_1 \ \hat{x}_2 \ \cdots \ \hat{x}_{2N-1} \ \hat{x}_{2N}]^T$$

and  $L = P \bar{C}^T R_{v_2}^{-1}$  represents the optimal gain of the observer, and  $P$  is the solution to the Riccati equation, given as

$$\dot{P} = Q_{v_1} - P \bar{C}^T R_{v_2}^{-1} \bar{C} P + A P + P A^T. \quad (11)$$

and

$$\bar{C} = [1 \ k_1 \ k_2 \ \cdots \ k_{2N-1} \ k_{2N}]^T$$

with  $k_1, k_2, \dots, k_{2N}$  as design parameters, which are defined by the user.

**Remark 1** For the observer design, usually are used the matrices given in (8)–(9); nonetheless, matrix  $C$  in (9) is not available since the values for  $A_n$  and  $\theta_n$  are unknown; indeed, those are the parameters to be determined. Hence, as a part of the observer design, it is required to specify the values of the parameters in  $\bar{C}$ , which will be used to calculate the values for matrix  $C$ .

Based on the analysis of (3), the harmonic estimation for  $Am$  and  $\theta$  is given by considering that  $\hat{A}m \cos \hat{\theta} \sin(\omega t) + \hat{A}m \sin \hat{\theta} \cos(\omega t) = k_1 \hat{x}_1 + k_2 \hat{x}_2$  and by taking its time derivative, then a set of two algebraic equations and two variables is formed, whose solution becomes

$$\hat{A}m = \sqrt{(k_1^2 + k_2^2)(\dot{\hat{x}}_1^2 + \dot{\hat{x}}_2^2)}$$

and

$$\hat{\theta} = -\omega t + \arctan\left(\frac{k_1 \hat{x}_1 + k_2 \hat{x}_2}{k_1 \hat{x}_2 - k_2 \hat{x}_1}\right).$$

For this research, the parameter of interest is only the amplitude of each  $n$ -th harmonic, i.e.  $A_n$ . Hence, in a general way, the amplitude estimation of each harmonic in a signal is calculated as

$$\hat{A}_N = \sqrt{(k_{2N-1}^2 + k_{2N}^2) (\hat{x}_{2N-1}^2 + \hat{x}_{2N}^2)}. \quad (12)$$

As an example, numerical values are used in a digital simulation for signal (2), with  $N = 1$ ,  $a_0/2 = 0.5$ ,  $A_1 = 0.2$ ,  $w = 0.9$ ,  $\theta_1 = 30 \text{ deg}$ ,  $k_1 = 6$  and  $k_2 = 0.01$ . Then, the estimation of the signal  $s(t)$  through  $\hat{y}$ , and the harmonic content amplitude by means of (12), are depicted in Fig. 2 and Fig. 3, respectively. As can be noted, the variables of the observer converge after a few seconds to the actual values, demonstrating the capability in the harmonic content estimation of the optimal observer. Once the convergence is achieved, the signal can be used to extract harmonic remarkable information over time, which is a difference with respect to the basic Fourier series, where a complete period of the signal is required to determine the harmonic content.

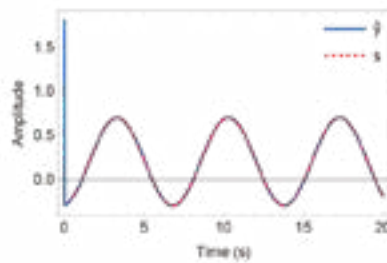


Fig. 2:  $\hat{y}$  vs  $s$

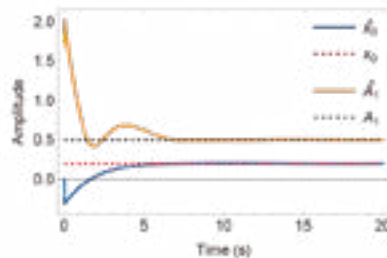


Fig. 3: Estimated components vs real components



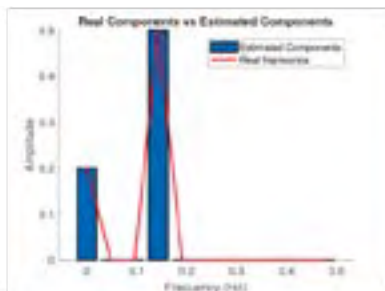


Fig. 4: Estimated components vs real components (Fourier Spectrum)

### 3 Harmonic Content Determination of ECG

This section presents the usage of the optimal observer to estimate the harmonic content of the ECG signals, and based on the content, its salient characteristics will be used as patterns to classify heart pathologies. Notice that this procedure is performed over time; that is, the harmonic content is fastly determined and, in the same way, immediately classified to obtain the heart diagnosis. Additionally, and only for comparison purposes, the fast Fourier transform (FFT) is used to validate the estimation of the harmonic content. It is worth remarking that the coefficient in the Fourier series requires at least a period of time to be calculated; for its part, using a state estimator allows the Fourier coefficients to be instantaneously adapted along the signal acquired over time, which is known as an online process.

#### 3.1 Diagnosis General Scheme

Fig. 5 shows the general scheme of the process that is carried out, starting with the acquisition of the ECG signal, which is preprocessed by normalizing the data to an appropriate range and separating the signal into individual cycles to determine its current frequency. Then, the harmonic content is obtained through an optimal observer. Finally, the harmonic content is classified by a KNN algorithm, which determines the heart diagnosis.



Fig. 5: Process flow diagram

### 3.2 Simulation results

Fig. 6 displays the estimated harmonics (blue bars), which are compared with the FFT (red line), showing the correct harmonic estimation. Fig. 7 presents the estimation error, which is small, giving confidence in the proposed fast procedure to be used by the classifier. On the other hand, Fig. 8 and Fig. 9 show the convergence over time of the optimal state observer toward the references provided by the FFT. In Fig. 8, the reference is the DC component, and in Fig. 9, the reference corresponds to the first harmonic of the Fourier spectrum. The rest of the harmonics present a similar behavior. Finally, the harmonic content is processed by the classifier as described as follows.

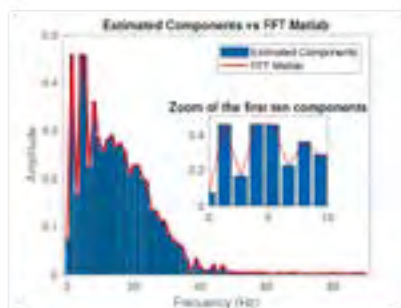


Fig. 6: FFT Matlab vs Estimated Harmonics

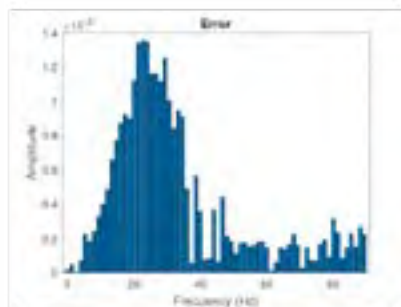


Fig. 7: Error

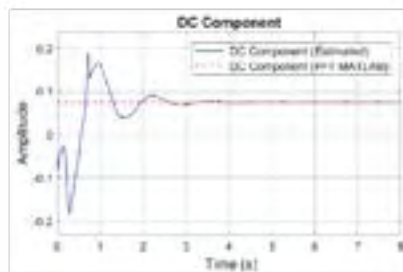


Fig. 8: DC Component

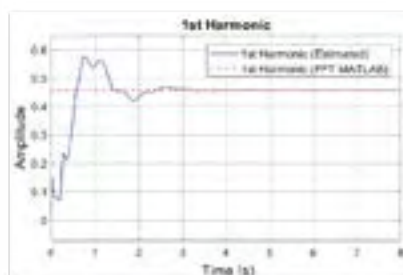


Fig. 9: 1st Component

## 4 ECG Classification and Diseases Detection

ECG classification is necessary to determine different heart diseases. The number of classes to classify depends on the number of available classes on the training dataset. In this research, including the healthy condition, three cardiac pathologies are also considered: arrhythmia, heart failure, and myocardial infarction. The pathology classification will be performed by identifying patterns in the harmonic content of the ECG by using a machine learning algorithm. The patient databases are obtained from the PhysioNet website [1]. For this research, a total of 105 ECG signals were used, including 24 from healthy patients, 29 with arrhythmia, 42 with myocardial infarction, and 10 with heart failure. Each signal contains 10 cardiac cycles, resulting in a total of 1050 cardiac cycles analyzed and used to train the KNN classifier.

There are various techniques for ECG classification, such as Traditional ECG interpretation by experts, where doctors visually analyze an ECG to diagnose heart problems, mainly when visible issues can be identified in the ECG, such as changes in the duration of the  $P_s$  and  $T_s$  waves or changes in the amplitude of the QRS complex. Another ECG classification method is the Classification by Machine Learning. Currently, there are many types of classifiers. Examples that have been used for ECG analysis through different approaches are artificial neural networks, such as those exposed in [3], [10], and [12]. In [24], authors use

the MKELM-based binary random forest classifier (MKELM-RF), while [16] uses a Support Vector Machine. Those classifiers are trained using data sets such that when exposed to new data, this new information can be classified.

#### 4.1 K-Nearest Neighbors

This research uses the KNN algorithm to classify ECG signals according to their harmonic characteristics. Although KNN has been applied in other studies, it is implemented differently since multiple classes are used in this work. KNN is a supervised machine learning classifier, meaning that it is trained using a labeled dataset [21]. In our case, the database did not originally contain labeled classes, so the data are manually labeled to make it suitable for a classification task. The algorithm follows the following steps to classify a new data point whose class is unknown: (a) distance computation: the distance between the new data point and all training data points is reckoned using a distance function. In MATLAB, Euclidean, Chebychev, Correlation, Cosine, and Mahalanobis are available. Generally, Euclidean distance is used, as done in this research; (b) identify the nearest neighbors: the  $K$  closest data points to the new data point are selected; (c) classify: the class of new data is computed as a majority vote decision, selecting the most common class (i.e., the mode) between the  $K$  nearest neighbors.

Fig. 10 illustrates the classification process, in which the KNN algorithm is observed using a new data point and  $K = 3$ ; then, in this case, the 3 closest data are considered, and the majority vote results in class A because there are 2 data of class A and 1 data of class B. Now, for  $K = 12$ , the majority vote considers class B the winner because there are 7 data from class B and 5 from class A, and the new data will be classified as class B. An alternative to classifying is by a weighted vote using the distance between the data query and their neighbors. In this case, the closest points will have greater weight in the decision, while the farthest ones have less influence.

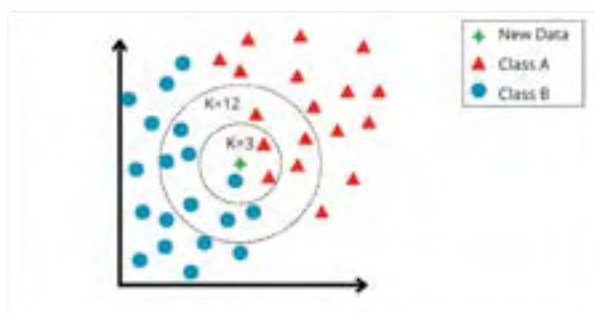


Fig. 10: K-Nearest Neighbor (KNN).



## 4.2 Metrics

The tools (metrics) used to evaluate the classifier performance and their values are shown in Table 1. *The Accuracy* expresses how well the classifier works in terms of the ratio of correct predictions out to the total number of predictions. [19]. *The Precision* measures how many of the predicted classes for a specify class are actually correct. [19]. *Recall* calculates the number of actual instances of a specific class that were correctly predicted [19]. *The F1 score* is a metric that combines precision and recall in a single value. This metric is particularly useful when working with datasets with imbalanced classes [7]. The area under the curve (*AUC*) is a metric used to evaluate the performance of a classification model, specifically regarding its ability to discriminate between classes. The AUC varies between 0.5 and 1, where a value closer to 1 means a better classifier, a value of 1 is a perfect classifier, and a value closer to 0.5 is equivalent to a very bad classifier; this means that the classifier is working randomly. The AUC of a classifier represents the probability that the classifier ranks a randomly chosen positive instance higher than a randomly chosen negative instance [4]. In other words, a higher AUC value means that the classifier has a greater probability of correctly predicting that a data item belongs to the specified class.

Table 1: Metrics

| Metrics          | Value    |
|------------------|----------|
| Accuracy         | 91.8831% |
| Precision        | 90.7487% |
| F1 Score         | 92.0694% |
| F1 Score (Micro) | 91.8831% |
| AUC              | 0.9336   |

In this research, the KNN classifier was implemented in MATLAB, and it was configured with two closest neighbors ( $K = 2$ ).

## 4.3 Confidence

Confidence in classification models evaluates how certain the model is about its predictions. In this research, the receiver operating characteristic (ROC) curve will be used to evaluate the performance of the KNN classifier. The ROC curve is a visual representation of the model performance, which is the relationship between the false positive rate and the true positive rate [5]. The false positive rate is the data that is false but classified as true, and the true positive rate is the true data that is classified as true [4]. For the KNN classifier, the ROC curves shown in Fig. 11 are generated including four classes: Class 0 (Healthy person), class 1 (Arrhythmia), class 2 (Myocardial Infarction) and class 3 (Heart failure). These curves are interpreted by the AUC, whose results are presented in Table 1.

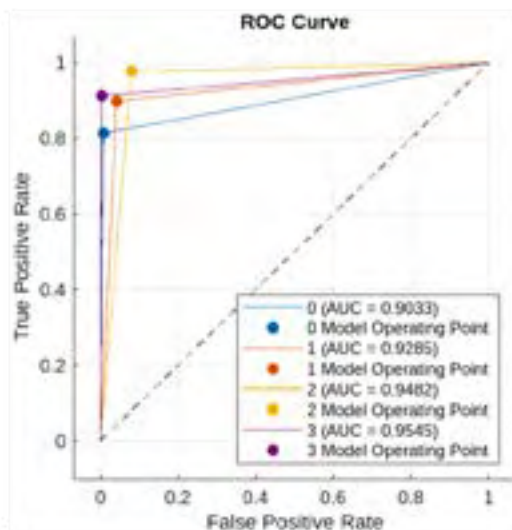


Fig. 11: Curve ROC.

#### 4.4 Results Discussion

The proposal of this research requires high computational effort; however, modern computer equipment is able to perform the required algorithms. Although the system works correctly with the available data, work is being done to have a larger database to improve the results. These limitations do not affect the performance of the entire system because it has a high performance that can be seen in the metrics presented in Table 1. Also, from Fig. 11 it can be seen that the classifier used in this research has a better performance for class 3 (Heart failure) with a 95.45% probability of being correct for that pathology and the lowest but not bad performance for class 0 (Healthy person) with 90.33%.

Finally, the system was tested for the four categories: heart failure, myocardial infarction, arrhythmia and healthy people, using new ECG test signals that were not included in the training of the classifier. Each ECG consisted of 10 cardiac cycles and predictions were made cycle by cycle to finally assign a final pathology to each patient based on the category with the highest number of predictions. The effectiveness of the research proposal is summarized as follows. The results presented in Table 2 show a performance greater than 93%, highlighting the effectiveness in correctly classifying ECG signals in the four categories: heart failure, myocardial infarction, arrhythmia, and healthy individuals. The metrics obtained emphasize the ability of the system to provide accurate and reliable classifications. Furthermore, an important characteristic of this work is that each cardiac cycle of the ECG is analyzed individually, ensuring more precise classifications and improving the overall diagnostic accuracy.

Table 2: Results

| Condition             | Patients | Effectiveness (%) |
|-----------------------|----------|-------------------|
| Heart Failure         | 3        | 93.3              |
| Myocardial Infarction | 11       | 93.7              |
| Arrhythmia            | 9        | 93.6              |
| Healthy               | 5        | 93.1              |

## 5 Conclusions and Future Work

This research develops a methodology based on ECG signals capable of identifying heart diseases. The obtained results show high confidence levels and elevated effectiveness in classifying three pathologies: arrhythmia, myocardial infarction, and heart failure, as well as the condition of a healthy person. In this sense, this contribution demonstrated its effectiveness and to be a functional method for the automatic detection of cardiac pathologies. For future studies, there is the possibility of implementing other algorithms for signal classification, such as support vector machines, artificial neural networks, etc. In addition, there is the possibility of expanding the database with new data on the pathologies studied in this research by adding new pathologies. Also, it is expected to develop an experimental prototype to perform tests on real patients.

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# Single Neuron Proportional-Derivative trained with Regularized Extended Kalman Filter for Leader-Follower Formation Control

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**Abstract.** This work presents a single neuron proportional-derivative (SNPD) control strategy for leader-follower formation control trained with the Extended Kalman Filter (EKF). SNPD trained with unregularized EKF may adapt its weights without limits, which is most significant over time which drives the formation control to instability. To address this issue, we propose to include a regularization strategy in the EKF. Since pose estimation with wheel odometry lacks precision, in this work we propose a pose estimation based on visual sensors and apriltags to improve precision with robustness against external perturbations. The effectiveness and performance of the implementations are demonstrated through real-world experiments using Turtlebot3 Waffle PI robots.

**Keywords:** Extended Kalman Filter · Leader-Follower Formation Control · Turtlebot3 Waffle PI · Adaptive PD control · Weights regularization.

## 1 Introduction

Collaborative and cooperative robotic systems is crucial for solving problems related to surveillance, exploration, recognition, environmental monitoring, and cooperative manipulation [1–3]. This methodology is known as networked robot systems. The technique that ensures cooperation between robots is called cooperative control. Formation control for multiple agents is considered a special case of cooperative control [2]. The objective of formation control is to maintain a certain pattern or shape during the execution of the task. This pattern defines a formation, which is essentially the relative distances between robots [4]. There is a wide variety of strategies for formation control, in the Leader-Follower scheme, one of the robots is assigned as the leader, while the other robots are followers [3]. The control law is applied to each follower independently of the

<https://doi.org/10.61728/AE20255091>



leader. The purpose is for the follower robot to maintain a formation position relative to the leader.

Currently, the presence and importance of artificial intelligence cannot be ignored. It has enabled rapid progress in society and continues to advance in key areas like industry, education, science, and entertainment [5]. Neural PID controllers propose methodologies to improve the performance of classic PID controllers. Adaptive PID techniques trained with gradients have been introduced [6–8]. Although it has been shown that PD and PID controllers trained with the Extended Kalman Filter show superiority in learning rates and faster convergence times [9, 10]. However, the weight adaptations may grow without limits, in some cases, significant weight values might drive the systems to instability.

To improve the SNPD, we proposed to include a regularization strategy in the EKF to prevent weights grow without limits. Moreover, a pose estimation based on visual sensors and apriltags is proposed to avoid the use of wheel odometry. Since wheel odometry lacks precision, visual sensors and apriltags will provide better precision and robust pose estimation.

The paper is organized as follows: Section 2 presents the Leader-Follower kinematics and control. Section 3 describes the design of the SNPD controller trained with the regularized EKF. Section 4 introduces the description of the proposed approach, which is the SNPD control for Leader-Follower formation and the pose estimation based on visual sensors and apriltags. Section 5 presents the real-world experimental results. Finally, the conclusions are presented in Section 6.

## 2 Formation Kinematics

The leader-follower system considered in this work is presented in Fig. 1, which is composed of a leader  $i$  and a follower  $j$ . The linear ( $v_i, v_j$ ) and angular ( $\omega_i, \omega_j$ ) velocities are expressed respect to the local frames  $\{i, j\}$ . The position and orientation of the leader are  $(x_i, y_i)$  and  $\theta_i$ , in the world frame respectively. Similarly, the position and orientation of the follower are  $(x_j, y_j)$  and  $\theta_j$ . Finally, the position  $(x_{ij}, y_{ij})$  and orientation  $\theta_{ij} = \theta_j - \theta_i$  are related to the leader frame  $\{i\}$ . The position  $(x_{ij}, y_{ij})$  can be computed as

$$\begin{bmatrix} x_{ij} \\ y_{ij} \end{bmatrix} = \begin{bmatrix} \cos(\theta_i) & \sin(\theta_i) \\ -\sin(\theta_i) & \cos(\theta_i) \end{bmatrix} \left( \begin{bmatrix} x_j \\ y_j \end{bmatrix} - \begin{bmatrix} x_i \\ y_i \end{bmatrix} \right) \quad (1)$$

To deal with non-holonomic constraints, position  $(x_{ij}^b, y_{ij}^b)$  at distance  $d_j$  is defined for control purposes. It can be calculated as

$$\begin{bmatrix} x_{ij}^b \\ y_{ij}^b \end{bmatrix} = \begin{bmatrix} x_{ij} \\ y_{ij} \end{bmatrix} + d_j \begin{bmatrix} \cos(\theta_{ij}) \\ \sin(\theta_{ij}) \end{bmatrix} \quad (2)$$

Differentiating (2) respect to time, the following formation kinematics can be obtained [11]

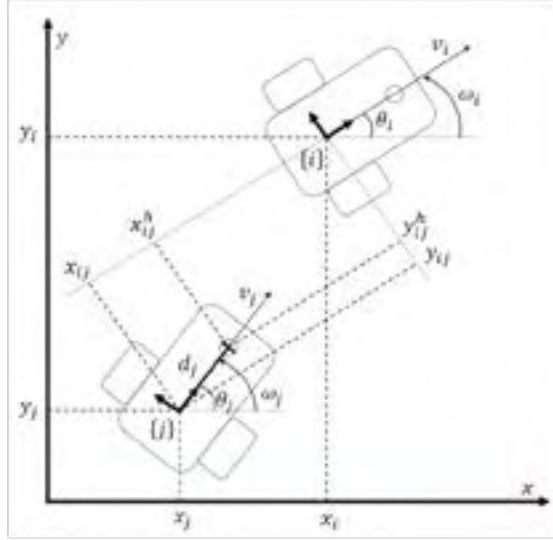


Fig. 1: The leader-follower setup based on relative Cartesian coordinates.

$$\begin{bmatrix} \dot{x}_{ij}^h \\ \dot{y}_{ij}^h \end{bmatrix} = \begin{bmatrix} \cos(\theta_{ij}) & -d_j \sin(\theta_{ij}) \\ \sin(\theta_{ij}) & d_j \cos(\theta_{ij}) \end{bmatrix} \begin{bmatrix} v_j \\ w_j \end{bmatrix} + \begin{bmatrix} -v_i \\ 0 \end{bmatrix} + \omega_i \begin{bmatrix} y_{ij}^h \\ -x_{ij}^h \end{bmatrix} \quad (3)$$

The leader-follower control scheme is designed with a control input  $(u_x, u_y)$  that drives the follower to a related position with respect to the leader. Considering  $\dot{x}_{ij}^h = u_x$  and  $\dot{y}_{ij}^h = u_y$  into (3) yields to

$$\begin{bmatrix} v_j \\ \omega_j \end{bmatrix} = \begin{bmatrix} \cos(\theta_{ij}) & \sin(\theta_{ij}) \\ -\frac{1}{d_j} \sin(\theta_{ij}) & \frac{1}{d_j} \cos(\theta_{ij}) \end{bmatrix} \left( \begin{bmatrix} u_x \\ u_y \end{bmatrix} + \begin{bmatrix} v_i \\ 0 \end{bmatrix} - \omega_i \begin{bmatrix} y_{ij}^h \\ -x_{ij}^h \end{bmatrix} \right) \quad (4)$$

In this work,  $(u_x, u_y)$  will be computed with adaptive neuron PD controllers trained with EKF. Detailed descriptions of leader-follower kinematics can be found in [11].

### 3 Adaptive single neuron PD controller

The adaptive single neuron PD controller (SNPD) is illustrated in Fig. 2. The error  $e$  defines the difference between the reference  $y_r$  and the system output  $y$  in step time  $k$ , see (5). The inputs  $x_1$  and  $x_2$  represents the proportional (6) and the derivative (7) errors [12]. The weights  $w_1$  and  $w_2$  represent the proportional gain, and the derivative gain, respectively. These gains will be adapted online



based on the EKF algorithm [10]. The output  $u$  is computed as the weighted sum of the inputs of the neuron (8).

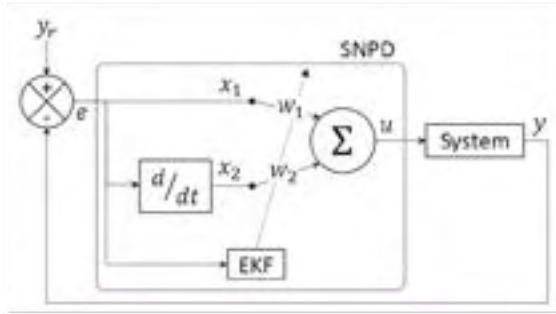


Fig. 2: Adaptive single neuron PD controller (SNPD).

$$e(k) = y_r(k) - y(k) \quad (5)$$

$$x_1(k) = e(k) \quad (6)$$

$$x_2(k) = e(k) - e(k-1) \quad (7)$$

$$u(k) = w_1(k) x_1(k) + w_2(k) x_2(k) \quad (8)$$

The EKF algorithm adjusts the weights  $\mathbf{w}(k) = [w_1(k) \ w_2(k)]^T$  for the single neuron using online training. The EKF settings are:  $\mathbf{K} \in \mathbb{R}^{2 \times 1}$  is the Kalman gain vector,  $\mathbf{P} \in \mathbb{R}^{2 \times 2}$ ,  $\mathbf{Q} \in \mathbb{R}^{2 \times 2}$ , and  $\mathbf{R} \in \mathbb{R}^{1 \times 1}$  are covariance matrices of weight estimation error, estimation noise, and error noise, respectively. Moreover,  $\eta \in \mathbb{R}$  is the Kalman filter learning rate, and  $\mathbf{H} \in \mathbb{R}^{2 \times 1}$  is a matrix whose entries are derivative of the neuron output with respect to each weight. Finally, the error  $e \in \mathbb{R}$  is given by (5), and  $\lambda$  is a regularization gain.

$$\mathbf{K}(k) = \mathbf{P}(k) \mathbf{H}(k) [\mathbf{R}(k) + \mathbf{H}^T(k) \mathbf{P}(k) \mathbf{H}(k)]^{-1} \quad (9)$$

$$\mathbf{w}(k+1) = (1 - \lambda) \mathbf{w}(k) + \eta \mathbf{K}(k) e(k) \quad (10)$$

$$\mathbf{P}(k+1) = \mathbf{P}(k) - \mathbf{K}(k) \mathbf{H}^T(k) \mathbf{P}(k) + \mathbf{Q}(k) \quad (11)$$

The matrix  $\mathbf{H}$  is defined as

$$\mathbf{H}(k) = \begin{bmatrix} \frac{\partial u(k)}{\partial w_1(k)} & \frac{\partial u(k)}{\partial w_2(k)} \end{bmatrix}^T = \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix} \quad (12)$$

During neuron training, the weights  $w_1(k)$  and  $w_2(k)$  could be adjusted with negative values; otherwise, they may grow without bound. It is important to

consider  $w_1(k) := \max(0, w_1(k))$  and  $w_2(k) := \max(0, w_2(k))$ . Moreover, by tuning  $\lambda$ , it helps prevent that weights grow without limit.

More detailed information about adaptive single neuron PD and PID controllers trained with the EKF are given in [9, 10].

#### 4 Description of the proposed approach

In order to perform the leader-follower control scheme (4), we propose to design  $u_x$  and  $u_y$ , based on two SNPD schemes. Let us define the formation errors  $e_{ij}^x = x_{ij}^* - x_{ij}^h$  and  $e_{ij}^y = y_{ij}^* - y_{ij}^h$ , where  $(x_{ij}^*, y_{ij}^*)$  is the reference of the formation scheme. In other words,  $u_x := \text{SNPID}(e_{ij}^x)$  and  $u_y := \text{SNPID}(e_{ij}^y)$ .

In this work, we estimate the pose of each robot based on visual markers called AprilTags, see Fig 3. Leader and follower are associated with a marker that provides a relative pose estimation and an ID to difference one of each other. The matrices  ${}^c\mathbf{T}_i$  and  ${}^c\mathbf{T}_j$  are the pose estimation by AprilTags of the leader and the follower, respectively. Both matrices are expressed with homogeneous transformations measured with respect to the camera frame  $\{c\}$ . To obtain the pose estimation with respect to the world frame  $\{w\}$ , we compute

$${}^w\mathbf{T}_i = {}^w\mathbf{T}_c {}^c\mathbf{T}_i \quad (13)$$

$${}^w\mathbf{T}_j = {}^w\mathbf{T}_c {}^c\mathbf{T}_j \quad (14)$$

where  ${}^w\mathbf{T}_i$  and  ${}^w\mathbf{T}_j$  are the homogeneous matrices of the leader and follower, respectively, in the world frame. Moreover,  ${}^w\mathbf{T}_c$  is a matrix transformation that describes the position and orientation of the camera with respect to the world frame.

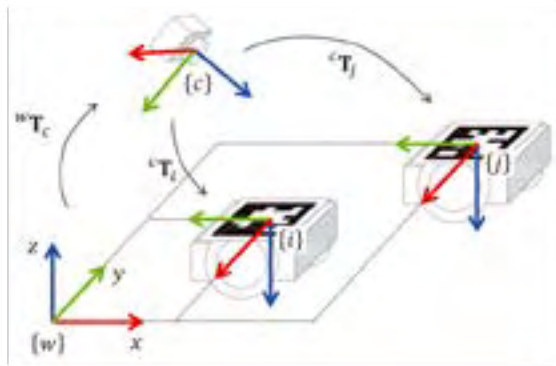


Fig. 3: Mobile robot pose estimation based on AprilTags.

Intrinsic camera calibration is required previously to the mobile robot pose estimation. Moreover, the matrix  ${}^w\mathbf{T}_c$  should also be previously known. The

positions  $(x_i, y_i)$  and  $(x_j, y_j)$  are available in the position vector of  ${}^w\mathbf{T}_i$  and  ${}^w\mathbf{T}_j$ , respectively. However, orientations  $\theta_i$  and  $\theta_j$  should be computed based on the representation of Euler angles of the rotation matrices in  ${}^w\mathbf{T}_i$  and  ${}^w\mathbf{T}_j$ .

## 5 Experimental Results



Fig. 4: Real-world setup for experimentation.

The applicability of the proposed approach is demonstrated through real-world experiments. All parameter settings for experimentation are given ahead. The reference for the formation control are:  $x_{ij}^* = -0.6$ ,  $y_{ij}^* = 0.0$ . The Kalman settings were set to:  $\mathbf{R} = 0.001$ ,  $\eta = 0.1$ ,  $\lambda = 0.001$ , and

$$\mathbf{P} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \mathbf{Q} = \begin{bmatrix} 0.01 & 0 \\ 0 & 0.01 \end{bmatrix}.$$

Moreover, the intrinsic parameters of the camera were calibrated as  $f = 623.71$ ,  $C_u = 317.97864$ ,  $C_v = 257.93234$ . Finally

$${}^w\mathbf{T}_c = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

For the experimentation, two Turtlebot3<sup>®</sup> Waffle PI robots were used. The Turtlebot3<sup>®</sup> is a ROS-based differential-drive robot for education and research. The ROS packages provide access to send velocity control inputs  $(v, w)$  and read its odometry. However, we used the proposed camera pose estimation rather than odometry measures. The real-world setup for experimentation is presented in

Fig. 4. The leader-follower control scheme is centralized in an external computer running in MATLAB<sup>®</sup> with the ROS toolbox.

It is important to mention that the linear and angular velocities are limited before being applied to the Turtlebot3<sup>®</sup> to prevent damage or wear to the actuators. The limits for linear velocity are  $-0.2 \leq v \leq 0.2$  and for the angular velocity  $-0.9 \leq w \leq 0.9$ .

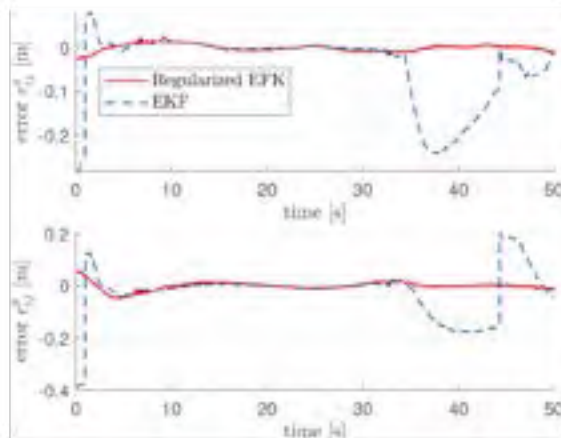


Fig. 5: Formation errors ( $e_{ij}^x, e_{ij}^y$ ) over time.

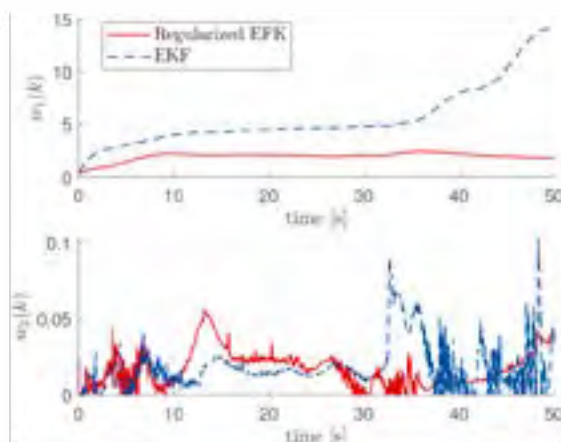


Fig. 6: SNPD weights adaptation over time.



Fig. 5 shows the formation errors ( $e_{ij}^x, e_{ij}^y$ ) over 50 seconds. We notice that around 35 seconds, the leader-follower formation task fails in the classical SNPD trained with unregularized EKF since errors become significant. In contrast, using the proposed SNPD with regularized EKF, errors were kept near zero keeping the desired formation. The SNPD weights adaptation is shown in Fig. 6, where  $w_1$  corresponds to the proportional gain and  $w_2$  to the derivative gain.

The gain  $w_1$  in unregularized EKF grows without limits over time, which provokes the formation task to fail. In contrast, the proposed regularized EKF prevents that gain  $w_1$  grows more than necessary. Moreover, both unregularized and regularized EKF adapts the derivative gain  $w_2$  similarly.

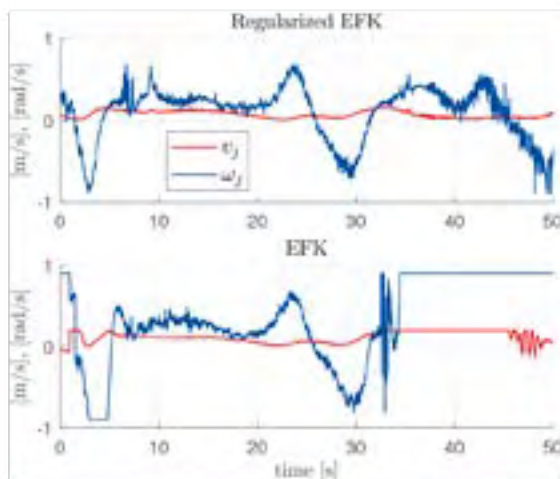


Fig. 7: Follower control input signals ( $v_j, \omega_j$ ) over time.

Finally, follower control signals ( $v_j, \omega_j$ ) during the formation task are given in Fig. 7. As expected, control signals become saturated around 35 seconds, when the proportional gain  $w_1$  becomes significantly big.

## 6 Conclusions

This work presented a single neuron PD controller for leader-follower formation control trained with a regularized EKF algorithm. Experimental results demonstrate that PD weight grows without limit over time if the EKF weight adaptation is not regularized, which could cause issues in the calculation of the control actions  $u_x$  and  $u_y$ , leading to decreased performance in the formation task. The weight regularization strategy provides better performance, the weights adapt only the necessary to keep the error near zero. Moreover, this paper also considers the use of visual sensors to estimate leader and follower poses, rather than wheel

odometry. Mobile robots were equipped with AprilTags onboard to measure the position and orientation with the advantage of obtaining a pose estimation in the face of external disturbances, such as the robot's tires getting stuck. We let as future work to use the proposed SNPD for consensus-based formation control.

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# Edge-Weighted Formation Control for Omnidirectional Mobile Robots

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**Abstract.** This paper presents a consensus-based formation control strategy for omnidirectional mobile robots based on weighted graphs. The proposed method drives a group of robots to achieve and maintain a desired formation, performing consensus in both positions and orientation agreements. Moreover, weighted graphs allow collision avoidance among robots by rotating and adapting the formation shape. Simulation experiments were performed to validate the effectiveness of the proposed strategy, demonstrating the successful convergence of formation in a network of four omnidirectional platforms.

**Keywords:** Formation control · Consensus · Omnidirectional Mobile Robots · Weighted Graphs · Multi-agent Systems.

## 1 Introduction

Formation control is a fundamental challenge in multi-agent systems, particularly in mobile robotics, where robots must coordinate their movements while maintaining a predefined geometric pattern. The significance of formation control is evident in various applications, including industrial automation, swarm robotics, search and rescue, and logistics [1]. Coordinated movement in multi-robot systems enhances efficiency, optimizes resource utilization, and enables robust performance in dynamic environments [2].

Traditional formation control approaches have included leader-follower structures, virtual structures, and behavior-based models, each offering unique advantages and trade-offs [3]. Leader-follower methods, for instance, rely on a designated leader dictating the movement of the group, which can introduce single-point failure risks. Virtual structure approaches treat the formation as a rigid body, ensuring precise control but reducing adaptability to obstacles. Behavior-based models, on the other hand, provide decentralized and flexible control but can suffer from instability in complex environments [4]. To overcome these limitations, consensus-based control strategies have emerged as an effective

<https://doi.org/10.61728/AE20255107>





method of decentralized coordination [2]. These strategies enable robots to reach agreement on position through local interactions with neighboring agents.

Consensus control has been proven to be robust against external disturbances and communication constraints [5]. Furthermore, recent studies have introduced adaptive formation control mechanisms that integrate noise-tolerant consensus algorithms to improve formation robustness [4]. Such techniques have been particularly effective in real-world robotic applications, where unpredictable obstacles and communication delays can degrade control accuracy [1]. However, challenges remain when dealing with collision avoidance mechanisms to ensure safety and efficiency [3].

The consensus in both position and orientation agreement has been solved using persistent excitation term for a group of non-holonomic mobile robots [6,7]. However, omnidirectional mobile robots are free from non-holonomic constraints, then, it is not necessary to incorporate a persistent excitation, which can degrade overall performance.

A promising approach to solving these challenges is edge-weighted formation control, where inter-agent interactions are modeled as weighted connections [3,8]. Edge-weighted consensus formation control has gained traction due to its ability to dynamically adjust inter-robot influence. By assigning adaptive weights to edges in the communication graph, this approach allows for better stability, collision avoidance, and responsiveness to environmental changes. However, edge-weighted consensus strategy is applied to agreement only in position rather than orientations [9].

In this paper, we enable the edge-weighted consensus strategy to incorporate consensus in both position and orientation agreements for omnidirectional mobile robots. The effectiveness of the proposed method is validated through simulations conducted in CoppeliaSim based on four omnidirectional mobile robots.

The paper is organized as follows: The next section introduces the kinematics of omnidirectional mobile robots composed by four wheels. The section 3 address the edge-weighted consensus-based formation control. Then, simulations results are presented in section 4. Finally, the conclusions and future work are given in section 5.

## 2 Omnidirectional mobile robot kinematics

The omnidirectional mobile robot in this work is composed of four mecanum wheels, see Figure 1. The pose of the robot with respect to the world frame is given by the positions  $(x, y)$  and the orientation  $\theta$ . The velocity  $v_m$  corresponds to the linear velocity of each wheel with  $m = 1, 2, 3, 4$ . The parameter  $L$  is half of the distance between the front and the rear wheels, and  $l$  is half of the distance between the left and right wheels.

The kinematics of the omnidirectional mobile platform is given by



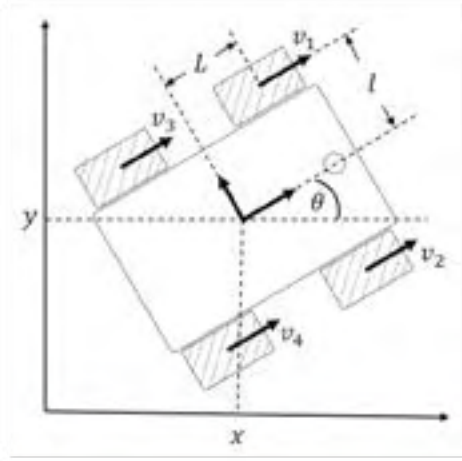


Fig. 1: Schematic of an omnidirectional mobile robot of four mecanum wheels.

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} \sqrt{2} \sin(\theta + \frac{\pi}{4}) & -\sqrt{2} \cos(\theta + \frac{\pi}{4}) & -(L+l) \\ \sqrt{2} \cos(\theta + \frac{\pi}{4}) & \sqrt{2} \sin(\theta + \frac{\pi}{4}) & (L+l) \\ \sqrt{2} \cos(\theta + \frac{\pi}{4}) & \sqrt{2} \sin(\theta + \frac{\pi}{4}) & -(L+l) \\ \sqrt{2} \sin(\theta + \frac{\pi}{4}) & -\sqrt{2} \cos(\theta + \frac{\pi}{4}) & (L+l) \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \quad (1)$$

where  $\dot{x}$  and  $\dot{y}$  are the linear velocities and  $\dot{\theta}$  is the angular velocity, all expressed in the world frame. These velocities will be designed for consensus formation control purposes. Detailed descriptions about kinematics can be found in [10,11].

### 3 Edge-Weighted Formation Control

The communication topology among a set of robots can be represented with an undirected graph with  $N$  elements defined as a pair  $G = (\mathcal{V}, \mathcal{E})$ , where  $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$  is the edge set of cardinality  $M$  and  $\mathcal{V} = \{v_i, i = 1, 2, \dots, N\}$  stands for the vertex set of cardinality  $N$ . An edge  $\mathcal{E}_k = (v_i, v_j)$  represents bidirectional communication between agents  $i$  and  $j$ , where  $\mathcal{E}_k$  is the  $k$ -th edge of  $G$ .

The position consensus problem for  $N$  agents can be solved with the Laplacian-based feedback method [3,9]. The feedback control is defined as

$$\dot{\mathbf{z}}_i = - \sum_{j \in \mathcal{N}_i} w_{ij}(\mathbf{z})(\mathbf{z}_i - \mathbf{z}_j), \quad (2)$$

where  $\mathbf{z}_i := [x_i, y_i]^T$ ,  $\mathcal{N}_i = \{\forall v_j \in \mathcal{V} \mid (i, j) \in \mathcal{E}\}$  is the Neighbors subset of the  $i$ -th robot. The edge-weight function  $w_{ij}(\mathbf{z})$  is defined as

$$w_{ij}(\mathbf{z}) = \alpha_{ij} \left( -\frac{1}{k_{ij}} \operatorname{csch}^2 \left( \frac{\|\mathbf{z}_{ij}\| - \delta}{k_{ij}} \right) + 1 \right), \quad (3)$$

where  $\alpha_{ij} > 0$  defines the inter-robot position influence,  $\mathbf{z}_{ij} := \mathbf{z}_i - \mathbf{z}_j$  is the position error, and  $k_{ij} > 0$  is a constant related to the distance between robots. Indeed, parameter  $k_{ij}$  defines the final formation shape. Moreover,  $\delta > 0$  is a safety distance parameter. Collision avoidance is guaranteed if  $\delta$  is strictly greater than the distance  $\|\mathbf{z}_{ij}\|$  [3].

In this work, we proposed to solve the orientation consensus problem as follows

$$\dot{\theta}_i := - \sum_{j \in \mathcal{N}_i} \beta_{ij} (\theta_i - \theta_j), \quad (4)$$

where  $\beta_{ij} > 0$  defines the inter-robot orientation influence.

Finally,  $\dot{\mathbf{z}}_i := [\dot{x}_i, \dot{y}_i]^\top$  and  $\dot{\theta}_i$  of each agent  $i$  are mapped to omnidirectional wheel velocities using (1).

## 4 Simulation results

This section presents simulations to validate the proposed formation control in a group of four omnidirectional mobile robots. The communication topology and the desired formation pattern are presented in Fig. 2. The formation pattern is established by selecting appropriate  $k_{ij}$  values.

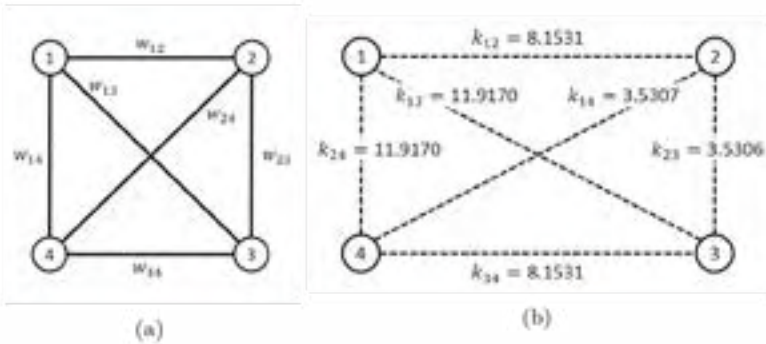


Fig. 2: Formation control topology. (a) Communication topology. (b) Desired formation.

The parameter configuration for the simulation are:  $\alpha_{ij} = 0.25$ ,  $\delta = 0.1m$ ,  $\beta_{ij} = 0.8$ ,  $L = 0.2355m$  and  $l = 0.15m$ . The controller parameters were experimentally selected. Moreover, control signals are bounded in the range  $[-0.8, 0.8]$

to simulate actuator limitations. Finally, the proposed approach is tested in the Coppelia simulator. The simulator setup is given in Fig. 3.



Fig. 3: Setup in Coppelia Simulator. Agents are shown in the initial configurations.

The position trajectories in the xy-plane and the resulting formation patterns are presented in Fig. 4. As can be seen, robots performed the desired formation pattern, see Fig. 2(b). The trajectories of agent 3 and agent 4 show that a possible collision is avoided. Notice that the formation shape is rotated, however, formation is achieved by avoiding collision among agents. Moreover, the final robot orientations are the same, which illustrates the consensus in orientations.

The time-varying position and orientation of agents are shown in Fig. 5. The Fig. 5(a) demonstrates smooth displacement to achieve consensus on positions after 6 seconds. Moreover, a consensus on orientation is reached after 3 seconds, see Figure 5 (b).

Control signals are illustrated in Fig. 6. At early seconds, signals are bounded, after that, the control signals are smooth and converge near zero after 10 seconds when the position and orientation consensus is reached.

## 5 Conclusions

This paper uses edge-weighted graphs to address the problem of formation control involving position and orientation consensus for omnidirectional mobile robots. The proposed method allows agents to achieve a desired formation pattern with smooth position control trajectories while also regulating the orientation of all robots to a common value. Additionally, position trajectories also demonstrate the capabilities of collision avoidance among agents. Moreover, Velocity control signals drive robots to consensus, even under velocity constraints, demonstrating the effectiveness of edge-weighted consensus control strategies.

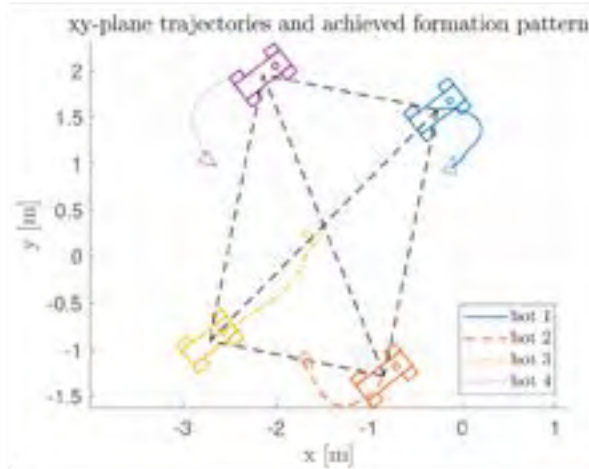


Fig. 4: Position trajectories and the achieved formation patterns. The initial position and orientation of each robot are represented by a triangle marker. The formation pattern achieved is highlighted with dotted lines.

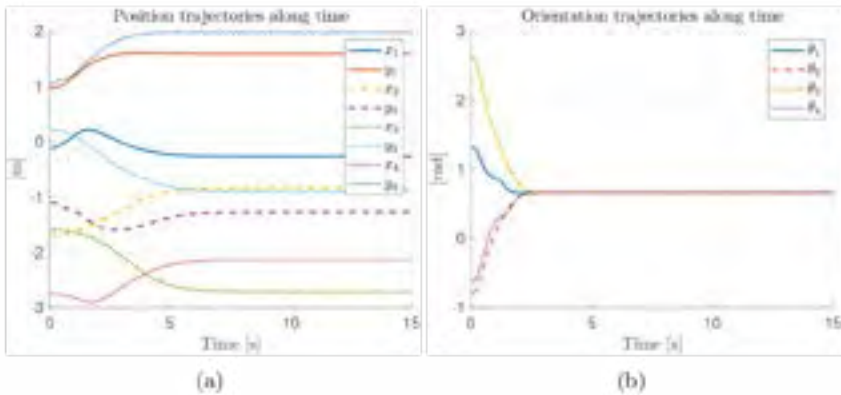


Fig. 5: Position  $(x_i, y_i)$  and orientation  $\theta_i$  trajectories along time.

Implementing this approach in real-world experiments is left to future work. Further research may explore integrating machine learning-based adaptive weighting, refining the model for complex multi-robot formations, and investigating the impact of communication delays and network constraints on formation stability. These directions will contribute to advancing autonomous robotic coordination and cooperative multi-agent systems.

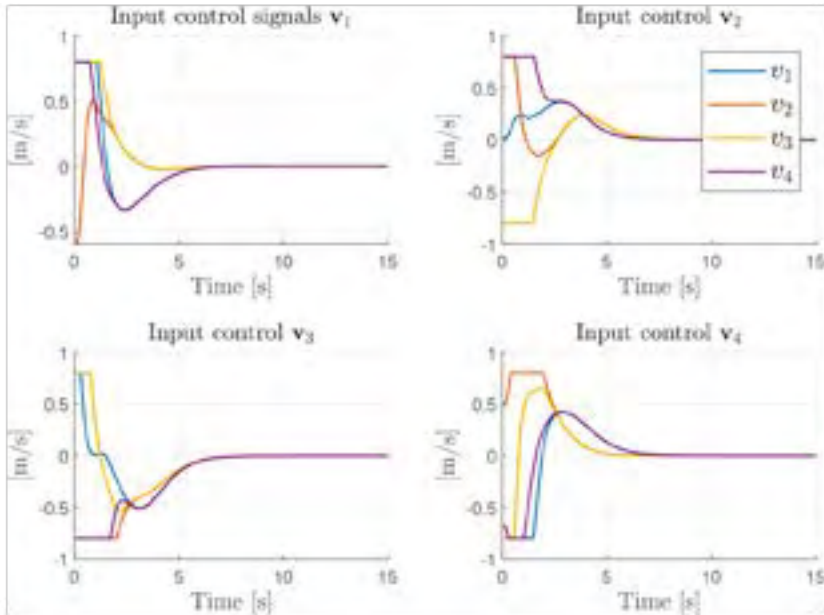


Fig. 6: Control input signals  $\mathbf{v}_i := [v_1, v_2, v_3, v_4]^T$  per along time per agent agent  $i$  with  $i = 1, 2, 3, 4$ .

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# Comparison of gamma calibration methods for fringe projection profilometry

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**Abstract.** A fringe projection profilometer is a system that retrieves tridimensional surface information by digital signal processing of sinusoidal patterns, projects and captures these patterns as they are being spatially modulated by an object. In this paper, we address the problem of calibrating the nonlinear intensity response of the projector, namely gamma distortion, by proposing a new calibration method that requires only a sinusoidal pattern to estimate the gamma factor. This value is used to generate and project the new set of fringe patterns for which we perform the inverse gamma compensation. We also compare the performance of the proposed method with the polynomial method and the least squares method. The numerical accuracy of these three models was compared by computer simulations, and we subsequently analyzed their performance in mitigating gamma distortion in experimental data. The results show the effectiveness of the proposed method in estimating and correcting gamma distortion.

**Keywords:** Fringe projection profilometry, Nonlinear intensity response, Calibration.

## 1 Introduction

Three-dimensional measurement theory based on structured light has developed rapidly with the rapid development of computer technology, optical and optoelectronic devices. Systems are already in place that allow us to achieve this contact system like the coordinate measuring machines (CMMs), time of flight (ToF) cameras, stereo vision sensors, and structured light projection systems. The most important in the industry is the CMM because of its high accuracy and not being sensitive to the reflectiveness of the object, it gets done through measurement of coordinates of an object in a point-to-point contact although it's not very efficient [1].

In contrast with the CMM, the fringe projection profilometer (FPP) is one of the most efficient systems, so much so that even real-time measurements are being actively considered and worked on [2]. The FPP is an instrument that utilizes structured light patterns to measure tridimensional object surfaces, and has several applications: in medical fields, automotive industry, reverse engineering, archaeological preservation, among others [3].

<https://doi.org/10.61728/AE20255114>



The 3D fringe pattern profilometer is composed of a camera and a projector. The latter projects sinusoidal patterns on a surface to be measured, where those undergo a spatial modulation, which is captured. Subsequently, the tridimensional surface is extracted from the acquired patterns through a phase shift algorithm and a phase unwrapping one [4, 5, 6]. Despite its simplicity of construction, each element composing the system introduces a set of distortions to the captured patterns [7,8], those distortions compromise system reliability, reducing the precision and accuracy of the measurements made. Regardless of the progress made, there is still room for improvement, so we propose a method for calibration of the nonlinear intensity response of a video projector and compared its performance with 2 other literature methods.

We start discussing the basic theory of phase retrieval in fringe projection. Second, we discuss the nonlinearity of the projector and how to correct according to the power law. Next, we talk about 2 literature methods, the first linearizing the projector intensity response estimating a high-degree polynomial on a ramp function projected in a reference plane [9]. The second estimates a global gamma constant by adjusting the least-squares plane to the estimated phase coming from the reference plane [10], and the proposed one that estimates by adjusting a gamma induced ideal signal to the captured pattern. In the simulation method we make a comparison using numerical simulations to understand the performance of each model as a function of the noise level and its respective processing time.

In the work, we present a new approach to estimate the gamma of a projection system used for reconstructing and measuring 3D surfaces. The estimation is performed as an optimization problem. Also, we compare our proposal with the methods that have been reported in the literature.

The remainder of this paper is structured as follows: Section 2 describes the proposed theory of each method for gamma correction. Section 3 presents experimental results and comparative analysis based on numerical simulations. Finally, Section 4 presents the conclusion of the presented work.

## 2 Theoretical framework

### 2.1 Fringe pattern profilometer (FPP)

A basic structured light projection system is illustrated in Fig 1. The setup consists of a computer to generate and process fringe patterns, a digital light projector to project the generated patterns, a high-resolution camera (CCD, Charged coupled device) that is used to acquire the fringe patterns modulated by the object surface under test, and the reference plane used to calibrate the system. Where  $\varphi$  is the angle between the camera and the projector,  $h$  is the height of the object, and  $p$  is the fringe pattern pitch.

In general, to measure a tridimensional surface by the projection of sinusoidal intensity patterns, one project and acquire sequence patterns shifted by the known phase angles. The acquired patterns can be described as:

$$I_n(x,y) = I_o(x,y) + I_{mod}(x,y) \cdot \cos(\varphi(x,y) + \delta_n), (n = 1, 2, 3, \dots, N), (1)$$

here  $(x, y) \in \mathbb{R}^2$  is the pixel location;  $I_0(x, y)$ , and  $I_{\text{mod}}(x, y)$  are the background and intensity modulation, respectively. While  $\varphi(x, y)$  is the phase to be retrieved containing the encoded information of the three-dimensional surface of the object, and  $\delta_n$  is a known phase shift defined as  $2\pi n/N$ , where  $N$  is the number of phase steps or patterns to be projected.

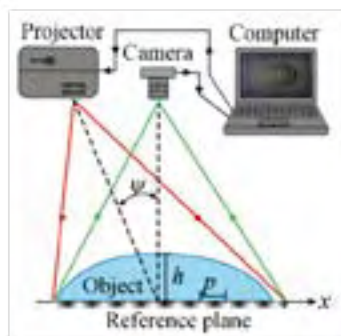


Fig. 1. Setup sketch of fringe projection profilometer.

Once the patterns are acquired, the phase can be estimated by phase shift algorithms, e.g., the phase  $\varphi(x, y)$  can be solved by [5]

$$\varphi_w(x, y) = \tan^{-1} \left[ \frac{\sum_{n=1}^N I_n(x, y) \sin(\delta_n)}{\sum_{n=1}^N I_n(x, y) \cos(\delta_n)} \right], \quad \delta_n = \frac{2\pi n}{N}. \quad (2)$$

This expression provides the wrapped phase  $\varphi_{w(x,y)}$  ranging  $\in (-\pi, \pi]$ .  $\delta_n$  is the phase shift that are equidistant angles in a range of  $[0, 2\pi)$ . The wrapped phase is later processed through an unwrapping phase algorithm that converts the phase defined in a range  $(-\pi, \pi]$  in a continuous range. As a final step, we convert the retrieved phase to height through phase-height calibration procedure [12].

## 2.2 Gamma correction

A variety of devices used for image projection, capture, printing, and displaying response according to the power law, i.e.

$$I_{\text{out}} = I_{\text{in}}^\gamma, \quad (3)$$

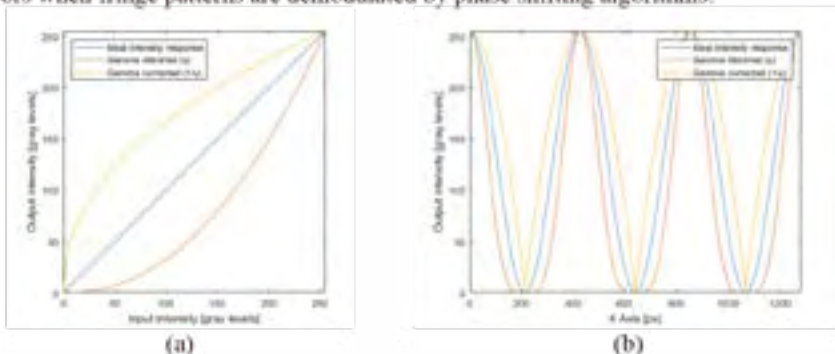
where,  $\gamma$  is a positive constant (By convention, the exponent in the power-law equation is referred to as gamma). According to Fig. 1 and the acquired patterns  $I_{\text{out}}$  will be distorted by this nonlinear transformation, assuming that one generated ideal sinusoidal intensity patterns, when the gamma value is different from 1.

By inspection of the Eq. (3), one could correct the distortion in the acquired patterns, if we know the gamma value, before projecting patterns, i.e.,

$$I_{\text{in}} = (I_{\text{out}})^{1/\gamma} = (I_{\text{in}}^\gamma)^{1/\gamma}. \quad (4)$$



Although this relation gives us an easy way to correct the gamma. In real systems, one required to estimate the gamma value and digitally generate sinusoidal intensity patterns power to  $1/\gamma$ . In Fig 2, we can see how the intensity response of the projector modified the gray levels to be projected and how it distorts the acquired fringe patterns. For example, in systems based on the projection of sinusoidal intensity patterns the nonlinear response introduces higher order harmonics, which introduced phase errors when fringe patterns are demodulated by phase shifting algorithms.



**Fig. 2.** (a) Plots of Eq. (3) and Eq. (4) for: blue line,  $\gamma$  equal to 1 and for yellow and red lines equal to 2.2. (b) Linear response of the digital light project when the input is a sinusoidal intensity and gamma values according with cases shown in (a)

### 3 Calibration mathematical models

#### 3.1 Preprocessing image

In addition to the gamma problem, the reflectance of the object and illuminance is not uniform on the object's surface. Thus, the Eq. (4) should be rewritten as

$$I_a(x, y) = F(x, y)I_p(x, y) + \eta(x, y). \quad (5)$$

Where  $I_a(x, y)$  is the acquired intensity pattern under more realistic conditions,  $I_p(x, y)$  is the input pattern,  $\eta(x, y)$  is noise, and  $F(x, y)$  is reflectance and emittance of the projector. As we can see in equation (5), to get an ideal projected pattern, we need to remove the inhomogeneities in the acquired patterns that are due reflectance and no uniform illumination projector. One way to estimate the  $F(x, y)$  is projecting a pattern with constant illuminance on the reference plane, as shown in Fig. 3(a) and perform basic digital manipulations between images, e.g.

$$\frac{I_a(x, y)}{I_C} = \frac{I_d(x, y)F(x, y) + \eta(x, y)}{I_C}, \quad (6)$$

where  $I_d(x, y)$  is the constant illuminance pattern and  $I_C$  is the known constant illuminance, where we know that

$$I_d(x, y) = I_C. \quad (7)$$



by solving it further we can write it as

$$F'(x, y) = \frac{I_a(x, y)}{I_c} = F(x, y) + \frac{\eta(x, y)}{I_c}, \quad (8)$$

where  $F'(x, y)$  approximates the reflectance and emittance of the projector because the term  $\eta(x, y)/I_c$  is not significant, the acquired patterns: tilt plane and sinusoidal intensity patterns can be normalized, i.e.,

$$I_p \approx \frac{I_a}{F'(x, y)}. \quad (9)$$

In Fig. 3(b) one can see a fringe pattern before correction, where we could observe a nonhomogeneous illumination and the normalized pattern in Fig. 3(c).

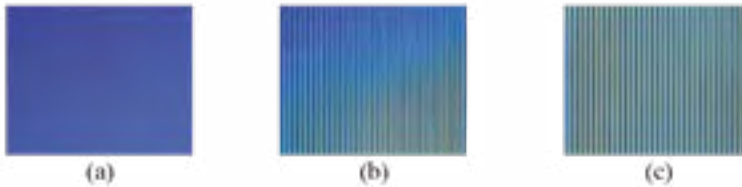


Fig. 3. (a) Captured image with a uniform illuminance on reference plane, sinusoidal intensity pattern; (b) before correction and (c) after normalization.

### 3.2 Polynomial estimation method

We know that the projector intensity response is determined by power law, that means that if we project intensity ramp in the range from 0 to 255 gray levels in a reference plane. The acquired ramp will be modulated by the power law. We need to estimate the gamma value to correct for the non-linear relationship between projected and acquired gray levels (projected and acquired patterns, respectively). An alternative method proposed in the literature is to fit a polynomial of order  $N$  to the (normalized) intensity profile, which is obtained from the linear-wedge grayscale image, previously projected onto the reference plane. The linear-wedge grayscale image to be projected can be described by

$$T(x, y) = R(x), \quad R(x) \begin{cases} 0, & x < 0; \\ x, & 0 \leq x \leq 255 \end{cases} \quad (10)$$

where the acquired pattern could be a nonlinear intensity map along the tilt axis. All we need to do is the estimation of the coefficient for a polynomial of order  $N$  that fit the acquired, nonlinear-wedge grayscale image. For example, third order polynomial,

$$I_{out} = C_0 + C_1 I_{in} + C_2 I_{in}^2 + C_3 I_{in}^3, \quad (11)$$

with  $C_0, C_1, C_2, C_3$  as the estimated coefficients. For simplicity we will define that the non-linear relationship, between the input and output, which is given by the polyno-

mial, as an operator,  $P\{\cdot\}$ . Then, we preprocess the input image before inputting it into the DLP by performing the transformation.

When the input into the same projector, the input corrected inverse polynomial produces an output that is close in appearance to the digital image.

$$I'_{in} = 2R(I_{in}) - P\{I_{in}\}, \quad (12)$$

where  $I_{in}$  is the ideal intensity and  $P\{I_{in}\}$  is the estimated third order polynomial that defines our intensity response model.

### 3.3 Least squares method

The least squares optimization proposes the estimation of the gamma value as an optimization problem defined by

$$J(\gamma) = \|\varphi(x, y)^{1/\gamma} - \varphi_p(x, y)\|_2^2, \quad (13)$$

where  $\varphi(x, y)^{1/\gamma}$  is the unwrapped phase estimated after applying a digital correction in the fringe patterns by certain gamma factor,  $\varphi_p(x, y)|_{\varphi^{1/\gamma}}$  is the best fitted plane over a region in the unwrapped phase map, and  $J(\gamma)$  is the optimization problem solved by a free-derivative for unconstrained minimization problems called the Nelder–Mead simplex method [11], with a range for searching the optimal value.

### 3.4 Ideal pattern differentiation method

Based on the least squares we propose a new method based on intensity where the estimation of the gamma value is an optimization problem defined by

$$D(\gamma) = \|I_n(x) - I(x, y)^\gamma\|^2, \quad (14)$$

where  $I_n(x)$  is a cross-cut of the sinusoidal intensity of acquired pattern when the ideal patterns is projected on reference plane, and  $I(x, y)^\gamma$  is the ideal sinusoidal intensity pattern whose frequency is same to that of the captured pattern, modified with the gamma value, and  $D(\gamma)$  is the optimization problem solved by a free-derivative for unconstrained minimization problems called the Nelder–Mead simplex method [11], with a range for searching the optimal value. Once we capture and compensate a sinusoidal pattern, we make a cut in the x axis direction of the pattern retrieved to get a row of data, after compensation we assume that all columns have the same data.

## 4 Results

In this section, the exposed schemes for gamma calibration are numerically analyzed through computer simulations. However, we also performed a series of experiments with a commercial DLP projector (model PJD7820HD, ViewSonic) with a native spatial resolution of 1920 x 1080 pixels. The images were acquired with an 8-bit sin-

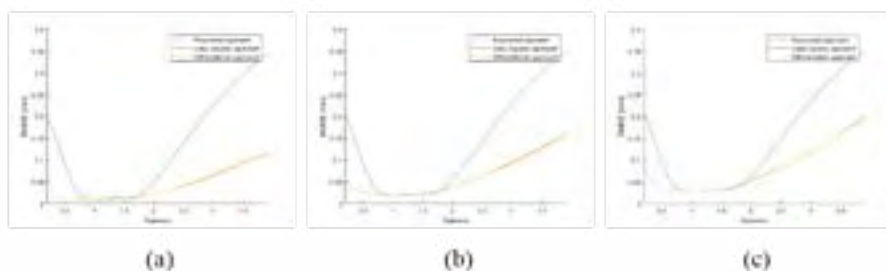
gle-CCD camera (model DCU 224C, Thorlabs) with a spatial resolution of 1280 x 1024 pixels. The angle in the experiment setup is  $\varphi \approx 12$  degrees as seen in Fig. 1.

#### 4.1 Simulation

To check the feasibility and validity of the compared methods without the influence of the experimental setup of an FPP system, simulations of 3D measurements of ideal planes distorted by distinct gamma values were carried out. In the first simulation we generated a set of 3 phase shifted fringe patterns for gamma values between 0.2 and 3.9 with increments of one tenth. Each pattern was corrupted with Gaussian noise with different percentages: 2%, 4%, and 6% respectively. We used the root-mean-square error (RMSE):

$$RMSE = \sqrt{\frac{\sum_{i=1}^N [\varphi(x,y) - \hat{\varphi}(x,y)]^2}{N}} \quad (15)$$

Where  $\varphi(x,y)$  is the ground truth phase,  $\hat{\varphi}(x,y)$  is the estimated phase which is retrieved from the simulated fringe patterns. Fig. 4(a) shows RMSE error in function of gamma value for the three calibration methods under different levels of noise, where one can observe that the polynomial method has worst performance with respect to the least squares and differentiation methods with exceptions around 1 and 1.6. In Fig 4(b) and Fig. 4(c) we observe the RMSE in function of gamma values for the least squares and the differentiation methods, respectively.



**Fig. 4** Root-mean-square error as a function of gamma value for the methods used for gamma correction: blue, red and yellow lines correspond to: polynomial approach, least squares approach and differentiation approach, respectively. These were evaluated in three different levels of noise: (a) 2%, (b) 4% and (c) 6%.

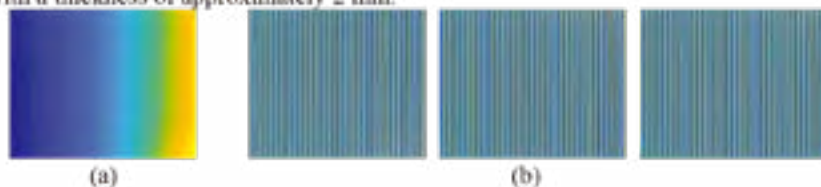
**Table 1.** Computer processing time (seconds)

| Model           | Noise Level |         |         |
|-----------------|-------------|---------|---------|
|                 | 2%          | 4%      | 6%      |
| Polynomial      | 0.0092      | 0.0120  | 0.0122  |
| Least squares   | 10.4432     | 13.8095 | 13.8255 |
| Differentiation | 0.0041      | 0.0048  | 0.0050  |

Table 1 depicts the computer processing time for the data reported on Fig. 4, employing a commercial laptop with an Intel(R) Core (TM) i7-1065G7 CPU and 12GB-DDR4 of RAM, MATLAB R2023b, and Windows 10 as the operating system. We can see in Table 1 that the polynomial and differentiation method have similar computational performances, while the least squares method has higher execution time.

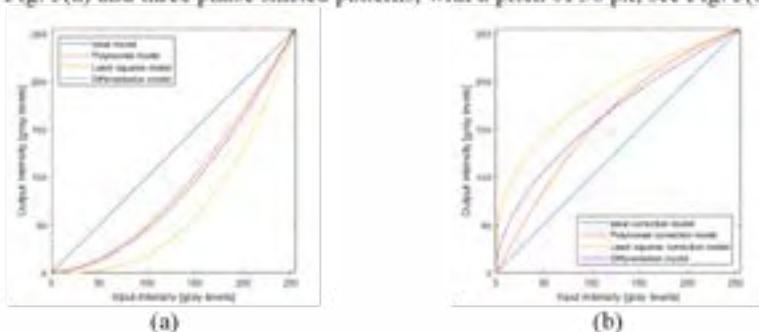
## 4.2 Experimental results

In this section, we perform a series of experiments to compare performance of previously described three methods to correct the gamma distortion and their effects on retrieved three-dimensional surfaces. As test object was used a resin semi-sphere printed with a precision of 0.05 mm, whose diameter is approximately 60 mm and has a height of 30 mm, the semi-sphere is attached to the plane with double-sided tape with a thickness of approximately 2 mm.



**Fig. 5.** Acquired intensity patterns to model the nonlinear intensity response of the projector after the calibration. (a) Tilt plane pattern. (b) 3 phase shift patterns.

At first step, we project and acquire a series of patterns on the reference plane. For the polynomial calibration procedure, a linear-wedge grayscale image was projected see Fig. 5(a) and three phase shifted patterns, with a pitch of 36 px, see Fig. 5(b).



**Fig. 6.** Plots the intensity response models acquired by each method reviewed. Being the blue line the ideal model, with the red, yellow and purple line being the polynomial, least squares, and differentiation model respectively. (a) shows the acquired models, while (b) shows their respective correction models.

After the estimation, we get a polynomial function with the following coefficients: -0.3499, 1.3416, 0.0017, 0.0080, and gamma values of 2.7836 and 1.8469 for the least squares and differentiation, respectively, the models can be seen in Fig. 6(a) and the



inverse model is shown Fig. 6(b). Next with the estimated correction models we generate fringe patterns to get the wrapped phase with a 36px pitch and shift of  $2\pi/3$ , and fringe patterns with a pitch of 216px to unwrap the phase based on the double frequency method described in [5], after unwrapping we convert to height through the construction of an empirical model from known surfaces and a linear least squares regression process as described by [12]. After, we compare surface information of an object retrieved with 3 shifted fringe "corrected" patterns, with its respective surface information retrieved with 12 shifted fringe patterns without correction. We do that because as we increase the number of shifted fringe patterns  $N$  in a fringe projection profilometer the effects of second and higher order harmonics decrease, 12 shifted fringe patterns should reject the most significant harmonics that distort the phase, giving us a comparison point to review the methods [13].

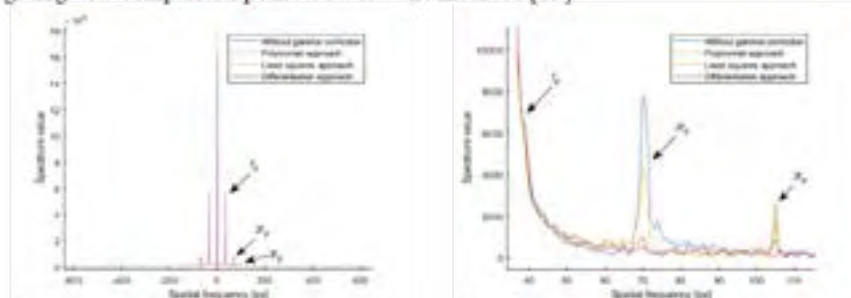
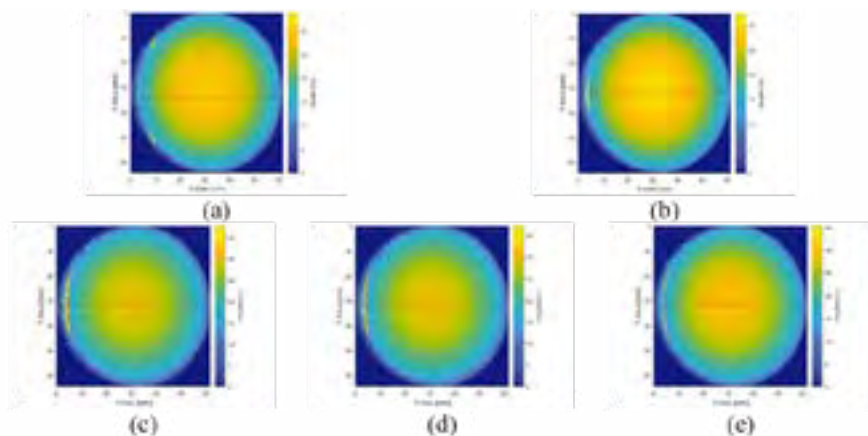


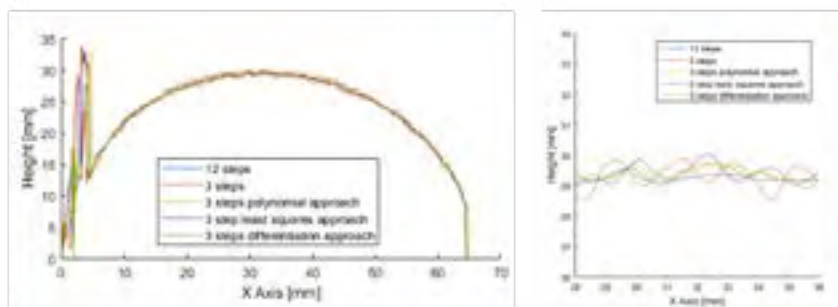
Fig. 7. Plots a frequency domain comparison of gamma corrected pattern with each method reviewed. Being the blue line the 12-steps phase, the red line the 3-steps uncorrected phase, with the red, yellow and purple line being the polynomial, least squares, and differentiation corrected phases respectively. The left figure shows the complete signal, while the right one is a zoom in of the first 3 harmonics.

With that we proceed to recover 3D measurement of the object as a final test. In simulations, the least squares and differentiation methods have similar performances even though the estimated values have a difference of almost 1; this deviation is seen in Fig. 6 and it is because of the mathematical model of the least squares is sensitive to small deviations in the estimated value and despite that, we can observe that both methods correct partially the gamma distortion as we can see in Fig. 7, Fig. 8, and Fig. 9. In Fig. 7 we can observe the amplitude of the harmonics, in the Fourier domain, of a fringe pattern corrected by each method. In Fig. 9, we can see that the polynomial method and differentiation method have better results. However, In Fig. 7 conclude the method that best cancels the harmonics is the differentiation one. Also, in experimental results, Fig. 8, This is observed better in the horizontal cut of the phase in Fig. 9 and in Fig. 8 we confirm that the methods that best cancel the ripple in the object height profile are the methods, this ripple is due to the second harmonic. Assuming that the ideal reconstruction is the one obtained by the 12-step method, we estimate the rms value for each method: RMSE for the uncorrected 3-step algorithm was 0.4895 mm. While RMSE values for the polynomial method, least squares method and differentiation method were 0.21 mm, 0.32mm, and 0.22mm, respectively.





**Fig. 8.** Comparison of a horizontal of the phase of an object by each reviewed method. Being the red line a horizontal cut, (a) Shows the 3 steps phase without corrections and (b) the 12 steps phase, while (c) shows a 3 steps phase by the polynomial approach, (d) a 3 steps phase by the least squares approach, and (e) a 3 steps phase by the differentiation method.



**Fig. 9.** Comparison of a horizontal cut of the phase of an object by each reviewed method. Being the blue line the 12-steps phase, the red line the 3-steps uncorrected phase, with the red, yellow and purple line being the polynomial, least squares, and differentiation corrected phases respectively. The left figure shows the complete signal, while the right one is a zoom in.

## 5 Conclusions

In this work, we present a new scheme to estimate the gamma of a projection system proposed for reconstructing and measuring 3D surfaces. The estimation is performed as an optimization problem, where the objective function is the difference between the sinusoidal intensity of acquired pattern and its ideal sinusoidal intensity pattern (gamma modified) whose spatial frequency and phase are the same as that of the acquired pattern.

Also, we compare its performance with two other calibration methods, the least squares, and the polynomial method. In simulations, we found that the proposed

method and the least squares have similar gamma-correcting performances with lower RMSE over a wider range of gamma values in contrast with the polynomial the latter being slightly better around a gamma value of 1.6.

We implemented and tested these calibration methods on a fringe projection profilometer. Experimentally, the proposed method, the least squares method and polynomial method reduced the RMSE by a factor of 2.15, 1.52, and 2.32, respectively. Where the proposed method and the polynomial method have similar performances, but unlike the polynomial, it is not necessary to acquire a tilt plane to estimate the nonlinear intensity response of the projector. Therefore, our algorithm requires only a sinusoidal pattern and can be useful in dynamic applications, where having high processing speed is essential.

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# Deep Learning Approach for Fault Identification of Contact Reliability for Electrical Test Connectors in Testing Environments

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**Abstract.** Electrical connectors are widely used in modern-day technology and products and they play a key role in manufacturing facilities. Specifically in testing equipment in production lines, the contact reliability of electrical test connectors is critical for obtaining correct measurements of a wide variety of signals coming from the unit under test (UUT) or from the test equipment (TE). Because modern production environments submit testing connectors to constant cycles of contact, which includes several grades of physical and electrical stress, the reliability of any given connector becomes a very important factor in production quality and continuity. Failure of contact may result in unreliable testing results, product failure or even physical damage to product or even testing equipment. Damage to connector terminals due to wearing may induce different degrees of contact failure of contact, which may result in unreliable testing results, product failure or even physical damage. As global modern production quality requirements become more prominent, test processors are expected to be increasingly reliable in modern day industry. In this paper, we provide an approach to identify failure of contact reliability in testing connectors using Deep Learning.

**Keywords:** Deep Learning, Testing Equipment, Electrical Connectors, Industry 4.0

## 1 Introduction

To this day, there are several well established testing procedures to qualify an electrical connector's reliability like contact resistance measurement, low current impedance measurement, high resistance metrics, among others. These methods are part of the ANSI C119 Standard Test Methods [3] and are widely used internationally. Lately, novel methods for contact reliability are being published that aim to specific measurement parameters like the HAST test for electrical connectors [2] which presents a degradation model of the electrical contact considering temperature and humidity factors, in the accelerated Life Testing for Marine Cables and Connectors [4] that provides a delamination predictive model of such connectors. On more production-related grounds, systematic approaches have been proposed for connector reliability [1][8] which offer a quantitative solution and offers insight on analysis of material, electrothermal, structure and contact characteristics of a given connector.

On the other hand, there are several industry-grade instruments designed specifically for connector reliability testing that aim to measure both continuity and isolation of the connector under test (CUT) [5]. In the case of isolation, a high resistance is expected to be measured between non-contact terminals (typically:  $1M\Omega-1T\Omega$  depending on settings), for continuity of contact, a value of low resistance is expected to be measured end-to-end connector wise (typically:  $<10\Omega$  depending on settings). This type of equipment uses current and current-sense matrix to test electrical characteristics of the connector but are susceptible to noise, wiring capacitance and thermoelectric EMFs, which need to be attended beforehand.

Connector Testing Programs are test sequences and procedures that aim to determine the connector reliability based on several factors like mechanical stability, durability cycling, mechanical shock response, among others [6]. These particular sequences are used in several steps of modern industry environments which include: design verification, quality assessment, performance analysis and reliability assessment. Typical generic test plans are divided among several testing groups, each group will evaluate a set of characteristics from the connector, this is shown in Fig. 1.

<https://doi.org/10.61728/AE20255121>







Fig. 1. Generic test plan group order and their hierarchy as defined by [6].

Each of the groups shown in Fig. 1. Evaluates a different aspect of the connector reliability and provides a complete performance assessment, which follows the following general criteria:

- First group comprises mechanical tests and the overall initial testing phase.
- Second group adds thermal and corrosion metrics as well as physical forces involved in connecting cycles.
- Third group is an environmental performance testing aimed to measure connector's construction reliability.
- Fourth group involves preconditioning conditions like corrosion or wear.
- The Fifth group comprises the same analysis as the Second group but with extreme temperature ratings.
- Finally, the Sixth group will have application-specific tests.

Considering all of the above, we can infer that the testing scenario for connector reliability is well established, well defined and supported by precision equipment up to this day. Now, by using the resulting data from a well-modelled connector and the measurements of a well-defined connector's test plan we can define the correct parameters of any given test connector during its normal operation. Furthermore, we can use this information to create a structured data frame that contains all the expected behaviors during connection cycles of a given electrical connector and use them as a reference database.

In modern industry standards, like Industry 4.0, Artificial Intelligence (AI) is rapidly gaining notoriety in numerous applications like autonomous driving and assembly, battery lifespan and degradation analysis, renewable energy optimization, stock markets forecasting, semiconductor anomaly detection, among others [7].

Alongside several artificial intelligence models, Deep Learning (DL) stands as a reliable and successful approach for several problems that involve visual and nonvisual problems in wide areas like: engineering, medical, transportation, security and many others [8][11][12]. The Convolution Neural Network (CNN) that comprises the base of the algorithm, allows the extraction of relevant data known as characteristics without losing significant information during the deep process of the scheme: Convolution-Rectification-Max pooling-Padding [10]. Finally, the fully connected section (FC) of the DL algorithm consists of a multilayer perceptron (MLP) and a hierarchical statistical output (SoftMax) that provides a very precise classification output [13].

One of the key factors in Deep Learning success is its innate ability to identify data structures that are high-order, unknown and non-linear, which might be difficult or impossible for the human eye to perceive [10][15].

If we use data from several electrical connector models and their corresponding test plan results with varying degrees of reliability, then we can train a DL model to correctly identify any deviation from acceptable electrical connector reliability.

## Model Description and Limitations

In order to create the DL model needed to identify the correct data structure and how this data will be used to define characteristics to be convoluted by the CNN and processed by the several following layers, it is crucial to select the relevant data that has relevant information on the connector performance during operation; this data will be known in the rest of this document as *reliability vector* and will be used as the input vector for the DL model. In many cases it will contain consecutive measurements like sliding coefficient during contact process or contact pressure; but also can have parametric values like coefficients that are defined by connector's modeling.

Once we select the relevant data to be fed into the CNN, we need to define the DL configuration that will be used; that is the number of layers to be used (depth) and the amount of neurons for the MLP and the number of desired outputs for the connector's contact reliability; in this case will be using only two possible outcomes: *reliable* and *non-reliable contact*.

Because electrical connectors can be used in a wide variety of applications, the signals across these connectors can have several orders of magnitude of current, voltage, power, electromagnetic fields and frequency that can severely affect both the modeling and testing schemes needed to understand and measure contact reliability. For this reason the scope of this work is limited to low power, direct current (DC) and low transmission length applications of electrical contact.

### 2.1 Contact Reliability Vector Description

The data considered in modern modeling of connectors is vast and varying, because it must consider all possible factors from design to manufacture of the aforementioned product; however, for the scope of this work, we will focus on the operating cycle of the connector and because of this, the selected vector to train the DL solution will be the one that is relevant for the electrical connection performance. For this matter this work will not consider any modeling of degradation due to extreme temperatures, wear due to oxidation, delamination or any other environmental stress, as this data is considered to be reflected in either physical or electrical characteristics of the connection during operation.

#### Contact Pressure

The first parameter of the vector is the *Contact Pressure*, which is defined as the pressure force exerted over the connector and its corresponding counter force[8]. This value is obtained by (1) in the following manner:

$$F = \frac{E \delta}{l} \quad (1)$$

where  $E$  is the elastic modulus of the base material,  $I_s$  is the inertial moment of the rod,  $l$  is the connectors length and  $\delta$  is the need deflection coefficient of the connector's material.

#### Contact Bounce

One of the most common phenomena in electrical contact is the contact bounce. This can be defined as the mechanical sway and posterior oscillation that occurs upon initial switch closure or physical contact between two moving connectors. This phenomena has been widely analyzed, simulated and modeled by several authors [15-17] and while a mathematical modeling of contact bounce is difficult to obtain due to the complexity of the mechanical-electrical perturbations involved in it, the measurements and waveforms are well known and might hold hidden structured data showing contact behavior. Because of this, the generated time series data from electrical contact bounce will be constructed by taking a single value of the contact force during bounce. A graphical approach of bouncing effect can be seen in Fig. 2.

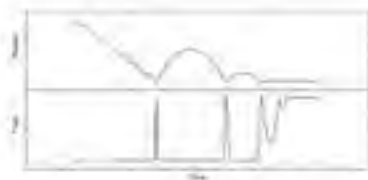


Fig. 2. General diagram of switch bounce as defined by [44].

### Conductivity and Isolation

As introduced in the previous section, these parameters are expected to be constant during the entire slide of the contact cycle. Therefore, any significant variation in the measurements during the operation cycle might indicate a poor reliability on contact.

### Contact Voltage Drop

The voltage drop upon contact should be negligible ( $V_d \rightarrow 0$ ) as the connector's impedance is close to 0 ohms. The equivalent circuit of a low power, DC short transmission line neglects any significant capacitance and inductance [18] and can be calculated by applying Ohm's law:

$$V_d = V_c - I_c R_d \quad (2)$$

where  $V_c$  is the input voltage;  $V_d$  is the voltage drop on the connector;  $I_c$  is the test current delivered to the contact circuit and  $R_d$  is the known testing resistance of the test circuit. In this document we will consider that maximum voltage drop is  $V_d \rightarrow 1mV$ .

### Stress relaxation

After metal collides in the contact event, occurs a phenomena known as *metal relaxation* which can be modeled by considering the initial restoring force of every spring, the maximum allowable contact resistance and the minimum contact force [1]. This can be represented as a percentage given by:

$$\Omega = 1 - e^{(kA - B)/T} \quad (3)$$

where  $\Omega$  is the number of relaxation percentage,  $t$  is time,  $kA$ , and  $B$  are material-related coefficients, and  $T$  is absolute temperature.

Finally, each different element of the input vector has a limit in which the values can vary, however, to maintain the data symmetry necessary for correct classification, normalized data will be used on the *identity* of the vector. Table 1 shows the 6th order input vector that will be used as input for the proposed AI Model.

Table 1. Modeling and testing data for the input vector

| Data                 | Description                            | Type of data | Min | Max     |
|----------------------|----------------------------------------|--------------|-----|---------|
| Stress Relaxation    | Stress Coefficient after Contact Force | Scalar value | 0   | 1       |
| Contact Voltage Drop | Voltage drop after contact             | Scalar value | 0   | 0.001 s |
| Conductivity         | Resistance after contact               | Time series  | 0   | 10      |
| Isolation            | Isolation from other terminals         | Time series  | 1M  | -       |
| Contact Lifetime     | Electrical Work hours per contact      | Time series  | 0   | 1       |
| Contact Pressure     | Force applied from connector           | Time series  | 0   | 1       |

## 2.2 Two Dimensional Convolutional Neural Network Model

Once all the behavior information on the connector is obtained as an input vector, the well-known 2D-CNN methodology shown in [4] can be used to identify any significant deviations for the contact reliability. In this case, a high-order vector is constructed from modeling and testing data to train the network to recognize patterns and characteristics of the connector and then to classify them as compliant or not.

For Deep Learning to be used in this approach, we need to reconfigure the input vector as a tensor by slicing the data as defined by [20]. In this case, each slice is no other than the time series representation of the  $n$  parameters shown in Table 1, but fed into the CNN as a matrix format of  $m$  by  $l$  size, as shown in Fig. 3 and the proposed DA model is represented in Fig. 4.

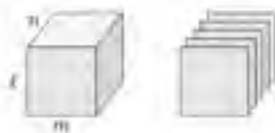


Fig. 3. Tensor representation of input vector

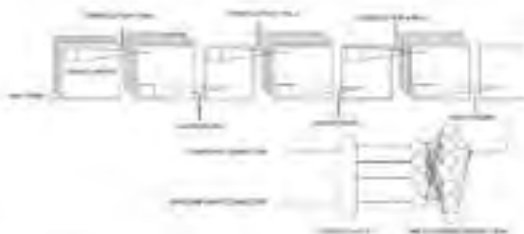


Fig. 4. Deep Learning Model for Electrical Connector Reliability Compliance



## Simulation Data Generation and Model Configuration

### 3.1. Simulation algorithms

Simulation of the *input vector* requires that compliant values and non-compliant values are considered in a wide spectrum between physical boundaries (metal stress, electrical properties, etc); for each element of the input vector a different behavior is considered to create a reliable simulation vector field.

In order to use this data in the DL model, two sets of simulations should be built: Compliant Data and Non-Compliant data.

For creating the Compliant Data modeling vector, it was considered to simulate a normal environment that involves; manufacturing processes, material defects and unknown physical events during the contact cycle; the way of the values of each element of the *input vector* is considered to be unknown but normal distribution in nature because physical limits exist that *push* the values to a certain limit. Because of this, the simulation function chosen for this work will be the Gaussian Distribution and will simulate 10,000 normalized samples.

The probability distribution of one sample of the 10,000 randomly selected values whose boundaries are normalized is shown in Fig 5.



Fig. 5. Simulation Sample Probability Distribution for Compliant Connector

For the Non-Compliant Data modeling, the Weibull probability distribution was selected because it is considered to be a Time-to-Failure distribution.



Fig. 6. Simulation Sample Probability Distribution for Non-Compliant Connector

High order vectors can have a considerable impact in the computational requirements of training of a DL model, like GPU capacity, memory usage and power consumption [in also, model's accuracy can be affected significantly by the input image size and the depth of the model (number of layers) [10]. Due to these restrictions we will constrain the model to the configuration shown in Table 2.

Table 2. DL Model Configuration

| Parameter                  | Value   |
|----------------------------|---------|
| Input Vector Size          | 25*25*6 |
| Number of DL filters       | 6       |
| 1st Layer CNN feature size | 32      |
| 2nd Layer CNN feature size | 64      |
| 3rd Layer CNN feature size | 128     |
| Kernel size                | 3       |
| Training epochs            | 50      |
| MLP 1st layer size         | 128     |
| MLP hidden layer size      | 64      |

To simulate the problem at hand as much accurate as possible, the training vector will be constructed by taking randomly a value from the simulation distribution for each element of the input vector and then construct a training vector, once the vectors are created, 80% of the created vectors will be used for training the model and 20% for testing it.

## Results

The model proposed in Section 3 of this document was implemented using a computer with AMD Ryzen 5 CPU, NVIDIA 3080 RTX GPU and 56 GB of DDR5 RAM. Initial training results after training and validating the DL model can be shown in Fig. 7 and the Loss function plot can be seen in Fig. 8.



Fig. 7. Fault Identification results for simulation environment

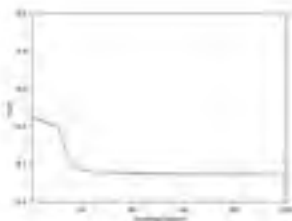


Fig. 8. Loss result for fault identification during simulation environment.

After initial results, a MonteCarlo round up of 10 simulations was executed to observe simulation accuracy behavior. Which resulted in a simulation accuracy average of 0.8. Which can be appreciated in Fig. 9 and their corresponding Loss results can be seen in Fig. 10.

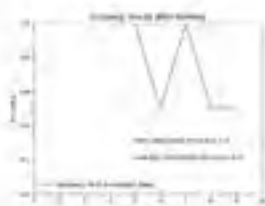


Fig. 9. Fault Identification average accuracy after 10 cycles.

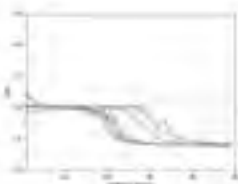


Fig. 10. Loss results for fault identification after 10 cycles.

## Conclusions

In this work, an Artificial Intelligence Model based on Deep Learning was proposed for Fault Identification of Contact Trajectory for Electrical Connectors. Several modeling and electrical test parameters were identified and grouped to form a high order input vector eligible for Convolution operations. The simulated data fed into the DL algorithm followed Gaussian distribution for compliant simulation and Weibull distribution for non-compliant simulation. The results were satisfactory (average accuracy = 0.8) although maximum accuracy reached 100% a couple of times as seen on Fig. 9, these two exceptional results are more likely anecdotal rather than regular. Finally the results of this work demonstrates the successful application of a Deep Learning approach to identify faulty contact trajectory on electrical connectors.

Future work on the subject involves deeper simulation data construction using empirical data, because probability functions were used to build simulation, these results are to be tested under a more complex simulation environment. Additionally, real-time data from real industry measurements would complement the results and provide better insight on field applications of the proposed model.

The authors would like to thank the University of Guadalajara and CONSIDAL for their support in the materialization of this work.

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# State-of-the-art of Imagined Speech: Analysis in Basic Needs, Syllables and Commands for Brain-Computer Interfaces

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**Abstract.** Imagined Speech decoding through brain-computer interfaces has emerged as a promising approach for assisting people with severe communication challenges. Imagined speech refers to brain activity generated when a person internally simulates Speech without vocalizing, enabling communication through non-invasive methods like electroencephalography. This work comprehensively reviews Imagined Speech research, categorizing studies into three strands: syllable imagination, command imagination and basic needs. Comparative tables highlight the methodologies, languages, classifiers, and performance metrics used across studies. Results show significant variability in accuracy due to differences in data acquisition, signal processing, and classification algorithms. Despite notable advances, challenges remain in generalizing models to real-world applications and improving usability outside laboratory settings. Future research should focus on standardized methodologies, larger datasets, and hybrid systems to enhance accuracy and applicability. Development of Imagined Speech based BCIs holds significant potential for restoring communication and autonomy for individuals with speech impairments.

**Keywords:** Basic Needs, Brain-Computer Interface, Commands, Electroencephalography, Imagined Speech, Review, Syllables.

## 1 Introduction

### 1.1 Communication

Communication is an essential process in human life that enables the transmission of ideas, thoughts, emotions, and needs between people. Through communication, individuals can interact with their environment, establish relationships, learn, and actively participate in society [1].

<https://doi.org/10.61728/AE20255138>



There are various forms of communication, with verbal and non-verbal being the most common. Verbal communication is carried out through spoken or written language, while nonverbal communication encompasses gestures, facial expressions, body postures, and other methods that either complement or replace spoken language.

**Disabilities in Human Communication.** Difficulties in human communication can limit a person's ability to express their thoughts, needs, and emotions, negatively impacting their quality of life. These difficulties might be due to a range of factors, including neurodegenerative diseases, brain injuries, developmental disorders, or paralysis [2].

According to 2020 Population and Housing Census conducted by Mexico's National Institute of Statistics, Geography, and Information (INEGI, by its Spanish acronym), around 6.18 million individuals, roughly 4.9% of the country's population, live with some form of disability. Within this group, around 15% experience difficulties in speaking or communicating, affecting more than 945,000 people. This sector includes individuals who struggle to articulate speech comprehensibly as well as those who cannot communicate verbally [2]. Main causes of communication disabilities include stroke, amyotrophic lateral sclerosis (ALS), and cerebral palsy.

## **1.2 Bioelectronics Interfaces for Communication**

Bioelectronic interfaces for communication are systems designed to establish direct interaction between human body and electronic devices, enabling transmission of information without relying on verbal or written communication methods. These interfaces are particularly beneficial for individuals with severe disabilities that prevent them from speaking, writing, or performing voluntary motor movements, such as those with neurodegenerative diseases or speech impairments [3].

Relevance of these interfaces on the lives of individuals with speech difficulties is significant, as they provide the possibility of regaining communication abilities and control over their environment. Their implementation contributes to improving quality of life by promoting autonomy in daily activities and fostering social and emotional integration for patients. In this regard, these technologies are not only a technical advancement but also a key tool in the rehabilitation and inclusion processes of individuals with speech disabilities [4].

**Brain Computer Interfaces (BCI).** Among advanced technologies in bioelectronics interfaces for communication are Brain-Computer Interfaces. They establish a direct link between the brain and an external device without the need for muscular activity. They function by recording electrophysiological signals, usually through Electroencephalograms (EEG), to interpret the user's intentions in real time [5]. These innovations allow individuals with locked-in syndrome or conditions like amyotrophic lateral sclerosis (ALS) to communicate by using their neural activity to operate devices [6].

BCIs come in various forms, depending on the signals they employ and the objectives they are designed to achieve. Common BCIs rely on electrophysiological sources

such as EEG, which detects the electrical activity generated by large populations of neurons.

### **1.3 Imagined Speech**

Imagined Speech (IS) refers to the brain activity that occurs when a person mentally simulates the act of speaking without performing the physical movements necessary to produce sound. Recent research has shown that imagining the pronunciation of words activates brain regions like those involved in actual speech, such as Broca's area and other regions related to motor control of language [7]. This neural activity generates specific patterns that can be detected using techniques such as EEG, enabling the decoding of imagined speech through BCIs.

BCIs based on imagined speech represent a significant advancement in the development of assistive communication systems for individuals with severe disabilities that prevent them from speaking or moving, such as those with locked-in syndrome or severe brain injuries. However, decoding imagined speech remains a challenge due to the complexity of brain signals, which are subtle and vary significantly between individuals.

These BCI systems can be used to facilitate communication by generating commands based on imagined words or syllables. For example, a user could imagine a specific word or command, and the BCI system would interpret those signals to translate them into instructions that allow controlling a device or typing on a screen.

Humans engage in internal dialogue most of the time. Unlike engaging in an actual conversation with another person, this discourse is entirely imagined, meaning that we voluntarily simulate speaking without making intentional movements of speech articulators. Therefore, even in cases where a person has muscle paralysis and cannot move their articulators, they are still capable of imagining speech or actively thinking in words [8].

In these circumstances, it is essential to have systems that enable spoken communication without the need to produce a comprehensible acoustic signal [9]. Since speech facilitates the most direct interaction among humans, there has been growing interest in the decoding of imagined speech. A system designed to interpret imagined speech has various applications, including the ability to facilitate communication for patients with speech limitations, as well as devices operation such as computers through mental control [2, 8].

In the last decade, numerous researchers have developed various implementations of systems to decode imagined speech from EEG signals. However, progress in this field has been slower compared to other areas within brain-computer interfaces, such as BCI spellers, Blink-to-speak, or subvocal speech [9, 11-13].

This slowdown is largely due to the heterogeneity of studies in various aspects, ranging from data collection methods to the machine learning algorithms used for decoding, as well as the criteria employed for evaluation. These differences make direct comparisons between studies difficult, posing a challenge for the standardization of the field [2].



Despite these difficulties, the study of imagined speech and its decoding continues to evolve through the implementation of new approaches and tools, aiming to improve its accuracy and applicability [2].

In the field of research on IS, multiple types of IS have been identified based on what is intended to be expressed. The classification into different categories and the development of a comparative table facilitate the identification of recurring patterns, effective methodologies, and underexplored areas of research. Keeping this classification updated helps reflect the latest advancements, fostering collaborative efforts and the sharing of knowledge within the scientific community. Moreover, by including the dimension of basic needs, this study expands the scope of imagined speech toward more practical applications, with the goal of enhancing the quality of life for individuals with severe disabilities.

### 3 Methodology and Results

A comparative table is developed that compiles the main characteristics of studies on IS. This table facilitates the analysis of methodologies, results, and trends in each study, providing a dynamic and useful tool for researchers in this field.

#### 3.1 Imagination of Syllables

The syllable imagination strand focuses on decoding basic units of language, such as vowels, consonants, and syllables. This approach aims to identify specific patterns associated with imagining individual sounds. Commonly used stimuli in this strand are auditory or visual, presenting subjects with tasks such as imagining a specific vowel or syllable (see Table 1).

**Table 1.** Imagination of Syllables: Compendium of Research

| References                     | Imagined Tasks                                                                                                     | Language and Country     | Classifier and Performance                                                                   |
|--------------------------------|--------------------------------------------------------------------------------------------------------------------|--------------------------|----------------------------------------------------------------------------------------------|
| DaSalla, C.S., (2009) [12]     | Vowel articulation involving /a/ and /u/, along with a baseline condition where no action is taken                 | USA - English            | SVM with 78% accuracy                                                                        |
| Sharon, R.A., (2020) [13]      | Three tasks: Perception, Imagination and Speaking of 25 and 54 syllables such as "a", "am" and "give", and others  | USA - English            | GMM-HMM with 37.2% accuracy                                                                  |
| Kara One Database, (2015) [14] | Seven phonemic or syllabic prompts combined with four words taken from the Kent list of phonetically similar pairs | USA - English            | DNN and SVM with 87% accuracy in binary classification and 53% in multi-class classification |
| Jahangiri, A., (2019) [15]     | "BA", "FO", "LE" and "RY"                                                                                          | United Kingdom - English | Davies-Bouldin index Pseudo-Linear                                                           |

|                             |                                                                                                                                                                                                 |                          |                                                                                                           |
|-----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|-----------------------------------------------------------------------------------------------------------|
| Brigham, K., (2010)<br>[16] | Syllables "ba" and "ku"                                                                                                                                                                         | USA - English            | Linear SVM classifier with 99.76% accuracy                                                                |
| Brigham, K., (2010)<br>[17] | Syllables "ba" and "ku"                                                                                                                                                                         | USA - English            | k-NN with 61% accuracy                                                                                    |
| Min, B., (2016)<br>[18]     | Vowel classification                                                                                                                                                                            | Korea - Korean           | ELM, SVM and LDA, using binary classification and 69.68% accuracy on average across the three classifiers |
| Cooney, C., (2018)<br>[19]  | Seven phonemic or syllabic prompts combined with four words                                                                                                                                     | United Kingdom - English | SVM and ANN and the best performance SVM (-21%), while the worst SVM (-11%)                               |
| Totrup, L., (2019)<br>[20]  | Seven distinct actions: producing three words, executing two arm movements and a resting state                                                                                                  | Denmark - English        | Random Forest with 61% accuracy                                                                           |
| Saha, P., (2019)<br>[21]    | Seven phonemic or syllabic prompts combined with four words                                                                                                                                     | Canada - English         | CNN with accuracy of 83.42%, six binary classification.                                                   |
| D'Zurra, M., (2009)<br>[22] | Binary classification /ba/ and /ku/ syllables                                                                                                                                                   | USA - English            | Matched-Filter Classification using binary classification with 75% accuracy                               |
| Deng, S., (2010)<br>[23]    | Binary classification /ba/ and /ku/ syllables                                                                                                                                                   | USA - English            | SOBI and Hilbert-Huang Transform (HHT) with the highest classification accuracy was 26% (S6)              |
| Chi, X., (2011)<br>[24]     | Imagined pronouncing ten phonemes, categorized by articulation: jaw movement (/aa/, /ae/), tongue movement (/i/, /r/), nasals (/m/, /n/), lip movement (/au/, /ou/), and fricatives (/s/, /x/). | USA - English            | Naïve Bayes and LDA with the overall classification performance was 67.31% on average                     |



|                                   |                                                                                          |                          |                                   |
|-----------------------------------|------------------------------------------------------------------------------------------|--------------------------|-----------------------------------|
| Cooney, C., (2020)<br>[25]        | Vowel classification                                                                     | United Kingdom – English | CNN with vowel: 35% best accuracy |
| Tamm, M., (2020)<br>[26]          | Vowel classification and six words: "down", "right", "left", "up", "back", and "forward" | Estonia – English        | CNN and 24% accuracy              |
| Chengayyan, et al. (2020)<br>[27] | Vowel classification                                                                     | India – English          | RNN with 72% average accuracy     |
| Matsumoto and Hori (2014)<br>[28] | Japanese vowels classification                                                           | Japan – Japanese         | RVM with 79% average accuracy     |

### 3.2 Imagination of Commands

On the other hand, the command imagination strand focuses on tasks that allow subjects to imagine words or short phrases that can be interpreted as "commands." The stimuli in this approach are usually visual or textual, with the most common classes being, "down", "up", "right", "left" and "select" (also in their Spanish versions: "abajo", "arriba", "derecha", "izquierda" and "seleccionar"), which are associated with specific actions. This approach combines linguistic processing with Motor Imagery, activating both language areas and motor regions of the brain (see Table 2).

**Table 2.** Imagination of Commands: Compendium of Research

| References                     | Imagined Tasks                                                                                                   | Language and Country | Classifier and Performance                                                                   |
|--------------------------------|------------------------------------------------------------------------------------------------------------------|----------------------|----------------------------------------------------------------------------------------------|
| García, J. S., (2018)<br>[29]  | These words were selected to represent common directional commands: "arriba", "abajo", "izquierda" and "derecha" | Mexico – Spanish     | MT, FID with 65% accuracy                                                                    |
| Torres, A.A., (2016)<br>[30]   | "arriba", "abajo", "izquierda" and "derecha"                                                                     | Mexico – Spanish     | ETS 3x3 with 68.18% accuracy using 7 channels and 70.33% using all channels                  |
| González, E.F., (2017)<br>[31] | "arriba", "abajo", "izquierda", "derecha" and "seleccionar"                                                      | Mexico – Spanish     | Random Forest with 58.41% accuracy (raw), 63.82% (sonification), and 83.34% (textification). |

|                                             |                                                                                                                                                                                                     |                          |                                                                                                                                                                     |
|---------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Torres, A.A., (2012) [32]                   | Control words for moving a cursor on the computer: "arriba", "abajo", "izquierda", "derecha" and "seleccionar"                                                                                      | Mexico - Spanish         | Random Forest, Support Vector Machines and Naïve Bayes and Bagging-RF using multiclass classification and Accuracies above 20%                                      |
| Torres, A.A., (2013) [33]                   | Control words for moving a cursor on the computer: "arriba", "abajo", "izquierda", "derecha" and "seleccionar"                                                                                      | Mexico - Spanish         | Random Forest, Support Vector Machines and Naïve Bayes. Highest accuracy was 60.11% using 14 channels and 47.93% with 4 channels                                    |
| Moctezuma, L.F., (2019) [34]                | "arriba", "abajo", "izquierda", "derecha" and "seleccionar"                                                                                                                                         | Mexico - Spanish         | Random Forest, Support Vector Machines, Naïve Bayes and k-NN. The best accuracy obtained was 92% using linear Support Vector Machine with 10-fold cross-validation. |
| García, J.S., (2018) [35]                   | "arriba", "abajo", "izquierda", "derecha" and "seleccionar"                                                                                                                                         | Mexico - Spanish         | Tensor decomposition technique, specifically Parallel Factor Analysis (PARAFAC), with 59.7% classification accuracy.                                                |
| Torres, A.A., (2011) [36]                   | "arriba" and "abajo"                                                                                                                                                                                | Mexico - Spanish         | Naïve Bayes, MLP, Random Forest and Support Vector Machine, with The average classification accuracy across all classifiers and subjects was 68.75%                 |
| Jimenez-Guarneros and Gomez-Gil (2021) [37] | Short and long words classification: "arriba" (up), "abajo" (down), "izquierda" (left), "derecha", (right) and "seleccionar" (select), "cooperate" and "independent" for long words classification. | Mexico - Spanish/English | Random Forest, Support Vector Machine, RMDM with 63.42% accuracy for Spanish words and 62.99% accuracy for long words.                                              |
| Rezaadeh Sereshkeh, A., (2017) [38]         | Three mental tasks: Rest, "yes," or "no."                                                                                                                                                           | Canada - English         | Regularized neural networks and 63.1% accuracy                                                                                                                      |

|                               |                                                                                                                                 |                         |                                                                                                                                |
|-------------------------------|---------------------------------------------------------------------------------------------------------------------------------|-------------------------|--------------------------------------------------------------------------------------------------------------------------------|
| Balaji, A., (2017) [39]       | The tasks featured "Yes" and "No" in English, as well as "Haam" and "Na" in Hindi.                                              | India - English / Hindi | Support Vector Machines, Random Forest, AdaBoost, and a Neural Network reached an accuracy of 85%                              |
| Panachakel, A.G., (2020) [40] | Two words: "in" and "cooperate"                                                                                                 | USA - English           | DNN with 83% accuracy                                                                                                          |
| Rezaradeh, A., (2017) [41]    | Two sets of tasks:<br>Mental repetition of the word "no" vs. unrestricted rest.<br>Mental repetition of the word "yes" vs. "no" | Canada - English        | Support Vector Machine with 75.9% accuracy for "no" vs rest classification and 69.3% accuracy for "yes" vs "no" classification |
| Zhang, X., (2020) [42]        | Participants imagined pronouncing the syllable /ba/ in the four Mandarin tones                                                  | China - Mandarin        | Support Vector Machine with 80.1% accuracy using audiovisual condition and 67.7% using only visual condition                   |

### 3.3 Imagination of Basic Needs

Finally, basic needs strand represents an innovative approach that focuses on tasks related to fundamental daily life activities, such as "comer", "dormir", "beber", and "excretar". This approach has a clearly communicative purpose, aimed at improving the quality of life of individuals with severe disabilities by developing systems that enable them to express these essential needs. In this strand, auditory stimuli (such as an audio cue stating the word related to the need), visual stimuli (representative images), and textual stimuli (written words) are used.

The basic needs strand is proposed in our work to give a more communicative and functional approach to the study of Imagined Speech, considering its relationship with Motor Imagery (see Table 3).

**Table 3.** Imagination of Basic Needs: Compendium of Research

| References                               | Imagined Tasks                                                        | Language and Country | Classifier and Performance                                                                                                                                 |
|------------------------------------------|-----------------------------------------------------------------------|----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Gutierrez-Zermeno, M., et al. (2022) [7] | Four common words in Spanish: "Comer", "Baño", "Descansar" and "Okay" | Mexico - Spanish     | Decision Tree and Support Vector Machine using CSP. One vs Rest models and 93.1% for "Descansar", 81.2% for "Comer", 73.7% for "Baño", and 70% for "Okay". |

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|                                  |                                                                         |                  |                                                                                           |
|----------------------------------|-------------------------------------------------------------------------|------------------|-------------------------------------------------------------------------------------------|
| Barajas Gonzalez, E., (2024) [2] | Four common words in Spanish: "Beber", "Dormir", "Comer" and "Excretar" | Mexico - Spanish | The highest accuracy was achieved with Naïve Bayes at 24% using multiclass classification |
|----------------------------------|-------------------------------------------------------------------------|------------------|-------------------------------------------------------------------------------------------|

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## 4 Discussion, Applications, Trends and Opportunities

The development of BCIs for Imagined Speech decoding has garnered increasing interest in recent years, yet their application in real-world scenarios still faces multiple obstacles. Although various studies have demonstrated the feasibility of classifying words, phonemes, and basic commands from EEG signals, the effective translation of thoughts into comprehensible language remains an open challenge. Beyond speech restoration, integrating these systems into environments such as smart device control or user identification through neural patterns suggests a broad range of potential applications. However, the complexity of imagined speech lies in its highly variable nature across individuals, which limits the generalization of current models and underscores the need for more personalized approaches to neural decoding.

One of main challenges in this field is ability of these systems to function under dynamic and uncontrolled conditions. Most reviewed studies have been conducted in laboratory settings with strictly defined experimental paradigms, which contribute to achieving high accuracy rates in artificial scenarios but do not guarantee success in everyday life. Additionally, the reliance on high-density EEG and the need for multiple training sessions hinder the implementation of these systems outside academic environments. Development of accessible hardware with configurations optimized for daily use is a key requirement for the adoption of these technologies in clinical or personal settings.

Another aspect to consider is the difference in accuracy between brain signal acquisition techniques. Methods such as Electroencephalography (EEG) and Magnetoencephalography (MEG) have shown significantly higher results compared to EEG, raising the possibility that imagined speech decoding heavily depends on the type of signal used. However, while these techniques offer greater spatial resolution and precision, their implementation is invasive or costly, limiting their applicability to a small group of users. In this regard, future research should focus on improving EEG processing algorithms to bridge the accuracy gap without compromising usability.

Despite current challenges, there are strategies that could accelerate the transition of imagined speech BCI systems toward more functional applications. On the one hand, the use of deep learning models trained on large datasets could enhance the generalization capability of algorithms, reducing reliance on individual calibration sessions. Additionally, the incorporation of hybrid approaches that combine EEG signals with additional biomarkers (such as residual muscle activity or pupillary responses) could increase the reliability of these systems without resorting to invasive methods.

## 5 Conclusions

Research on imagined speech has advanced significantly over the past decade, although its development has been slower compared to other areas of brain-computer interfaces, owing to complexity and variable nature of EEG signals. Lack of standardization in methodologies and decoding algorithms has made it difficult to compare studies, highlighting need for unified approaches. In this context, proposals to classify imagined speech into different categories based on the intended content represent a key advancement, as it facilitates the identification of recurring patterns, effective methodologies, and research opportunities.

This classification not only improves the systematization of knowledge but also expands practical applications, particularly in assistive communication for individuals with severe disabilities, paving the way for the development of technologies that are more accessible and effective. Despite the challenges, use a new tools and methodological approaches continues to enhance the accuracy of decoding systems, driving the integration of these technologies into real-world scenarios and fostering greater collaboration among researchers. In this regard, state-of-the-art provides a comprehensive overview of the advances and limitations in imagined speech decoding, laying the foundation for future research and encouraging the development of more effective and applicable strategies in the fields of neurotechnology and assistive communication.



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# Multispectral Image-Based Binary Classification of Avocado Leaves' Vegetative Health Using Vegetation Indices and Convolutional Neural Networks

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**Abstract.** Avocado crops face challenges in detecting nutritional deficiencies that impact yield. This study proposes a binary classification of avocado leaves using multispectral imaging and convolutional neural networks (CNNs). Leaves are classified as healthy or affected based on visible symptoms. The dataset consists of 81 multispectral images (Green, Red, Red Edge, NIR) acquired with a DJI Mavic 3 Enterprise drone. Five vegetation indices (NDVI, GNDVI, NDRE, OSAVI, SAVI) and their statistical features were extracted to enhance learning. Data augmentation and dropout reduced overfitting. The CNN achieved 100% validation accuracy, and a comparative analysis of activation functions identified the best performers. Results demonstrate the potential of multispectral imaging and CNNs in precision agriculture. Future work will expand the dataset and spectral bands to improve detection.

**Keywords:** Convolutional Neural Networks · Multispectral Imaging · Vegetation Indices · Nutritional Deficiencies.

## 1 Introduction

Hass avocado (*Persea americana*, Hass variety) is one of Mexico's main export products, playing a crucial role in the national economy and international trade. The state of Michoacán, as the primary producing region, positions Mexico as the world's leading exporter of this fruit, making its study and monitoring essential to ensure its quality and sustainability [1]. However, avocado production faces challenges due to nutritional deficiencies that can impact yield if not detected in time.

<sup>1</sup> DJI Mavic 3 Enterprise Multispectral<sup>®</sup> is a registered trademark of DJI Technology Co., Ltd.





Recent advances in precision agriculture technologies have significantly improved the monitoring of crop vegetative health. The integration of sensors, meteorological stations, and satellite imagery has enhanced agricultural analysis. However, multispectral drones have proven to be particularly effective in the early detection of nutritional deficiencies [7].

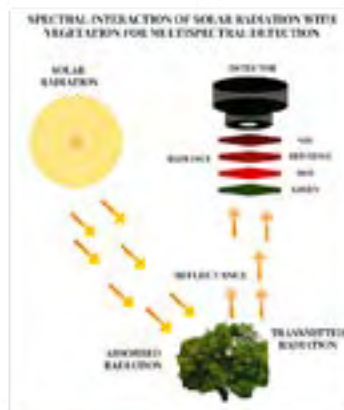


Fig. 1: Solar radiation strikes vegetation, where part of the energy is absorbed, another portion is transmitted through the leaves, and a fraction is reflected. The multispectral sensor captures the reflected radiation in different spectral bands, allowing the characterization of the vegetation's physiological state.

These sensors capture spectral information at different wavelengths, enabling the assessment of photosynthetic activity and the physiological state of the crop through vegetation indices such as the Normalized Difference Vegetation Index (NDVI), Green Normalized Difference Vegetation Index (GNDVI), Normalized Difference Red Edge Index (NDRE), Optimized Soil-Adjusted Vegetation Index (OSAVI), and Soil-Adjusted Vegetation Index (SAVI), which are widely used for detecting plant stress [6].

The cellular structure of leaves significantly influences the way they reflect electromagnetic radiation [7]. The **palisade mesophyll** is the primary photosynthetic region of the leaf, efficiently absorbing light in the blue ( $0.43\ \mu\text{m}$ ) and red ( $0.66\ \mu\text{m}$ ) bands, while the green band ( $0.54\ \mu\text{m}$ ) is more strongly reflected, giving the leaf its characteristic color [7].

The **spongy mesophyll**, with its intercellular spaces, internally scatters light, a notable effect in the NIR ( $0.7 - 1.2\ \mu\text{m}$ ), where reflectance increases due to the air-cell interaction within the leaf tissue [7]. Understanding this spectral interaction is essential for the accurate interpretation of multispectral images and the evaluation of crop physiological status.

Nutritional deficiencies in avocado crops have been identified through the visual analysis of specific symptoms on the leaves. These deficiencies affect the plant's physiology and can be detected based on their impact on leaf reflectance across different spectral bands [8].

- **Nitrogen (N)**: Its deficiency causes uniform chlorosis in older leaves due to reduced chlorophyll synthesis [8]. It can be detected using indices such as NDVI and GNDVI, which reflect light absorption in the R band [6].
- **Potassium (K)**: It manifests as necrosis on the leaf edges with a chlorotic halo around the affected area [8]. Changes in reflectance in the RE and NIR bands can indicate the presence of this deficiency [6].
- **Phosphorus (P)**: It appears as brown or purple spots on the leaves [8], with alterations in NIR reflectance, reflecting changes in water and protein content [6].
- **Calcium (Ca)**: In young leaves, its deficiency causes necrosis at the tips and deformations [8]. Its detection is based on decreased reflectance in the G and NIR spectrum [6].

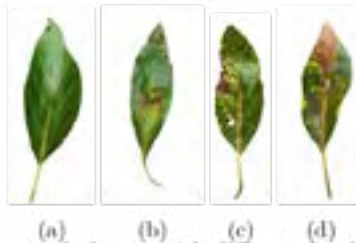


Fig. 2: Comparison of avocado leaves with different levels of nutritional deficiencies: (a) no symptoms, (b) mild, (c) moderate, and (d) severe.

## 2 Related Work

The use of multispectral imagery for detecting nutritional deficiencies in crops has been widely studied, demonstrating the effectiveness of vegetation indices in identifying physiological issues in plants and enabling early detection of nutritional deficiencies [2, 3].

Previous studies have applied various machine learning and CNN-based approaches for crop analysis. For example, in [3], a CNN was used to classify avocado leaves affected by thrips, demonstrating the effectiveness of deep learning in identifying foliar diseases. Other recent and highly relevant studies have employed neural networks to detect deficiencies and predict nitrogen (*N*) percentages in gulupa leaves, using multispectral images combined with segmentation techniques to enhance model accuracy, yielding very promising results [2].

Drones equipped with multispectral cameras have been widely used in precision agriculture due to their ability to capture high-resolution images across multiple spectral bands [4, 7]. Their use, in combination with artificial intelligence techniques, has shown promising results in the automatic detection of crop anomalies. While there are studies on the use of CNNs and vegetation indices in agriculture, their specific application in the classification of avocado leaves still requires further research.

## Methodology

This study proposes a methodology for the binary classification of avocado leaves using multispectral imaging and deep learning, leveraging the effectiveness of convolutional neural networks (CNNs) in agricultural pattern recognition [2]. Unlike previous research, this approach integrates five vegetation indices (NDVI, GNDVI, NDRE, OSAVI, and SAVI) as inputs for a CNN, optimizing the detection of nutritional deficiencies. The fusion of multispectral data with artificial intelligence enhances classification accuracy, enabling more informed decision-making in precision agriculture [2,6].

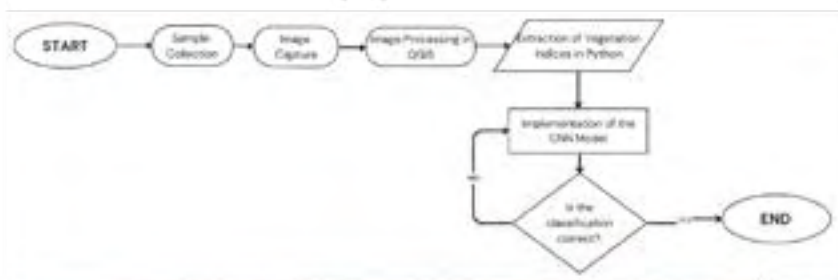


Fig. 3: Flowchart of the methodology used in this study.

The research was conducted at two institutions: (1) the Association of Producers and Packers of Avocados of Mexico (APEAM), where sample collection, visual classification of leaves, and multispectral image acquisition were performed, and (2) the Center for Exact Sciences and Engineering of the University of Guadalajara (CUCEI), where image processing, data analysis, and the development of the CNN model were carried out.

### 3.1 Leaf Collection

Hass avocado leaf samples were collected from an orchard located in Salvador Escalante, Michoacán, bordering Cuitzán and Santa Clara del Cobre. The orchard spans 43 hectares. The leaf collection was conducted in collaboration with an agronomist specializing in avocado orchards, who assessed symptoms associated with nutritional deficiencies and visible diseases in the leaves, focusing on deficiencies of N, P, K, Ca, B, and Zn [8].

The collected leaves were transported to the Asociación de Productores y Empacadores Exportadores de Aguacate de México (APEAM), where a secondary classification was performed based on identified deficiencies. A total of 134 leaves were photographed for analysis and labeled into two categories: (1) healthy leaves, showing no visible deficiency symptoms, and (2) affected leaves, exhibiting signs of nutritional stress.

### 3.2 Multispectral Image Acquisition

The capture of multispectral images was conducted using the DJI Mavic 3M drone, which is equipped with a multispectral camera equipped with four 5-megapixel sensors, designed to capture information in the following bands:

- **G:** 560 nm  $\pm$  16 nm
- **R:** 650 nm  $\pm$  16 nm
- **RE:** 730 nm  $\pm$  16 nm
- **NIR:** 860 nm  $\pm$  26 nm

Thanks to these features, the DJI Mavic 3M is a high-precision tool for smart farming, enabling detailed crop development monitoring and early detection of nutritional deficiencies [4].

To capture the images, a custom mount was implemented to achieve the necessary height for the camera to focus on the leaves. Additionally, a black background was used to prevent shadows or noise in the reflectance. The photographs were taken using sunlight as the reflectance source.



Fig. 4: DJI Mavic 3M drone used for multispectral image capture.

### 3.3 Initial Image Processing in Quantum Geographic Information System (QGIS)

The captured images were processed in QGIS, where georeferencing was applied to align them with geographic coordinates, spectral calibration was performed to correct distortions, and raster segmentation was used to isolate avocado leaves, removing noise. Finally, the four multispectral bands (G, R, RE, NIR) were combined for each leaf, generating a complete spectral representation for analysis.

<sup>2</sup> QGIS® is a registered trademark of the QGIS Development Team.

<sup>3</sup> Python® is a registered trademark of the Python Software Foundation.

<sup>4</sup> OpenCV® is a registered trademark of OpenCV.org.



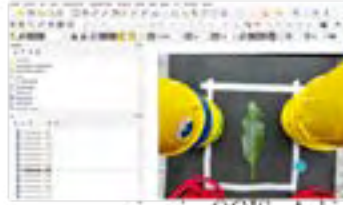


Fig. 5: Multispectral image processing in QGIS. A higher resolution image is available at the link in the supplementary material section.

### 3.4 Dataset and Data Augmentation

To enhance the model's generalization capability and compensate for the limited size of the original dataset, various strategies were implemented to expand the available information for deep learning, including data augmentation, which is explained later in the text. It is important to highlight that although the initial dataset consists of 81 multispectral images, each image is composed of four spectral bands (G, R, RE, and NIR) resulting in a total of 324 individual spectral representations. Additionally, statistical data extraction from five vegetation indices was performed.

### 3.5 Image Processing and Vegetation Index Extraction

Image processing was performed in Python using Rasterio and OpenCV for raster data manipulation. From the multispectral images, five vegetation indices were computed to assess photosynthesis, chlorophyll content, and cellular structure, providing an accurate estimation of vegetative health.

- **NDVI:** Uses the NIR and R bands. It is calculated using the following formula:

$$NDVI = \frac{NIR - R}{NIR + R} \quad (1)$$

This index is used to assess biomass and photosynthetic activity in leaves. In this study, healthy leaves are expected to have higher NDVI values due to greater absorption in the red band and higher reflectance in the NIR band [6].

- **GNDVI:** Uses the NIR and G bands. Its formula is:

$$GNDVI = \frac{NIR - G}{NIR + G} \quad (2)$$

This index is more sensitive to chlorophyll concentration in leaves compared to NDVI. In healthy leaves, a high GNDVI value is expected, indicating a high photosynthetic capacity. In leaves with **N**, **P**, or **K** deficiencies, GNDVI values are likely to decrease due to reduced chlorophyll production and the onset of chlorosis [6].



- **NDRE**: Uses the NIR and RE bands. It is expressed as:

$$NDRE = \frac{NIR - RE}{NIR + RE} \quad (3)$$

NDRE is particularly useful for detecting early-stage stress, as the RE band is more influenced by the internal cellular structure of leaves. In leaves with visible symptoms of **Ca** and **Zn** deficiencies, NDRE tends to be lower due to cellular damage and reduced nutrient transport efficiency [6].

- **OSAVI**: This index adjusts for soil influence in vegetation measurements. It is defined as:

$$OSAVI = \frac{(NIR - R)}{(NIR + R + 0.16)} \quad (4)$$

Unlike NDVI, OSAVI corrects for soil effects, making it useful in conditions where vegetation is not dense [6].

- **SAVI**: The SAVI index is a variation of NDVI that incorporates a soil correction factor  $L$ , which is useful in areas with intermediate vegetation cover ( $L = 0.5$ ). Its equation is:

$$SAVI = \frac{(NIR - R)}{(NIR + R + L)}(1 + L) \quad (5)$$

In this study, it is used to assess leaf hydration. Low values indicate water stress or severe nutritional deficiencies due to reduced water absorption and alterations in NIR reflectance [6].



Fig. 6: Comparison of multispectral images in the four spectral bands. (a) Avocado leaves with no visible symptoms of nutritional deficiencies. (b) Avocado leaves showing visible symptoms of nutritional deficiencies. High-resolution images are available in the supplementary material section.

## 4 Statistical Analysis of Vegetation Indices

The statistical data for the five vegetation indices used in the analysis of avocado leaves are presented below. The data include the mean, minimum, maximum, variance, and standard deviation.<sup>5</sup>

<sup>5</sup> Statistical data can be accessed at: <https://drive.google.com/drive/folders/1y1AxyrNt-nRh2wIdKnbwYnnw8zgvrOf?usp=sharing>.

Table 1: Statistical Data of NDVI

| Leaf            | Mean    | Minimum | Maximum | Variance | Std. Dev. |
|-----------------|---------|---------|---------|----------|-----------|
| No Symptoms 1   | -0.2405 | -0.9999 | 0.4231  | 0.1005   | 0.3171    |
| No Symptoms 2   | -0.2232 | -0.9999 | 0.5338  | 0.0952   | 0.3085    |
| With Symptoms 1 | -0.3026 | -0.6551 | 0.4127  | 0.1014   | 0.3185    |
| With Symptoms 2 | -0.2739 | -0.5631 | 0.4457  | 0.1104   | 0.3322    |

Healthy leaves exhibit higher NDVI values (-0.14 to -0.33), whereas those with symptoms show lower NDVI values (-0.28 to -0.38), indicating lower light absorption in the red band and reduced photosynthetic efficiency.

Table 2: Statistical Data of GNDVI

| Leaf            | Mean    | Minimum | Maximum | Variance | Std. Dev. |
|-----------------|---------|---------|---------|----------|-----------|
| No Symptoms 1   | -0.2037 | -0.9999 | 0.3651  | 0.0566   | 0.2378    |
| No Symptoms 2   | -0.2277 | -0.9999 | 0.3051  | 0.0533   | 0.2308    |
| With Symptoms 1 | -0.1569 | -0.7199 | 0.4498  | 0.0568   | 0.2384    |
| With Symptoms 2 | -0.1757 | -0.6572 | 0.5999  | 0.0719   | 0.2681    |

GNDVI shows that unhealthy leaves exhibit greater chlorophyll variability and lower light absorption in the green band, indicating physiological stress. Its usefulness lies in the early detection of nutritional deficiencies, as the damage is progressive and non-uniform.

Table 3: Statistical Data of NDRE

| Leaf            | Mean    | Minimum | Maximum | Variance | Std. Dev. |
|-----------------|---------|---------|---------|----------|-----------|
| No Symptoms 1   | -0.0289 | -0.3801 | 0.9999  | 0.0053   | 0.0726    |
| No Symptoms 2   | -0.0368 | -0.3203 | 0.9999  | 0.0056   | 0.0746    |
| With Symptoms 1 | -0.0127 | -0.5855 | 0.3884  | 0.0050   | 0.0707    |
| With Symptoms 2 | -0.0309 | -0.3427 | 0.4221  | 0.0053   | 0.0725    |

NDRE shows that unhealthy leaves exhibit greater variability in red edge light absorption, indicating early structural changes in the leaf. Its variability makes it useful for detecting stress before symptoms become visible.

Table 4: Statistical Data of OSAVI

| Leaf            | Mean    | Minimum | Maximum | Variance | Std. Dev. |
|-----------------|---------|---------|---------|----------|-----------|
| No Symptoms 1   | -0.1648 | -0.8581 | 0.3588  | 0.0606   | 0.2461    |
| No Symptoms 2   | -0.1534 | -0.8576 | 0.4726  | 0.0592   | 0.2434    |
| With Symptoms 1 | -0.2266 | -0.5575 | 0.3652  | 0.0644   | 0.2537    |
| With Symptoms 2 | -0.1941 | -0.4618 | 0.3895  | 0.0677   | 0.2601    |

OSAVI shows that unhealthy leaves exhibit lower values compared to healthy ones, indicating reduced reflectance in the NIR band.

Table 5: Statistical Data of SAVI

| Leaf            | Mean    | Minimum | Maximum | Variance | Std. Dev. |
|-----------------|---------|---------|---------|----------|-----------|
| No Symptoms 1   | -0.1437 | -0.9889 | 0.4067  | 0.0657   | 0.2562    |
| No Symptoms 2   | -0.1334 | -0.9877 | 0.5699  | 0.0668   | 0.2584    |
| With Symptoms 1 | -0.2202 | -0.6351 | 0.4412  | 0.0722   | 0.2687    |
| With Symptoms 2 | -0.1763 | -0.5011 | 0.4608  | 0.0737   | 0.2715    |

SAVI indicates that unhealthy leaves have more negative values compared to healthy ones, suggesting lower water content and structural alterations in the leaf. Their lower reflectance in the NIR band confirms the presence of physiological stress.

## 5 CNN Architecture

### 5.1 Environment Setup and Libraries

For the development of the model, numerical processing and multispectral image manipulation libraries were used, such as `NumPy`, `rasterio`, `OpenCV`, and `TensorFlow`. The core code was implemented in `Python`, using `Keras` for building the CNN.

### 5.2 Calculation and Analysis of Vegetation Indices

From the multispectral images, five vegetation indices were calculated. Additionally, their statistical features were extracted to enrich the dataset and improve classification in the CNN.

### 5.3 Image Preprocessing

The multispectral images in `.tif` format were processed using `rasterio` and resized to  $224 \times 224$  pixels for use in the CNN. The preprocessing steps included calculating vegetation indices, extracting statistical features, and labeling the images as either 'leaf without symptoms' or 'leaf with symptoms'.

### 5.4 Feature Vector Construction

A feature vector was created by combining the normalized multispectral image ( $224 \times 224 \times 4$ ) with a set of 25 statistical features from the vegetation indices. This combination allows the CNN to leverage both spatial information and numerical metrics, enhancing classification accuracy.

### 5.5 Data Loading and Concatenation

The images and labels from both groups were loaded and concatenated into a single data matrix, along with the statistical features of the vegetation indices.

## 5.6 Dataset Splitting

To ensure proper generalization of the model, the dataset was divided into two subsets:

- **Training (80%):** Used to adjust the model's weights during the learning process.
- **Testing (20%):** Used to evaluate the model's performance on unseen data and assess potential overfitting issues.

The partitioning was performed using the `train_test_split()` function from *Scikit-learn*, setting the `random_state` parameter to 42 to ensure experiment reproducibility.

## 6 CNN Model Design

### 6.1 Dual-Input Model

To improve the classification of avocado leaves, a CNN model with a dual-input architecture was designed. This approach allows the combination of visual information from multispectral images with numerical statistics from vegetation indices, providing a more comprehensive representation of each sample.

### 6.2 Image Processing Pathway

The model processes multispectral images of size  $224 \times 224 \times 4$  (corresponding to the G, R, RE, and NIR bands) through three convolutional layers with  $3 \times 3$  filters, each followed by a non-linear activation function and a *MaxPooling* layer to reduce dimensionality. Several activation functions were tested, including *LeakyReLU*, *ReLU*, *Sigmoid*, *Tanh*, *ELU*, *SELU*, *Softplus*, *Softsign*, *Swish*, and *GELU*, to evaluate their effectiveness in classification.

### 6.3 Statistics Pathway

A second input channel processes a vector containing 25 features extracted from the NDVI, GNDVI, NDRE, OSAVI, and SAVI indices. This vector is processed through a fully connected layer with 64 neurons, using the activation function selected in each experiment.

### 6.4 Fusion and Classification

Both pathways are combined through a concatenation layer, followed by a dense layer with 128 neurons and a non-linear activation function. A *Dropout* layer with a 50% rate was applied to reduce overfitting. Finally, a single neuron with a sigmoid activation function generates the binary classification prediction (healthy or affected leaf).



6.5 Compilation and Optimization

The model was compiled using the *binary cross-entropy* loss function and the *Adam* optimizer with a learning rate of 0.0001. The performance of each activation function were compared in terms of accuracy, loss, and training time.

6.6 Model Training and Configuration

The CNN model was trained using a dataset that combines multispectral images ( $224 \times 224 \times 4$ ) and a statistical feature vector containing 25 characteristics extracted from vegetation indices.

To enhance the model's generalization ability and reduce overfitting, *data augmentation* was applied using *ImageDataGenerator*. The applied transformations included:

- Random rotation of up to 20°.
- Horizontal and vertical shifts of up to 20%.
- Shear transformations.
- Random zoom of up to 20%.
- Horizontal image flipping.

Training was performed with a batch size of 8, the *Adam* optimizer ( $lr = 0.0001$ ), and the *binary cross-entropy* loss function, for a total of 100 epochs.

6.7 Evaluated Activation Functions

To optimize the model's performance, various activation functions were tested in the convolutional layers. The comparative results in terms of accuracy, loss, and training time are presented in Table 6.

| Activation Function | Accuracy (%) | Loss   | Time (s) |
|---------------------|--------------|--------|----------|
| LeakyReLU           | 94.12        | 0.2028 | 190.40   |
| ReLU                | 100.00       | 0.0484 | 188.05   |
| Sigmoid             | 35.29        | 0.7014 | 191.15   |
| Tanh                | 100.00       | 0.0553 | 191.85   |
| ELU                 | 100.00       | 0.1215 | 195.92   |
| SELU                | 100.00       | 0.0391 | 195.88   |
| Softplus            | 35.29        | 0.6948 | 213.70   |
| Softsign            | 100.00       | 0.0890 | 192.22   |
| Swish               | 94.12        | 0.1351 | 228.14   |
| GELU                | 100.00       | 0.0507 | 250.25   |

Table 6: Comparative results of activation functions.



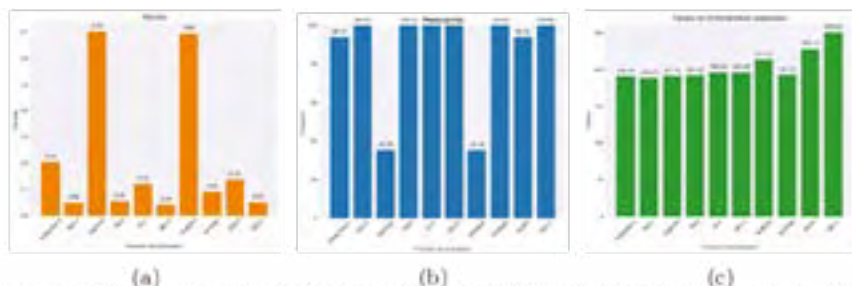


Fig. 7: Comparison of activation functions based on (a) loss , (b) accuracy , and (c) training time (seconds). High-resolution images are available in the supplementary material section.

As observed in Table 6, the ReLU, Tanh, SELU, Softsign, and GELU functions achieved high accuracy after 100 epochs, with variations in loss and training time. SELU performs well with low loss, while ReLU is one of the fastest and most effective activation functions.

Functions such as Sigmoid and Softplus are not suitable for this problem due to their low accuracies and high losses.

GELU provides a good balance between accuracy and loss; however, its high training time makes it less efficient for time-sensitive tasks.

## 7 Results and Analysis

### 7.1 Model Evaluation and Metrics

The model's performance was evaluated on the test set (20% of the data) to assess its generalization capability on unseen data. Metrics such as accuracy and loss were computed for both training and validation, along with the confusion matrix to identify false positives and false negatives. These metrics were used to monitor learning stability and detect potential overfitting issues. The obtained metrics were as follows:

<sup>3</sup> For better visualization, high-resolution images are available at: <https://drive.google.com/drive/folders/1yIAxyrnHt-nRh2wIdKmbwYnnv82gvRof?usp=sharing>.

| Leaf Type         | Precision | Recall | F1-score |
|-------------------|-----------|--------|----------|
| No Symptoms (0)   | 1.00      | 1.00   | 1.00     |
| With Symptoms (1) | 1.00      | 1.00   | 1.00     |

Table 7: Classification metrics of the CNN model.

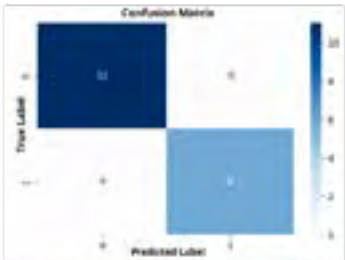


Fig. 8: Confusion matrix of the CNN model.

The CNN model achieved perfect classification, with 100% accuracy, recall, and F1-score. The confusion matrix indicates zero errors, correctly classifying all leaves with and without symptoms.

The accuracy and loss curves during training are presented in Figure 9:

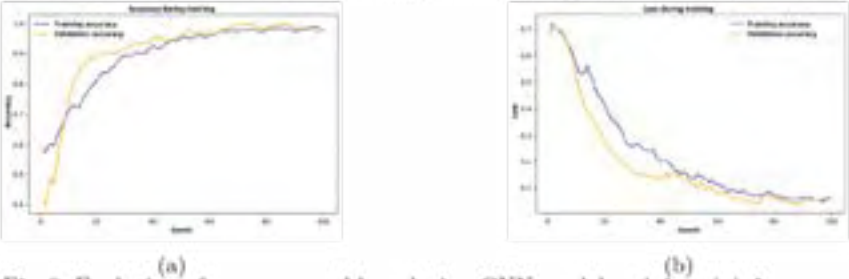


Fig. 9: Evolution of accuracy and loss during CNN model training. (a) Accuracy during training and validation, showing a progressive improvement in model performance. (b) Loss during training and validation, illustrating a gradual decrease in error. Both metrics stabilize over time, indicating that the model has reached optimal convergence without significant overfitting. High-resolution images are available in the supplementary material section.

## 8 Discussion

The obtained results demonstrate the effectiveness of the dual-input CNN model in classifying avocado leaves with and without symptoms of nutritional deficiencies. The combination of multispectral images and statistical vegetation index data improved the model's accuracy, achieving 100% accuracy on the test set.

The activation function analysis showed that *ReLU*, *SELU*, and *GELU* achieved better performance in terms of accuracy and loss, while *Sigmoid* and *Softplus* exhibited lower performance. Additionally, the NDVI and GNDVI indices revealed reduced photosynthetic activity in affected leaves, validating their usefulness in detecting nutritional stress.

The use of *data augmentation* helped prevent overfitting and improve the model's generalization, although some activation functions increased training time.

Despite the positive results, the dataset size remains a limitation. Although 324 multispectral images were processed, the combination of the four bands reduced the final dataset to only 81 images for training. Expanding the dataset and implementing a multiclass classification approach would enhance the model's capability, allowing for a more precise differentiation of foliar conditions. Additionally, incorporating nutrient concentration prediction, utilizing more spectral bands, and evaluating more advanced models could further optimize the system's accuracy.

## 9 Conclusion

This study confirms that combining multispectral images and statistical vegetation index data in a dual-input CNN model is an effective strategy for classifying avocado leaves based on their physiological state.

The model achieved 100% accuracy, demonstrating its ability to identify symptoms of nutritional deficiencies in avocado crops. The choice of activation functions significantly influenced the model's performance, with *ReLU*, *SELU*, and *GELU* being the most effective.

To further enhance the model's robustness, it is recommended to expand the dataset, explore the use of pre-trained neural networks, and consider self-supervised learning approaches. These advancements will improve the early detection of nutritional stress in crops, contributing to the development of precision agriculture.

## Acknowledgments

Special thanks to Ing. Samuel Carbajal Mercado, the Association of Producers and Exporters of Avocado from Mexico, for their support during the research.

## Supplementary Material

To facilitate access to the visual data used in this study, high-resolution images and statistical data can be found at the following link:

<https://drive.google.com/drive/folders/1yIAxyrNt-nRh2wYdKnwYnnw8zgwRoI?usp=sharing>

This supplementary material includes expanded versions of the figures presented in the document, allowing for better visualization and analysis of relevant details.

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# Within-subject vs. Multi-Subject Eye Movement Classification: A Comparative Study

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**Abstract.** People with speech disabilities face significant communication challenges, especially those with motor impairments that prevent them from using sign language. To address this issue, eye movement-based communication systems like Blink to Speak (BTS) have been developed, allowing users to convey messages through eight eye movement alphabets. This study evaluates the classification of BTS alphabets using electrooculography (EOG) signals, comparing two approaches: within-subject (WS) and between-subject (BS). A dataset of EOG signals from 38 subjects was used to train and test a Random Forest model, selected for its superior performance in BS classification. Results show that WS classification generally outperforms BS, with F1-score improvements in 33 out of 38 subjects and across all alphabets. Alphabets with lower inter-subject similarity, such as "Wink", "Roll" and "Left" achieved the most significant improvements in WS, while those with high similarity, like "Down" and "Blink," showed less enhancement. Despite the superior performance of the WS approach, it requires an extensive data collection and calibration process, which may hinder practical implementation. Future work should consider balancing quick adaptability (favoring BS classification) and model accuracy (favoring WS classification), depending on user needs and application context.

**Keywords:** Blink to Speak, Electrooculography, Machine Learning Algorithms, Multi-Subject, Speech disability, Within-subject.

## 1 Introduction

### 1.1 Speech disability

Communication is a fundamental process for human interaction that allows transmission of information, thoughts and emotions. Although non-verbal communication through gestures, symbols or elements may exist, verbal communication through speech facilitates direct expression and immediate feedback [1].

Unfortunately, there are some conditions, such as phonological disorders, in which speech can be affected, thereby impacting the quality of life of those who suffer from

<https://doi.org/10.61728/AE20255152>



them. In 2020 alone, National Institute of Statistics and Geography reported that 945,000 Mexicans are affected by these conditions, presenting speech disabilities [2]. While sign language may be an option for communication for these individuals, it is not for those suffering from amyotrophic lateral sclerosis, motor neuron disease, severe motor disabilities or neurodegenerative disorders, as they cannot use this language due to limitations in upper limb movement that characterize these types of diseases [3].

## **1.2 Devices for people with communication difficulties**

In recent years, technological advances have enabled development of devices that help meet communication needs of people with speech disabilities. Among these, Human-Computer Interfaces (HCIs) stand out, as they allow interaction between humans and devices through bioelectrical signals captured from different parts of body [4]. HCIs focused on communication typically capture brain activity [5], subvocal signals [6] and ocular signals [7], serving as effective alternatives for individuals with limited mobility.

In addition to these technological developments, communication languages based on ocular activity have been created: "Blink to Speak" (BTS) and "Blink to Live", the latter being inspired by the former [8]. BTS represents an innovative ocular language intended for universal application, featuring fifty everyday messages that support communication between patients and their caregivers or family members. This language is based on eight alphabets characterized by execution of relatively simple ocular movements such as closing eyes, blinking, moving eyes to left, moving eyes to right, moving eyes up, moving eyes down, winking and executing an ocular rotation with both eyes, that is an ocular turn in three quadrants. For simplicity, these eight alphabets are known respectively by following names: 1) Close, 2) Blink, 3) Left, 4) Right, 5) Up, 6) Down, 7) Wink and 8) Rotate (see Fig. 1). The combination of one or several of these alphabets gives rise to ocular movement patterns that represent messages. Some of messages are: "I feel like eating", which is communicated with Up and Down alphabets; "Call the doctor", expressed with a blink and a movement to left; and "I'm proud of you", represented by two consecutive blinks followed by closing eyes [9].

Interpreting BTS language can be a tedious process that requires significant attention from receiver, which makes it prone to errors. In this context, augmentative and alternative communication systems offer great assistance by proposing various solutions based on monitoring of ocular movements [10, 11].

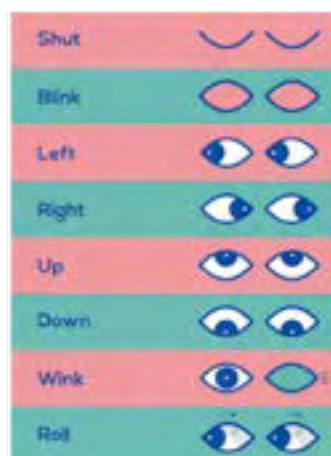


Fig. 1. Alphabets of Blink to Speak [9].

## 2 Related works

Studies found in state-of-art focused on interpreting BTS language messages are few and limited to recognizing only two alphabets [12, 13], in addition to fact that ocular movement patterns are not always interpreted as described in the BTS language manual [9]. Therefore, a search is conducted for works focused on activity of interest: monitoring of ocular activity.

### 2.1 Systems for eye movement monitoring

There are two main approaches to detecting ocular patterns: computer vision-based systems and sensor-based systems. Regarding computer vision-based systems, simple and affordable solutions have been presented, such as in [8], where a language of 64 messages is proposed using only 4 key alphabets based on BTS. This acquisition method is viable for classifying alphabets included in that language, but it is not suitable for BTS language since it cannot differentiate between moving eyes down and blinking. Another related work uses video frames, in which, by detecting 6 reference points around eye area, blinks are identified and counted, assigning interpretations to 4 patterns according to BTS language. The disadvantage of this work is that messages to be interpreted are limited, as only blinks can be counted [14].

Alternatively, there are sensor-based eye pattern recognition systems: in [15] an infrared sensor is used to count blinks and represent seven messages, two of these corresponding to BTS language. In addition, use of infrared reflectometry in an eye tracking system [16] stands out, where pupils are detected to identify eye movements. Another way to detect them is through magnetic field sensors, where the position of eye is detected by means of a special contact lens placed on eyeball [17]. Although these systems offer advantages, such as detection of specific patterns, some of them are limited by



need to control external factors such as lighting and position of detection device, as well as complication in detection of some movements related to alphabets of BTS language when position of pupil remains in the same position, as in the case of blinking since only eyelid moves and when at rest pupil remains looking towards center. Another sensor-based system is electrooculography (EOG), which has shown promising results for identifying users of BTS language alphabets, without posing a risk [7]. Work has been developed in which eye movement patterns composed of up to 4 movements considered as alphabets (left, right, up and down) are classified [18–20], with performances around 75% accuracy. Its reported good performance and practicality of its implementation, without need to control external conditions such as lighting, highlights it as a viable alternative.

However, the need for an EOG-based system that interprets BTS language messages is present, which is why research focused on interpretation of this language has been developed in recent years.

## **2.2 Systems for interpreting the alphabets of the Blink to Speak language**

Advanced works currently in state-of-art focused on interpretation of BTS language are based on EOG signals. First of them works with 10 messages of BTS language selected according to complexity of message and its communicative intention. EOG activity corresponding to each message is recorded in 20 subjects, from which features are extracted to train a decision tree model. 83.4% of accuracy of multiclass classification is reported. However, classification is dependent on length of record, which makes classification difficult when all messages of BTS language are to be classified [21].

Another study examines the classification of messages of BTS language from a general perspective, classifying 8 alphabets that make up the language [22]. This work records in 38 subjects EOG activity coming from 3 channels in bipolar configuration (horizontal channel, right channel and left channel). Each subject performs a series of 5 eye movements corresponding to each of alphabets of BTS language. EOG records are segmented to extract repetitions individually and they are featured in order to form dataset with which machine learning classifier models are trained. Random Forest (RF), Multi-Layer Perceptron Classifier and Decision Tree are tested, obtaining highest F1-score of 82% with RF model. This multiclass classification is performed considering records of all subjects, which makes it a between-subjects classification, however, there are also works that perform within-subject EOG signal classification.

## **2.3 Within-subject and between-subject classification of electrooculographic signals**

EOG signal classification can be approached from two main approaches: within-subject (WS) and between-subject (BS). In the WS approach, model is trained and tested using data from same subject, which allows capturing individual characteristics of signals. However, BS classification involves use of records from multiple subjects, which presents challenge of interindividual variability, but offers a more generalizable system to new users [23]. This distinction is crucial for development of personalized or universal

interfaces oriented to communication. Selection between these approaches depends on application and balance between desired precision and generalization in EOG eye movement recognition system.

Table 1 presents some of works found for classification of EOG signals corresponding to individual eye movements that in this context are considered alphabets of BTS language, regardless of their implementation. It is highlighted whether their classification is WS or BS.

**Table 1.** Within-subject and between-subject electrooculography activity classification work.

| Work | WS or BS | Number of records and/or subjects used                 | Eye movements recognized | Results                                      |
|------|----------|--------------------------------------------------------|--------------------------|----------------------------------------------|
| [24] | BS       | 3 subjects, each performed 6 sequences of 12 movements | Left, right, up and down | 94.11% correct                               |
| [25] | BS       | 3 subjects, each performed 5 times each movement       | Left, right, up and down | Statistically significant features by ANNOVA |
| [26] | WS       | 4 subjects, each performed 56 movements                | Left and right           | 96.9% Accuracy (classifier not reported)     |
| [27] | WS       | 5 subjects, 10 repetitions of each movement            | Left, right, up and down | 100% separable features                      |
| [28] | BS       | 10 subjects, 5 movement sequences                      | Shut, up and wink        | SVM classifier with 78% Accuracy             |
| [29] | BS       | 12 subjects, each performed 10 movement sequences      | Left and right           | KNN classifier with 99% F1-score             |
| [19] | WS       | 30 repetitions between the 4 movements                 | Left, right, up and down | MLP classifier with 75% Precision            |
| [20] | WS       | Sequence of the 4 movements during 10 seconds          | Left, right, up and down | SVM classifier with 76.9% Jaccard index      |

Although classification of EOG records corresponding to eye movements considered as alphabets of BTS language shows good performance, it is desired to know if for classification of all alphabets that make up BTS language it is convenient to perform a BS classification as reported in [22] or a WS classification.

### 3 Methodology

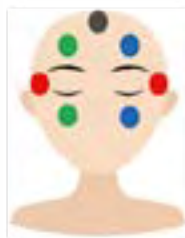
In order to make comparison between BS and WS classification, it is proposed to use dataset used in [22]. Next, we explain how it is composed and the analysis of similarities found in EOG records, which is why we decided to carry out this work.

Regarding WS classification, Random Forest model is used, which is machine learning model that obtains the best F1-score in BS classification.



### 3.1 Data Used

Dataset used to train classifier model is made up of features extracted from recorded EOG signals. Ocular activity was recorded using 7 gold cup electrodes in a bipolar configuration around eye area (see Fig. 2). It should be noted that recording was carried out under the approval of research protocol of University of Guadalajara, CUCS campus, with folio 24-16.



**Fig. 2.** Placement of gold cup electrodes for bilateral EOG recording (red electrodes for horizontal channel recording, green for right channel, blue for left channel and black for reference) [22].

Features were extracted from separate EOG channels: horizontal, right and left channels, and from signals resulting from combination of separate channels, such as subtraction of horizontal channel minus right channel, horizontal channel minus left channel and subtraction of right channel minus left channel, as well as sum of 3 separate channels. Arithmetic mean, variance, kurtosis, skewness, area under the curve, difference between maximum and minimum values and coefficients of a degree 5 polynomial of separate channels are calculated. As for characterization of signals resulting from combination of channels, they are characterized with arithmetic mean, variance, kurtosis, skewness, area under the curve and difference between maximum values (this last feature is not extracted from the sum signal of 3 channels). It should be noted that before extracting features, each record is added to its minimum value in order to ensure that all its values are positive and thus avoid arithmetic means close to zero.

Pearson correlation is calculated for 59 features calculated from EOG records and one of features with a correlation greater than  $\pm 0.9$  is eliminated. In total, 21 attributes were eliminated, corresponding to arithmetic means and attributes from sum signal of 3 channels, except for area under the curve. Resulting data set with which the classifier models are trained and tested is composed of 38 attributes corresponding to the features obtained from EOG records and 1498 instances, belonging to repetitions of alphabets of BTS language that could be extracted from the 38 test subjects.

### 3.2 Similarity in electrooculographic recordings

In studies focused on BS classification, a comparison is conducted by analyzing average repetitions of each subject across different BTS alphabets (see Fig. 3).

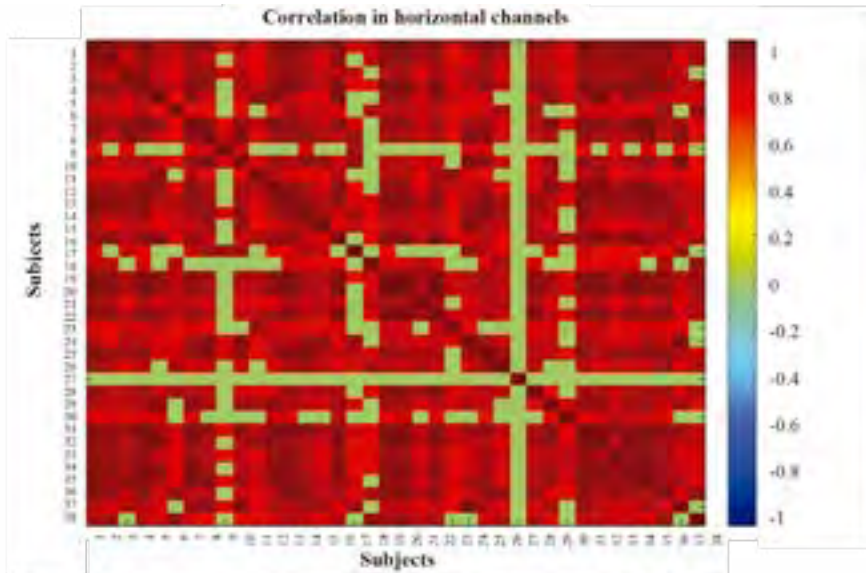


Fig. 3. Correlation matrix between the “Blink” alphabets in its horizontal channel: Modified from [22].

Correlations greater than 0.7 are counted and shown as a descending percentage in Table 2, where alphabets that appear at beginning of table are more replicable between different subjects, that is, they are more similar between different people and last ones are those that are made with greater differences between different people.

Table 2. Similarity between within-subject models of alphabets by channel. Modified from [22].

| Alphabets | Horizontal Channel | Right Channel | Left Channel | Percentage of similarity between different subjects |
|-----------|--------------------|---------------|--------------|-----------------------------------------------------|
| Down      | 90.33 %            | 93.03 %       | 93.31 %      | 92.22 %                                             |
| Blink     | 83.93 %            | 90.18 %       | 90.04 %      | 88.05 %                                             |
| Up        | 46.23 %            | 72.40 %       | 70.55 %      | 63.06 %                                             |
| Right     | 95.59 %            | 60.46 %       | 30.87 %      | 62.30 %                                             |
| Shut      | 52.49 %            | 54.34 %       | 54.62 %      | 53.82 %                                             |
| Left      | 79.66 %            | 54.20 %       | 18.78 %      | 50.88 %                                             |
| Roll      | 41.11 %            | 45.09 %       | 30.61 %      | 38.74 %                                             |
| Wink      | 13.51 %            | 20.91 %       | 13.51 %      | 15.98 %                                             |

Originally, comparison of each alphabet by channel is used to determine whether or not it is feasible to eliminate a recording channel. In context of this work, it is used to define alphabets that are most similar between different subjects. As observed in Table 2, "Down" and "Blink" are quite similar between different people, so in WS classification is not expected to improve for these particular alphabets. However, it is observed that "Wink", "Roll" and "Left" are very different between different subjects, so classification performance is expected to improve.

### 3.3 Training and testing of Random Forest

Since a comparison with BS classification results is desired, it is decided to use algorithm with the best reported F1-score, which is Random Forest. It is decided to take F1-score metric as a reference for performance of classification model since it is metric that encompasses precision and recall.

It is desired to obtain performance of WS models, that is, for each of 38 subjects that make up dataset, a Random Forest algorithm will be trained and tested, all with the same configuration. For each of subjects, only instances of dataset that belong to it are selected (around 40 instances) and data is divided randomly and stratified in order to ensure balance in number of instances per class both in training and testing. 60% of data is used for training and 40% for testing, and it is validated with cross-correlation. For each subject, model is trained and tested 20 times, using different training and testing data in each iteration, and average performance is reported at the end of 20 iterations.

## 4 Results and Discusión

Table 3 shows F1-score metric obtained from average of 20 iterations of Random Forest model, for each of subjects. Average performance of model and performances for each BTS alphabet are reported.

**Table 3.** F1-score performances for within-subject models.

| Subjects  | Average F1-score | Shut    | Blink   | Left    | Right   | Up      | Down    | Wink    | Roll    |
|-----------|------------------|---------|---------|---------|---------|---------|---------|---------|---------|
| Subject 1 | 88.04%           | 100.00% | 69.00%  | 76.17%  | 100.00% | 86.67%  | 73.50%  | 100.00% | 99.00%  |
| Subject 2 | 86.27%           | 94.67%  | 62.17%  | 100.00% | 92.33%  | 72.67%  | 89.00%  | 91.67%  | 87.67%  |
| Subject 3 | 76.94%           | 69.17%  | 76.02%  | 100.00% | 85.67%  | 95.33%  | 95.33%  | 0.00%   | 94.00%  |
| Subject 4 | 93.44%           | 97.00%  | 88.33%  | 100.00% | 100.00% | 76.33%  | 100.00% | 100.00% | 85.33%  |
| Subject 5 | 97.67%           | 98.00%  | 100.00% | 96.00%  | 91.67%  | 100.00% | 99.00%  | 96.67%  | 100.00% |
| Subject 6 | 90.75%           | 93.33%  | 69.86%  | 100.00% | 96.33%  | 70.83%  | 95.67%  | 100.00% | 100.00% |
| Subject 7 | 89.58%           | 78.17%  | 83.50%  | 99.00%  | 94.00%  | 68.33%  | 100.00% | 93.67%  | 100.00% |
| Subject 8 | 77.33%           | 90.67%  | 89.00%  | 97.33%  | 49.50%  | 53.33%  | 49.50%  | 92.33%  | 97.00%  |
| Subject 9 | 98.33%           | 91.67%  | 95.00%  | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% |



|            |        |         |         |         |         |         |         |         |         |
|------------|--------|---------|---------|---------|---------|---------|---------|---------|---------|
| Subject 10 | 89.71% | 87.67%  | 88.33%  | 85.33%  | 100.00% | 97.00%  | 93.33%  | 83.67%  | 82.33%  |
| Subject 11 | 68.56% | 25.76%  | 30.05%  | 100.00% | 74.00%  | 56.52%  | 89.67%  | 100.00% | 72.50%  |
| Subject 12 | 93.44% | 90.67%  | 76.50%  | 100.00% | 98.00%  | 93.67%  | 95.00%  | 98.00%  | 95.67%  |
| Subject 13 | 88.69% | 83.33%  | 85.33%  | 95.00%  | 99.00%  | 90.00%  | 87.33%  | 69.50%  | 100.00% |
| Subject 14 | 96.67% | 100.00% | 98.00%  | 96.67%  | 91.67%  | 98.33%  | 91.33%  | 99.00%  | 98.33%  |
| Subject 15 | 95.46% | 92.00%  | 80.00%  | 100.00% | 96.67%  | 100.00% | 95.00%  | 100.00% | 100.00% |
| Subject 16 | 84.69% | 90.33%  | 88.67%  | 100.00% | 62.17%  | 51.67%  | 84.67%  | 100.00% | 100.00% |
| Subject 17 | 94.46% | 97.00%  | 99.00%  | 98.33%  | 95.67%  | 83.33%  | 95.33%  | 96.67%  | 90.33%  |
| Subject 18 | 84.77% | 90.00%  | 51.83%  | 97.00%  | 93.33%  | 63.00%  | 92.00%  | 100.00% | 91.00%  |
| Subject 19 | 82.13% | 86.67%  | 62.17%  | 99.00%  | 95.86%  | 91.33%  | 86.67%  | 43.33%  | 92.00%  |
| Subject 20 | 89.35% | 87.00%  | 76.33%  | 100.00% | 95.67%  | 74.83%  | 93.00%  | 93.33%  | 94.67%  |
| Subject 21 | 67.56% | 50.50%  | 34.95%  | 90.00%  | 78.52%  | 84.02%  | 75.67%  | 22.83%  | 98.00%  |
| Subject 22 | 88.77% | 79.17%  | 63.67%  | 100.00% | 100.00% | 75.36%  | 95.00%  | 97.00%  | 100.00% |
| Subject 23 | 84.77% | 87.67%  | 80.67%  | 99.00%  | 82.83%  | 61.33%  | 66.67%  | 100.00% | 100.00% |
| Subject 24 | 82.61% | 51.33%  | 72.19%  | 100.00% | 96.67%  | 62.33%  | 98.33%  | 90.33%  | 89.67%  |
| Subject 25 | 82.20% | 61.17%  | 48.83%  | 83.33%  | 95.83%  | 82.17%  | 97.00%  | 96.33%  | 93.67%  |
| Subject 26 | 79.15% | 75.00%  | 67.33%  | 95.00%  | 53.83%  | 77.50%  | 82.00%  | 90.00%  | 92.57%  |
| Subject 27 | 88.56% | 88.00%  | 76.50%  | 99.00%  | 83.33%  | 80.67%  | 83.00%  | 99.00%  | 99.00%  |
| Subject 28 | 89.23% | 85.17%  | 87.33%  | 99.00%  | 99.00%  | 82.00%  | 76.33%  | 85.00%  | 100.00% |
| Subject 29 | 88.33% | 46.67%  | 75.50%  | 99.00%  | 100.00% | 90.50%  | 100.00% | 100.00% | 95.00%  |
| Subject 30 | 93.67% | 95.67%  | 96.33%  | 94.00%  | 87.33%  | 100.00% | 80.00%  | 99.00%  | 97.00%  |
| Subject 31 | 98.00% | 98.00%  | 98.33%  | 96.67%  | 96.67%  | 98.33%  | 100.00% | 99.00%  | 97.00%  |
| Subject 32 | 94.46% | 94.67%  | 88.33%  | 100.00% | 98.33%  | 100.00% | 100.00% | 77.33%  | 97.00%  |
| Subject 33 | 84.98% | 74.83%  | 55.67%  | 91.33%  | 100.00% | 69.33%  | 95.33%  | 100.00% | 93.33%  |
| Subject 34 | 86.30% | 99.00%  | 100.00% | 100.00% | 91.67%  | 81.33%  | 100.00% | 48.83%  | 69.57%  |
| Subject 35 | 92.00% | 96.33%  | 87.50%  | 89.67%  | 98.00%  | 96.33%  | 87.33%  | 94.33%  | 87.00%  |
| Subject 36 | 94.67% | 92.00%  | 86.67%  | 100.00% | 99.00%  | 100.00% | 86.67%  | 100.00% | 93.00%  |
| Subject 37 | 82.92% | 90.33%  | 93.00%  | 99.00%  | 92.19%  | 80.50%  | 60.86%  | 60.17%  | 87.33%  |
| Subject 38 | 91.17% | 95.33%  | 83.67%  | 96.33%  | 99.00%  | 81.67%  | 96.33%  | 87.33%  | 89.67%  |

Performance of Random Forest model in BS classification is compared with WS classification results obtained in this study, as shown in Table 4. First row of Table 4 presents the previously reported performance for BS classification, which serves as benchmark to surpass in WS classification. Second row indicates number of cases where performance improves, highlighted in green in Table 3. Conversely, third row displays number of cases where performance decreases by 60%, marked in red in Table 3.

**Table 4.** Performance evaluation for within-subject models.

|                                                             | F1-score | Shut   | Blink  | Left   | Right  | Up     | Down   | Wink   | Roll   |
|-------------------------------------------------------------|----------|--------|--------|--------|--------|--------|--------|--------|--------|
| Reported performance in between-subject classification [22] | 82%      | 81.65% | 72.11% | 88.07% | 93.74% | 70.46% | 90.41% | 68.28% | 84.34% |
| Number of subjects in which the F1-score improves           | 33       | 28     | 27     | 35     | 23     | 30     | 22     | 33     | 35     |
| Number of subjects with an F1-score below 60%               | 0        | 4      | 5      | 0      | 2      | 3      | 1      | 4      | 0      |

When considering only performances of Random Forest model, WS classification generally outperforms BS classification. As shown in second row of Table 4, performance improves in 33 out of 38 subjects, with enhancements observed across all alphabets. However, it must be considered that this does not apply to all subjects, since in case of subjects 8 and 21 average performance of model does not improve and 3 of alphabets lower their performance to less than 60%.

Based on BTS alphabet similarities presented in Table 2, it was expected that “Down” and “Blink” would not improve their performances because they are very similar between different subjects. This is confirmed, as these alphabets are among the three with the least improvement, showing gains in only 22 and 27 out of 38 subjects, respectively. In contrast, “Wink”, “Roll” and “Left” which exhibit the least similarity between subjects, benefit more from WS classification. This is validated by substantial improvements, with performance gains in 33, 35 and 33 subjects, respectively.

## 5 Conclusions and Future Work

Considering only performance of Random Forest classifier, WS classification, where the model is trained and tested with data from same subject, as done in this study, generally yields better results. However, applying this approach in real-life scenarios could present challenges, particularly regarding time required to record EOG patterns and train and test classification models. This process can be time-consuming, as it involves calibrating device that interprets BTS alphabets and performing multiple recordings of each alphabet.

WS classification can be especially beneficial for individuals who involuntarily perform movements outside the guidelines of BTS language. Examples include raising eyebrows when looking upward (“Up” alphabet), blinking when looking to “Left” or “Right” being unable to “Wink” with one eye, or struggling to perform “Roll” movement in specified direction.

For future work, to select what type of classification is desired to be performed for identification of BTS alphabets by means of EOG signals, it is essential to identify what priorities there are in research, if it is design of classifier models, it is suggested to train



and test model with data from a single subject (WS classification), or for those cases in which subjects cannot correctly perform eye movements. On the other hand, if what is desired is to adapt the system that interprets BTS alphabets to different subjects more quickly, a classification that considers all subjects can be used (classification BS), sacrificing a little of the model's designs, but still obtaining acceptable results.

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# ArchHero: Rehabilitation of Flatfoot in Adults by Means of a Serious Health Video Game

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**Abstract.** Flatfoot is a pathology that affects a large percentage (15-20%) of the Mexican population; however, little emphasis has been placed on the physical rehabilitation of this condition. One of the main associated problems is the limited availability of physical rehabilitation options, which can lead to long-term complications, such as pain, postural imbalances, and decreased mobility. In this context, serious video games for health have proven to be effective tools due to their ability to provide immersion and motivation, fostering adherence to therapeutic treatments.

This work proposes the development of a serious video game called ArchHero, focused on the rehabilitation of flatfoot. It is designed to stimulate foot musculature and promote the correction of plantar curvature through interactive exercises, mainly the Short Foot exercise, which strengthens the intrinsic muscles of the foot. This solution seeks to improve the accessibility and effectiveness of therapy, providing an innovative, comfortable, and immersive alternative that enhances patient engagement and long-term rehabilitation outcomes.

**Keywords:** Interactive therapy, Flatfoot, Plantar curvature, Rehabilitation, Serious video games.

## 1 Introduction

Flatfoot is a condition that affects a significant portion of the population [1] and, in many cases, does not receive adequate attention in terms of rehabilitation. This pathology is characterized by a decreased or absent plantar arch, which can cause pain, muscle fatigue, and postural issues, ultimately affecting mobility and quality of life. Although conventional treatments exist, patient adherence to physical therapy is often

<https://doi.org/10.61728/AE20255169>



low due to the monotony of the exercises and lack of motivation [4][2]. In this context, the goal is to develop ArchHero, a serious video game designed for flatfoot rehabilitation in adults. This project aims to integrate technology with therapeutic strategies to offer an immersive and motivating experience, facilitating treatment continuity. Through interactive exercises, it is expected to strengthen foot muscles and improve stability, contributing to the correction of plantar curvature. By incorporating gamification, the objective is to increase patient engagement in the rehabilitation process, reduce treatment dropout rates, and improve clinical outcomes. The target audience for this project consists of adults between 18 and 25 years old with moderate degrees of flatfoot, meaning they can benefit from physical therapy without requiring surgery.

Additionally, ArchHero is designed as a tool that can be used in both clinical and home settings, allowing patients to perform their exercises autonomously and at their own pace. Adult Acquired Flatfoot Disease (AAFD) is a progressive dysfunction of the posterior tibial tendon, leading to collapse of the medial longitudinal arch and alterations in foot biomechanics. This condition is more common in middle-aged women, particularly those who are overweight or have a sedentary lifestyle. Symptoms include ankle pain, instability while walking, and fatigue in the foot and leg. Depending on the severity of the deformity, treatment options range from therapeutic exercises and orthotic support to surgical interventions in advanced cases [2]. The diagnosis of this condition is made through clinical observation and imaging studies such as X-rays and MRI scans. Parameters like Meary's angle and the "too many toes" sign [4] help assess the severity of the deformity and guide appropriate treatment. However, access to advanced diagnostic tools and specialized therapies is often limited, emphasizing the need for accessible and effective alternatives like ArchHero. Through the development of this video game, we seek to provide a rehabilitation tool for patients with AAFD Grades 1 and 2A. The integration of pressure sensors will allow real-time monitoring of user performance, dynamically adjusting the difficulty of exercises according to progress. This solution aims to improve patients' quality of life by making functional therapies more accessible and promoting long-term adherence to treatment.



**Fig. 1.** Visual representation of the too many toes diagnostic method [4].



**Fig. 2.** Radiographs demonstrating the talonavicular angles and the heel-first metatarsal-sial angle [4].



**Fig. 3.** Radiographs demonstrating the Meary angle [4].

Additionally, the project proposes incorporating Galvanic Skin Response (GSR) sensors to monitor stress levels during rehabilitation sessions. By measuring electrodermal activity, it will be possible to assess the patient's physiological response to exercises, allowing for real-time difficulty adjustments. This approach seeks to optimize the rehabilitation experience by maintaining a balance between challenge and comfort, ensuring that therapy occurs in an environment that supports both physical progress and emotional well-being.

## 2 Related works

Adult flatfoot has been the subject of numerous studies analyzing its causes, diagnosis, and treatment options. According to the thesis by D. C. Bustos Madariaga [5], this condition affects the body's biomechanics, leading to both postural and functional problems. Traditionally, treatment has relied on the use of orthopedic insoles; however, recent research has examined the impact of therapeutic exercise in strengthening foot muscles to improve the plantar arch and reduce symptoms such as pain and fatigue [6][4][5]. Bustos Madariaga's study [5] classifies flatfoot into different degrees based on flexibility and severity. A distinction is made between flexible and rigid flatfoot; the former allows correction of the plantar arch when the foot is not bearing weight, while the latter presents a persistent deformity even in the absence of load. Additionally, depending on its progression, flatfoot may be managed through rehabilitation or require surgery. Moderate cases respond well to therapeutic exercises, orthotics, and physical therapy, whereas more severe cases characterized by persistent pain, advanced deformities, and instability may require surgical intervention to correct foot alignment and restore function. Recent studies have highlighted the importance of early re-habilitation, not only to relieve symptoms but also to prevent long-term complications and improve patient quality of life [4][2]. In this regard, developing accessible and engaging alternatives for physical therapy is essential to increase treatment adherence and optimize clinical outcomes.

### 2.1 Methods of flatfoot diagnosis

Flatfoot diagnosis relies on a combination of clinical tests and imaging studies. Henry [4] highlights the most commonly used methods, which include assessing foot alignment through functional tests such as the Too Many Toes marker and the Single-Limb Heel Raise test, along with weight-bearing radiographs to measure key angles like Meary's angle and talar coverage over the navicular bone.

Current diagnostic methodologies for flatfoot have several limitations. While the podoscope is useful for visualizing plantar pressure distribution, it provides only a two-dimensional representation, making it insufficient for a comprehensive assessment of foot dynamics. Additionally, result interpretation can be subjective and dependent on the examiner's experience, introducing variability and reducing diagnostic objectivity. Biomechanical measurements, joint mobility tests, and gait analysis require specialized equipment that is often expensive and available only in select centers. Moreover, the accuracy of these assessments depends on the practitioner's expertise, which can impact the reliability of results.

Advanced technologies such as 3D scanners and plantar pressure platforms enhance diagnostic precision, yet their high costs and complex data interpretation may limit accessibility. These methods are also sensitive to environmental factors and, in some cases, to measurement conditions, which can affect consistency in real world scenarios. While an effective combination of these techniques could improve diagnostic accuracy, technical and economic barriers remain.



Despite its usefulness in visualizing plantar pressure distribution, the podo-scope is limited by its two-dimensional nature and subjective interpretation, which can affect the accuracy of flatfoot severity assessment. Likewise, biomechanical measurements, joint mobility tests, and gait analysis require costly specialized equipment and rely heavily on the evaluator's expertise. These factors not only increase costs but may also compromise result validity when conducted in controlled environments that do not fully replicate real-life conditions. Additionally, advanced technologies such as 3D scans and plantar pressure platforms improve diagnostic accuracy, their high cost, data processing complexity, and sensitivity to external conditions hinder their routine use in clinical practice. These limitations highlight the need for diagnostic methodologies that integrate objectivity, precision, and accessibility.

## **2.2 Flatfoot rehabilitation**

Flatfoot treatment involves multiple rehabilitation strategies, given that the condition varies in severity. According to D. C. Bustos Madariaga [5], treatment options range from orthopedic insoles to therapeutic exercises and physiotherapy techniques aimed at preserving foot musculature and enhancing its function.

Common rehabilitation methods include proprioceptive exercises, functional taping, physical agents, and, notably, the Short Foot exercise [4]. This exercise focuses on activating the intrinsic foot muscles to enhance stability and postural control. Studies indicate that regular practice can help increase the plantar arch and reduce flatfoot symptoms. Additional ankle mobility and strengthening exercises, along with gait training, further optimize patient recovery.

Complementary techniques such as manual therapy, electrostimulation, and closed kinetic chain exercises have proven effective in flatfoot rehabilitation. Combining these approaches can enhance foot function and gait while preventing deformity progression and related complications [4].

## **2.3 Types of video games in physical rehabilitation**

This topic has gained relevance in recent years. According to Ravenet's review [3], the most used consoles and peripherals in physical rehabilitation are those equipped with motion sensors, such as the Nintendo Wii®, PlayStation EyeToy®, and Xbox Kinect®.

Video games have been incorporated into various rehabilitation approaches, ranging from neuromuscular to motor and postural rehabilitation.

The most used rehabilitation games include:

- **Balance games:** Designed to improve stability by challenging postural control in virtual or augmented reality environments.
- **Coordination games:** Require precise limb movements and promote neuromuscular synchronization.



- Strength and endurance games: Aim to increase muscle capacity and effort tolerance in patients with functional limitations [3].

Additionally, these games have proven effective for lower extremity rehabilitation by offering repetitive, predictable tasks that promote neuroplasticity and functional adaptation.

Studies have shown that rehabilitation video games enhance more than just mobility; they also provide engaging and motivating experiences that encourage treatment adherence. Combining video games with traditional physical therapy has yielded positive results in patients with neurological injuries, musculoskeletal disorders, and postural control issues, highlighting their potential as an effective complementary tool for functional recovery [3].

### 3 Methodology

Flatfoot is characterized by a weakness in the posterior tibial tendon, which serves as the primary force behind walking. This tendon plays a crucial role in maintaining the stability of the medial arch, providing cushioning, and contributing to propulsion during gait [2]. The medical community recognizes four common types of flatfoot based on the degree of foot arch collapse. Specifically, Type I is defined by a slight reduction of the plantar arch without significant functional impairment; Type II involves a moderate loss of the arch accompanied by some instability during the stance phase; Type III is marked by a more pronounced deformity that significantly affects alignment and load distribution; and Type IV represents the most severe cases, with structural deformities and considerable functional compromise [4].



Fig. 4. Posterior tibial tendon. [7].

Flatfoot diagnosis primarily relies on standing radiographs, which allow for the measurement of various interosseous and intermuscular angles. For instance, the talonavicular angle evaluates the lateral deviation of the navicular bone relative to the calcaneus, while Meary's angle assesses the alignment between the first metatarsal and the heel. Both parameters are critical for quantifying the severity of the deformity [6].

Additionally, the "Too Many Toes" test is employed, wherein the number of visible toes on the lateral aspect of the foot is observed; however, this test only confirms the presence of flatfoot without classifying its specific type [4].

In terms of treatment, three primary methods are currently used: surgical intervention, orthopedic insoles, and physical therapy. While surgery can correct structural abnormalities and insoles help redistribute weight, physical therapy is essential for strengthening the musculature and improving posterior tibial tendon function. Nonetheless, conventional physical therapy often suffers from low adherence due to the monotonous and effortful nature of the exercises.

To address these limitations, the present project proposes the development of ArchHero a device that incorporates serious video games for health. These video games, which have been successfully used in physical rehabilitation to enhance balance and gait [4], provide an immersive and rewarding environment that promotes the constant repetition of therapeutic exercises. In particular, the "Short Foot" exercise is integrated as the primary strategy for strengthening the posterior tibial tendon, offering both ease of implementation and objective progress measurement.

The project is structured around three fundamental pillars:

1. **Continuity in Physical Therapy:** The device is designed to encourage consistent treatment adherence through an interactive and motivating video game environment that promotes regular exercise repetition.
2. **Diagnosis and Monitoring:** It integrates pressure sensors based on the "Too Many Toes" technique to objectively evaluate foot load distribution, facilitating continuous monitoring of therapeutic progress.
3. **Stress Response-Based Difficulty Modulation:** By incorporating galvanic skin response (GSR) sensors, the device measures a user's stress levels in real time. This data dynamically adjusts the game's difficulty, ensuring the therapeutic environment remains both challenging and approachable. When stress levels are high, the device automatically reduces challenge intensity to prevent frustration and emotional fatigue; conversely, when stress is low or moderate, the difficulty increases progressively to keep the user engaged without causing overwhelm.

This adaptive feedback system optimizes the rehabilitation process by maintaining a balance between challenge and comfort. As a result, it is expected to boost user motivation and extend therapy duration, ensuring that exercises are performed consistently and effectively.

Understanding foot biomechanics is fundamental to addressing flatfoot rehabilitation, as it involves analyzing the interaction of anatomical components during activities like walking and running. While traditional rehabilitation focuses on exercises and physiotherapeutic treatments to improve foot function and prevent complications [4], the innovative use of serious video games in this project offers a dual benefit: enhancing both the therapeutic and entertaining aspects of the re-habilitation process.

ArchHero leverages pressure sensors and tracking systems to provide real-time feedback, thereby increasing patient participation. The modular design of the device

integrates insights from biomechanics, physical rehabilitation, biomedical engineering, and serious video game technology. Moreover, the thesis by D.C. Bustos Madariaga [5] supports this non-invasive therapeutic approach for treating adult flatfoot, further validating the rationale behind this innovative project.

## **4 Discussion, application, trends and opportunities**

### **4.1 Innovation**

The fusion of low-cost pressure sensors with interactive environments based on serious video games represents an innovative alternative that could transform the diagnosis and treatment of rigid flatfoot. By incorporating galvanic skin response (GSR) sensors, the device can adapt the difficulty of the video game in real time according to the user's stress levels, ensuring personalized treatment and preventing emotional overload. This gamified therapeutic process fosters greater adherence to treatment, thereby enabling effective long-term rehabilitation.

### **4.2 Social Impact**

The project has a significant impact on society, particularly for individuals with limited access to specialized rehabilitation services. By offering a more accessible and engaging treatment through gamification, this approach has the potential to improve patients' quality of life, reduce recovery time, and promote healthy habits from an early age. Early detection of anomalies combined with personalized rehabilitation via serious video games allows for more effective interventions, which can reduce pain, improve mobility, and prevent complications associated with the pathology. Additionally, the integration of biomedical data, engineering design, and biomechanical knowledge paves the way for new re-search and advancements in digital health, fostering collaboration across various disciplines.

### **4.3 Development or market potential**

The project demonstrates high development and market potential in response to the growing demand for technological solutions in rehabilitation. Its modular and cost-effective design makes it highly attractive for clinics, hospitals, and physiotherapy centers that seek to innovate in their treatment methods. Furthermore, the possibility of customization and adaptation for various biomechanical pathologies broadens its commercial reach and viability across different markets. Although the current approach remains theoretical, the robust rationale underlying the project lays the groundwork for future experimental implementations, clinical validations, and the development of functional prototypes to bring this proposal into practical application.



#### 4.4 Definition of system requirements

Based on previous research, specific requirements for the theoretical system have been established:

- **Functional:** The system must accurately capture plantar pressure distribution, integrate with video games, and adapt to different user profiles [8].
- **Technical:** It should utilize low-cost sensors, perform real-time data processing, and feature a user-friendly interface [8].
- **Ergonomic:** The device must be comfortable and should not interfere with the user's mobility [8].

#### 4.5 Evaluation of applied technologies

A thorough analysis of available technologies was conducted to determine the most appropriate options for the proposal:

- **Pressure Sensors:** These were selected for their affordability, flexibility, and ease of integration into the system [8].
- **Data Analysis Software:** Theoretical evaluations suggest that advanced processing algorithms can significantly enhance the interpretation of collected data [8].
- **Gamification and Visual Feedback:** A proposal was developed for a serious, adaptive video game that utilizes sensor-captured data to provide real-time visual feedback to the user.

### 5 Conclusion

ArchHero represents an innovative approach to flatfoot rehabilitation, combining technology and gamification to enhance therapy adherence. Conventional rehabilitation methods often suffer from low motivation and accessibility barriers, making this interactive approach a viable alternative.

By integrating pressure sensors and GSR monitoring, the video game is planned to adapt in real time to a user's performance and stress levels, ensuring personalized treatment. This approach not only improves adherence but also contributes to a more engaging rehabilitation experience.

The project's potential extends beyond flatfoot rehabilitation, as its modular design allows adaptation to other biomechanical pathologies. Further experimental implementations and clinical validations are recommended to assess its effectiveness in rehabilitation and potential applications in other physical therapy domains.

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# Anatomix+ Osteoblast

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**Abstract.** Serious games have become an essential educational tool for teaching human anatomy by fostering active learning and improving knowledge retention. Traditional methods often rely on rote memorization, making it challenging for students to engage with complex anatomical structures. Anatomix+ Osteoblast is a board game designed to enhance students' understanding of the skeletal system through an interactive and gamified experience. By incorporating playful elements into the learning process, this game encourages students to identify bones, recall their functions, and apply anatomical knowledge in a dynamic way.

This article explores previous studies on similar serious games, emphasizing their effectiveness in medical and scientific education. It also discusses the benefits of gamification in learning, such as increased motivation, higher engagement levels, and improved information retention. Additionally, a detailed analysis of the design and implementation of Anatomix+ Osteoblast is presented, showcasing how this game contributes to an immersive and practical educational experience. Future applications, including digital integration and the expansion of the game to other anatomical systems, are also considered. By leveraging serious games, Anatomix+ Osteoblast aims to transform the traditional approach to anatomy education, making learning both effective and enjoyable.

**Keywords:** Board game, anatomy, bones, education, playful learning.

## 1. INTRODUCTION

In today's world, knowledge evolves at an accelerated pace, and the skills required for professional success are becoming increasingly complex and diverse. Traditional educational methodologies face the challenge of motivating students while providing the necessary and effective tools for various work environments. In this context, serious games have emerged as an innovative solution that combines entertainment and learning, promoting an active

<https://doi.org/10.61728/AE20255176>



educational experience that transcends mere transmission and memorization of theoretical knowledge.

By incorporating game elements into university learning, especially in technical and scientific disciplines, serious games manage to capture students' interest, increase their motivation, and transform the classroom into a simulation laboratory where professional skills can be practiced and perfected in a safe and enjoyable environment. This article presents "Anatomix® Osteoblast," a board game specifically designed to support the learning of human anatomy, focusing on the skeletal system and offering a playful experience that facilitates comprehension and knowledge retention in the healthcare field.

## 1 Related studies

Games related to Anatomix® Osteoblast include:

1. Scientific Publishing Anatomy Flash Cards: This is a series of 335 illustrated flashcards featuring essential concepts of human anatomy and physiology [1].
2. Barron's Anatomy Flash Cards: Each card represents a part of the human body labeled with its medical name, location in the body, and function. There are 265 cards that display muscles, bones, and organs, and they are color-coded according to their general function in the human body [2].
3. Bodymagnet®: Learn anatomy while sticking and unsticking 76 magnetic pieces. You will get to know the skeleton, organs, muscles, and various parts of the human body [3].
4. Squishy Human Body: This set includes a transparent plastic model of the human body with 9 soft organs, 12 bones, and plastic muscles, along with forceps, tweezers, an organizer mat for body parts, and a 24-page illustrated anatomy book [4].
5. Anatomy Lab: This kit features 3D DNA molecules, organs, a skeleton to assemble, a skeleton stand, a set of cards (to study the organs and systems of the human body), and a puzzle, along with a comprehensive illustrated manual [5].

The University of Zaragoza, located in Spain, has conducted various studies on games to motivate the teaching of human anatomy. In one of their studies, they implemented the Kahoot platform to assess the knowledge of 84 students during the years 2019-2020. The results showed that most students had not used gamification tools and suggested their use in other subjects. Additionally, the vast majority of students who participated in this activity expressed that Kahoot improved the teaching-learning process and their motivation [6].

### 1.1 Serious Game in Education

Serious games have been implemented in education with the aim of contributing to the training of students. It has been demonstrated that they improve academic performance and student motivation [7].

Serious games are defined as interactive applications designed to educate, train, or raise awareness among players. They combine playful elements with educational objectives, enabling users to acquire knowledge and skills through immersive experiences and simulations of the real world. Serious games are used in fields such as education, health, and professional training, promoting active and effective learning [8].

Serious games are applied in teaching across various areas and offer benefits such as [9]:

- Active learning: Enhances retention.
- Simulates real situations: Allows students (players) to experience and practice skills in a safe environment.
- Development of social skills: Improves interpersonal and communication skills.
- Awareness and sensitization: Promotes critical reflection.
- Dynamic assessment: Enables real-time evaluation of student progress.

## **1.2 Success Cases in Medical and Biomedical Education**

### **CLINIX+**

The advancement of knowledge and the increasing complexity of the skills required in the healthcare field demand new pedagogical strategies that transcend traditional teaching methods. In this context, CLINIX+, a serious game developed at the University of Guadalajara, has emerged as a success story in medical and biomedical education, transforming the way students acquire and apply knowledge in clinical engineering.

This innovative board game allows students to take on the role of hospital managers, facing real challenges in the administration of medical resources, compliance with regulations, and strategic decision-making. By integrating the regulations of the Mexican healthcare system, CLINIX+ achieves meaningful learning, where participants experience firsthand the challenges of professional practice.

Preliminary results have been extraordinary. Over 300 biomedical engineering students have participated in trials of the game, reporting an increase in motivation and a better understanding of key concepts in hospital management and the use of



medical devices. Additionally, CLINIX+ has been recognized at academic events such as LUDICON 2024, where it won first place in the Best Board Game Design category, solidifying its status as a high-impact educational tool.

The success of CLINIX+ lies not only in its ability to improve knowledge retention but also in the development of soft skills such as teamwork, communication, and decision-making under pressure. Its implementation in various universities and its upcoming presentation at the National Congress of Biomedical Engineering (CNIB 2024) reinforce its value as a model of innovation in higher education.

With plans for a future digital adaptation and a potential expansion to international standards, CLINIX+ positions itself as a benchmark in the teaching of clinical engineering, demonstrating that learning can be interactive, effective, and highly motivating [10].



Fig. 1. Biomedical engineering students playing CLINIX+. It represents the cooperative work and active learning of the students.

### 1.3 Teaching Anatomy and Its Challenges

Teaching anatomy poses a challenge for educators, primarily concerning the effectiveness of learning. One of the main challenges is the lack of necessary resources, such as anatomical models and visualization technology, which complicates the understanding of human structure. Additionally, traditional teaching methods, which are primarily based on memorization, become insufficient for effectively engaging students [11].

Knowledge of anatomy is fundamental in various disciplines, such as medicine, physical education, and physiotherapy. Understanding this subject enables comprehension of the relationship between the structures and functions of the human body. Furthermore, this knowledge is essential for clinical practice, physical performance assessment, and rehabilitation [12].

Returning to the topic of traditional teaching methods, the fundamental methods in the training of healthcare professionals are [13]:

- Lectures: Presenting slides, models, and projecting images of anatomy.
- Dissection (currently not practiced).
- Anatomical models: Three-dimensional models of organs and systems of the human body.
- Anatomical atlases: Books containing detailed illustrations of human anatomy.
- Laboratory practices: Use of histological preparations and imaging studies (X-rays, CT scans, and MRIs).
- Practical exams: Identification of structures in cadavers or models.

#### **1.4 Gamification and Active Learning**

Gamification is an approach that uses elements and principles of game design in non-gaming contexts, such as education, marketing, and health, among others. The goal is to apply game mechanics to make activities that are commonly considered boring more engaging and motivating [14].

Gamification differs from serious games in that gamification focuses on implementing game elements into non-gaming activities to increase motivation and engagement, while serious games are gameplay experiences designed to educate or inform players about a specific topic.

The game design principles applied in education include interactivity, immediate feedback, and presenting challenges that are appropriate to the students' skills. Additionally, using engaging narratives and rewards such as points and badges helps motivate students, while collaboration and competition enhance the learning experience. By integrating these elements, educators transform learning into a motivating and effective process that promotes knowledge retention [15].

Motivation and knowledge retention through play are based on various factors, such as points and rewards that encourage active participation from students, increasing their interest and commitment. Furthermore, play provides a safe environment for practicing and experimenting without the fear of failure, facilitating the consolidation

of knowledge. Immediate feedback allows for real-time adjustments, while narrative and context make learning more meaningful [16].

## **2: Design of Anatomix+Osteoblast**

### **Objective of the Game**

The objective of the game is for players, divided into teams, to work together to identify parts of the human skeletal system, using clues and strategy to avoid the "pathological" words established by the opposing team and advance on the board.

### **Game Components:**

- 33 bone cards
- 15 challenge cards
- 5 skeleton tokens in different colors
- 1 game board

### **Game Setup:**

1. Divide players into teams of two or more.
2. Each team selects a representative to draw a card with the anatomical part.
3. Separate the body cards by regions: skull, spine, rib cage, upper limbs, and lower limbs. Once the cards are separated by regions, shuffle the cards by region and place them in the corresponding regions on the board, which is also divided into 5 regions.
4. There are challenge cards that will be placed outside the board but will also be shuffled; these will be used when a team lands on a space that indicates a challenge.
5. One member from each team will roll a die to determine who goes first; the team that rolls the highest number will go first, and so on until the team that rolls the lowest number.
6. Each team will choose a skeleton token of their preferred color and place it at the starting point on the board.

### **Game Development:**

1. The representative of the team will roll the dice and has two options, land on a space that indicates which region they must draw a card from or land on a challenge card where they will answer questions about the human skeleton.
2. Before starting to give clues, each team writes down two "pathological" words related to the anatomical part.
3. The representative must give clues to their teammates to guess the anatomical part, using only words (not phrases) and avoiding the "pathological" words established by the opposing team.
4. The representative cannot give another clue until one of their teammates says an incorrect anatomical part or the word "pass."
5. Teammates try to guess the anatomical part based on the clues provided, with a maximum of 5 attempts per turn.
6. If the team correctly guesses the anatomical part before time runs out (2 minutes), they roll the dice again to advance on the board.
7. If time runs out or they give incorrect answers, they do not advance, and the next team takes their turn.

#### Winner of the Game:

1. The team that first reaches 50 points is the winner.

#### How the Game Cards Will Look:





Fig. 2. Game component of Anatomix+Osteoblast. The image shows a card that will be used to develop the dynamics of the game. This card is designed for players to learn about the location, function, injuries, and characteristics of the bone it indicates.

### 3 Evaluation of the game in learning

The areas of learning that this game can impact include:

- Medicine
- Nursing
- Physiotherapy
- Physical Education
- Occupational Therapy
- Biology
- Health Sciences Education
- Public Health Education

#### 3.1 Method of Effectiveness Evaluation

The methods that will be used to evaluate the effectiveness of the game are:

| Evaluation Method        | Objective                                               | Tools                                          | Data Type                  | Application in the Game                          |
|--------------------------|---------------------------------------------------------|------------------------------------------------|----------------------------|--------------------------------------------------|
| User Experience Analysis | Evaluate player satisfaction, enjoyment, and perception | Post-game surveys, interviews, focus groups    | Qualitative & Quantitative | Opinions on game dynamics, rules, and mechanics  |
| Usability Testing        | Identify difficulties in interface and mechanics        | Observation during gameplay, error logs        | Qualitative                | Difficulty understanding rules, board, and cards |
| Learning Measurement     | Assess knowledge gained about the skeletal system       | Pre- and post-tests                            | Quantitative               | Compare knowledge before and after the game      |
| Motivation Assessment    | Analyze player interest and engagement                  | Motivation questionnaires, behavioral analysis | Quantitative               | Participation time, enthusiasm level             |

|                                   |                                                    |                                              |                            |                                                           |
|-----------------------------------|----------------------------------------------------|----------------------------------------------|----------------------------|-----------------------------------------------------------|
| Performance Data Analysis         | Measure player performance and progress            | Score tracking, board progress               | Quantitative               | Analysis of scores, correct and incorrect answers by team |
| Case Studies & Systematic Reviews | Identify patterns in learning and gameplay         | Literature review, game session observations | Qualitative & Quantitative | Evaluation of strategies used by teams                    |
| Method Triangulation              | Obtain a comprehensive evaluation of effectiveness | Combination of previous methods              | Qualitative & Quantitative | Cross-validation of obtained results                      |

Table 1: Methods for Effectively Evaluating Game Function. This table presents a summary of how the game evaluation will be conducted and what tools will be implemented to make this possible, as well as how the results will be presented and what they will be based on.

The variables that will be measured are:

- Information retention
- Engagement
- Test performance

These variables can be measured using the methods outlined above to evaluate the effectiveness of the game.

## II. CONCLUSION

Serious games like Anatomix+ Osteoblast demonstrate a promising approach to teaching complex subjects such as human anatomy. By leveraging gamification principles, this board game provides an engaging, interactive, and effective learning experience that improves retention, motivation, and understanding of the skeletal system. Future developments, including digital expansion and the incorporation of new anatomical systems, will further enhance its educational potential.

## 4 Future applications and project development

This game, designed to identify the human skeletal system, has the potential to expand and evolve in various directions. Some of the future applications and developments of the project include:

- **Expansion to Other Anatomical Systems:** Versions of the game that address other systems of the human body, such as the muscular, circulatory, and nervous systems, among others.
- **Digital Integration:** Creation of a mobile app or online platform that complements the physical game; this could include interactive images, explanatory videos, and quizzes. An online scoring system could also be added, allowing players to compete with other teams globally.
- **Augmented Reality (AR) and Virtual Reality (VR):** Players could interact with three-dimensional models of the skeletal system.

This game can be applied in biomedical engineering educational programs at institutions like CUCEI, specifically in the subject of mechanical anatomy, promoting active and collaborative learning.

The next steps in the research and testing of the game are:

- Testing will be conducted in educational environments to evaluate the effectiveness of the game in learning anatomy. Data will be collected on student participation, information retention, and overall satisfaction with the gaming experience.
- Feedback will be sought from educators and students to make adjustments and improvements to the game design, ensuring that it meets the established educational objectives.

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# Hybrid Detection and Segmentation of Wood Defects

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**Abstract.** This paper presents a hybrid approach for detecting and segmenting wood defects, designed for deployment on low-resource embedded devices. The approach combines the efficiency of YOLO (You Only Look Once) for defect detection with traditional image processing techniques for precise segmentation. The use of traditional methods helps reduce the computational burden, making the approach more suitable for resource-constrained environments. This methodology leverages the strengths of both approaches while mitigating their individual limitations.

**Keywords:** Computer Vision · Image Processing · YOLO (You Only Look Once) · Wood Defect Detection · Image Segmentation · Industrial Quality Control

## 1 Introduction

The wood industry constantly faces challenges in quality control due to the complex and variable nature of wood defects. Natural defects such as knots, cracks, and fiber deviations during tree growth. Additionally, processing defects occur during wood transformation, including cutting problems, inadequate drying, and incorrect classification, as shown in Fig 1.

<https://doi.org/10.61728/AE20255183>





**Fig. 1.** Examples of possible defects in a tangential wood cut [2].

All these issues can significantly compromise the mechanical strength of the material. These defects, along with environmental factors such as humidity and temperature, can cause structural deformations, reduced mechanical resistance, and increased susceptibility to biological deterioration [1].

Early and accurate detection of these defects is crucial to maintaining high-quality production standards. However, traditional manual visual inspection methods are prone to errors, time-consuming, and inconsistent. This has driven the need to develop automated inspection systems that can quickly and reliably identify and characterize defects.

Currently, multiple solutions for defect detection in the industry have emerged, many of these solutions with custom designs of convolutional neural networks [4]. Architectures such as YOLO (You Only Look Once) have emerged as efficient solutions for identifying objects or, in this case, wood defects. YOLO stands out for its ability to process images in real-time and its high detection accuracy, requiring only bounding box annotations. However, precise defect segmentation requires more complex manual labeling, which can be costly and time-consuming. Neural networks may also be computationally expensive and complex, which translates into a difficult industrial application.

In Table Fig 1 we can see the size and speed of a YOLO11N detection network compared to three segmentation networks. It is clearly evident that just the process of training a network will be more costly, not to mention the human work involved in the segmentation training.

**Table 1.** Comparative of segmentation and detection models [5].

| Model       | Parameters (M) | FLOPs (B) | CPU speed (ms) |
|-------------|----------------|-----------|----------------|
| YOLO11n     | 2.6            | 6.5       | 56.1           |
| YOLO11n-seg | 2.9            | 10.4      | 65.9           |
| MobileSAM   | 10.1           | -         | 98543          |
| FastSAM     | 11.8           | -         | 140            |

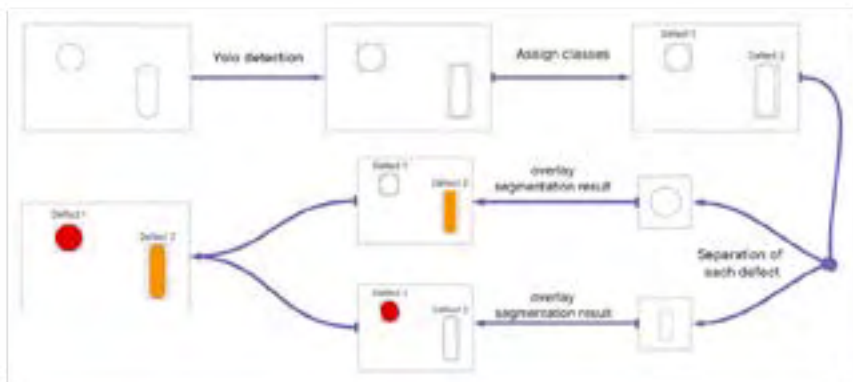
This is where classical computer vision methods, such as Otsu thresholding method, offer a practical and efficient alternative. These techniques, although simpler, can provide robust results when applied to specific regions identified by YOLO. Otsu method, in particular, is effective in automatically determining the optimal threshold to separate the defect from the background based on the image's intensity distribution, without requiring prior training or exhaustive annotations.

This hybrid approach, combines YOLO capabilities for initial detection with classical segmentation methods, represents a practical solution that balances precision with computational efficiency and ease of implementation. Additionally, it significantly reduces the need for annotated data and simplifies the system's development and maintenance process.

## 2 Defect detection

The process begins by extracting sub-images from the bounding boxes generated by YOLO. Each sub-image represents a specific region where a potential defect has been detected, reducing background noise and enabling local thresholding. The complete process is described in Fig 2.

In the first phase, an image is passed to the YOLO method which detects and assigns a class to all the defects on the image. Then in the second phase each detected defect is passed to the Otsu method. Finally, all the results of the Otsu method are combined into a single image that represents the segmented image.



**Fig. 2.** Defect detection Diagram

To observe the results of the process, the Fig 2, shows an image of dataset with their detection made by YOLO. Finally Fig 3 shows an image after the segmentation process, as described in the previous diagram.

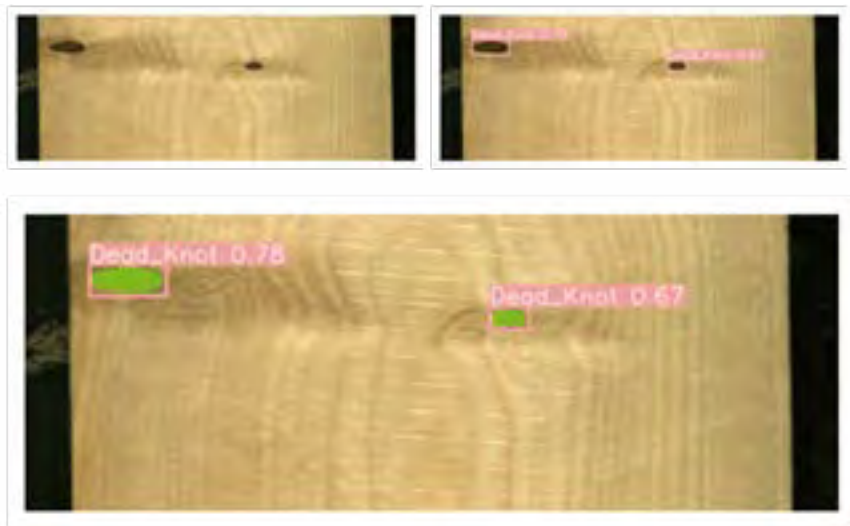


Fig. 3. Example of Defect detection including segmentation by Otsu

### 3 Experimental Results

The dataset [6] used in this work contains 20,276 images with annotations in COCO format. Due to computational limitations and the need for optimized training, a stratified sampling was performed, selecting 2,000 images for training and 100 for validation. This reduction maintained a balance between data representation and training efficiency.

The process for reducing the data set as shown in Fig 4, involved converting the COCO annotations to YOLO format, ensuring correct bounding box coordinate translation and label integrity. The images were converted from BMP to JPG format to reduce storage space, and their dimensions were resized from 2800x1027 pixels to 640x256 pixels, maintaining the original aspect ratio while optimizing computational efficiency.

In our case we have chosen YOLO11n, which in the experiments has shown a balanced efficiency and accuracy. A default learning rate of 0.01 was used with the Adam optimizer, a batch size of 4 images, and training over 50 epochs.



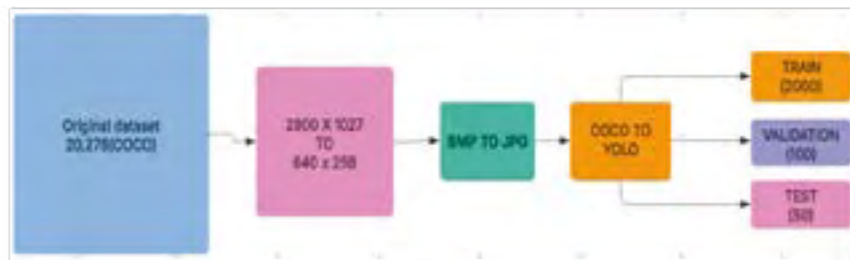


Fig. 4. Weight reduction for dataset

The implementation has been carried out on the Ultralytics framework, which provides an efficient interface for YOLO [7]. The data was organized following the structure required by the framework, with separate folders for training and validation, and labels in YOLO format. The model configuration was done using a YAML file specifying the data path and defect classes.

The training was initialized using the pre-trained YOLO on weights of COCO (Common Objects in Context) dataset to improve convergence. During inference, the framework facilitates image processing and prediction retrieval through the predict method, which provides the coordinates of the bounding boxes, confidence scores, and class labels needed for subsequent segmentation.

The second phase of the proposed approach focus on precise segmentation of the defects detected using YOLO. This process avoids complex neural networks and instead relies on sequential classical processing steps.

For defect segmentation, Otsu thresholding method [3] has been choosen. This technique determines an optimal threshold by minimizing intra-class variance. However, during experiments, the threshold calculated by Otsu method was often lower than required for effective class separation. To address this, an adjustment factor of 1.2 was introduced to the original threshold, enhancing segmentation precision to have a result like Fig 5 .

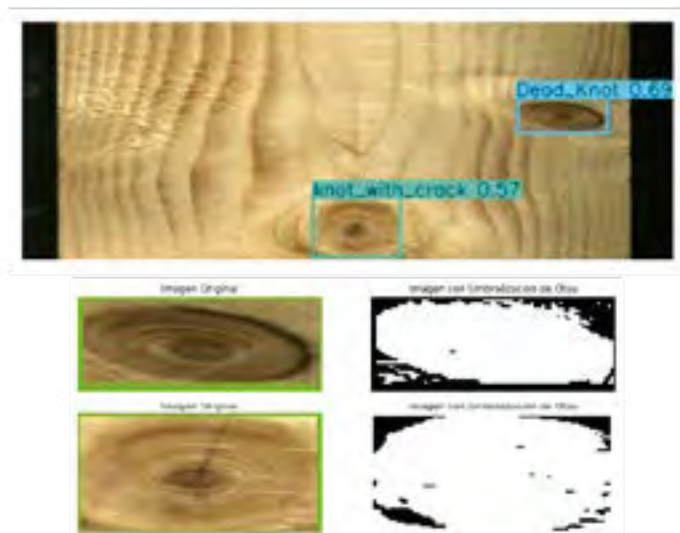
The final segmentation is applied to each sub-image, generating a binary mask that separates the defect from the background.

To visualize the results we can observe Fig 6 and Fig 7, in these examples a color channel composition technique was implemented. The original image is decomposed into its three RGB channels. The binary mask from Otsu thresholding modifies only the green channel, keeping the red and blue channels intact. This visualization technique clearly marks defects in green over the original image, achieving results comparable to more complex segmentation methods.

Experimental results shown in Fig 8, evaluated using the Intersection over Union (IoU) index against manual segmentation maps, demonstrate the feasibility and effectiveness of this combined approach.

To visualize efficiency, 4 tests were performed for each defect found; they are shown in Table 2.





**Fig. 5.** Detection by YOLO found 2 defects, then the segmentation of both defects is obtained using the Otsu method.



**Fig. 6.** Defect segmentation example.



**Fig. 7.** Multiple defect segmentation example.

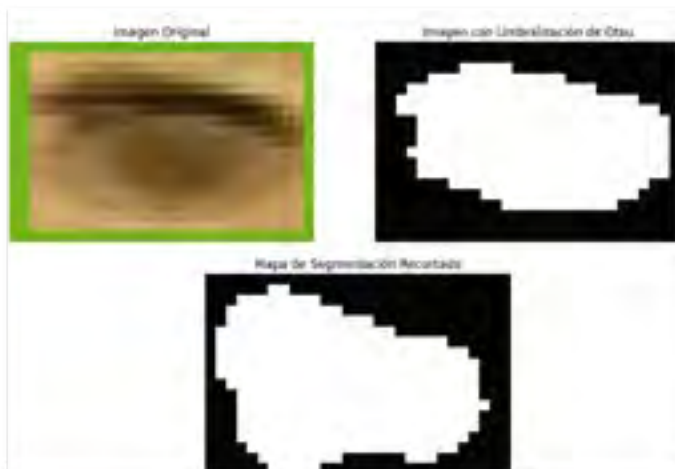
**Table 2.** This table shows the mean of the metrics

| IoU     | Accuracy | Precision | Recall  |
|---------|----------|-----------|---------|
| 0.74084 | 0.78845  | 0.88817   | 0.82385 |

These results suggest that your segmentation algorithm performs reasonably well, considering the low resources required by the Otsu method. Additionally, it is important to note that the segmentation maps provided for comparison are somewhat poor in pixel-by-pixel labeling. It is easy to see through visual inspection that, for the most part, the results of the proposed method are better than the existing manual segmentation, which clearly impacts the metric results, lowering their score, as seen in the example shown in Fig. 3 where the image below is the original semantic map, it is clear that the method had a better result, compromising the result of the metrics.



Fig. 8. original segmentation map and both defects compared by IoU



#### 4 Conclusion

The proposed methodology balances the advantages of both approaches: the speed and robustness of neural networks for detection and the pixel-level preci-

sion of traditional segmentation techniques. This balance is particularly valuable in industrial environments where speed, accuracy, and ease of implementation in compact and simple devices are key factors. Identified limitations include the dependency on accurate initial detection by YOLO for successful subsequent segmentation. In addition, classical segmentation techniques may require initial parameter tuning based on real-world experiments.

For future work, we propose to implement auto-tuning techniques for segmentation parameters to enhance adaptability. Developing specific metrics to evaluate each type of wood defect, considering both geometric precision and industrial relevance. Optimizing the processing pipeline for embedded systems and real-time applications. The results obtained suggest that this hybrid approach offers a viable alternative for automated quality inspection in the wood industry, providing an effective balance between accuracy, speed, and computational efficiency.

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# Neural network for automatic emotion classification using virtual environments

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**Abstract.** Given the inherent variability of human emotional responses, their objective measurement remains a complex challenge. Emotions are typically manifested through physiological changes, such as sweating, body temperature, and heart rate variations. This study utilized these three parameters to map participants' emotional states within the emotional space proposed by Kolakowska (2015). To elicit controlled emotional responses (happiness, anger, sadness, and fear) virtual environments were created using stimuli from the International Affective Picture System (IAPS) and the International Affective Digitized Sounds (IADS). Following data acquisition, signal processing techniques were applied to project the responses onto the emotional space, thereby enhancing the accuracy of emotional state monitoring. A neural network was subsequently trained for multiclass classification, achieving a 10% improvement in accuracy compared to previous models.  
**Keywords:** UAV, PID Control, Neuronal Control, Extended Kalman Filter, Hardware-in-the-Loop.

## 1 Introduction

### 1.1 Emotions and affective computing

"Emotion is an organism's response to a particular stimulus (person, situation, or event). Typically, it is an intense, short-lived experience, and the person is usually highly aware of it" [1].

In the last decade, technological advancements have enabled an increasingly deep integration of human emotions into the computational domain, giving rise to the field of affective computing. This interdisciplinary field focuses on the interaction between humans and machines, aiming not only to process logical information, but also to understand and respond to user emotions [2]. Affective computing has applications in various areas, from education to mental health, and draws on knowledge from psychology, neuroscience, and artificial intelligence to create systems that simulate empathy and enhance human-computer interaction [2].

<https://doi.org/10.61728/AE20255190>





One of the most promising approaches within affective computing is automatic emotion detection (AED), which refers to the ability of machines to identify and process emotions expressed by users through different modalities, such as voice, facial expressions and more recently body movements in virtual environments [4].

This recognition becomes particularly relevant in virtual environments, where users can interact with digital representations of themselves and others in three-dimensional spaces. Virtual environments provide a rich context for emotional expression and allow researchers and developers to experiment with new forms of interaction and communication [4].

Many of the studies related to emotion processing and detection involve the generation of biosignals for analysis. In this regard, a significant portion of state-of-the-art research uses resources such as videos, sounds, images, or questionnaires as emotional stimuli, which are typically displayed on a monitor or screen [8].

The convergence of AED and virtual environments presents a wide array of innovative opportunities. These environments can be systematically designed to foster immersive experiences in which emotions play a pivotal role, facilitating natural and intuitive interactions. For instance, in virtual reality applications for psychological therapy, automatic emotion recognition can assist therapists in dynamically adjusting their approaches based on patients' emotional responses. Likewise, in educational contexts, tailoring content to students' emotional states has the potential to enhance learning outcomes and improve information retention [9].

However, despite significant advances in this field, automatic emotion recognition in virtual environments faces several challenges. Cultural variability in emotional expression, individual differences in the perception and interpretation of emotions, and the complexity of human behavior are factors that complicate design of accurate and effective systems. In addition, ethics and privacy in the handling of emotional data represent crucial considerations that must be addressed.

## 1.2 Previous work

Previous research has already been conducted with this same focus, using virtual environments as a primary method of emotional stimulation. In these studies, classification relied not only on bio signals but also incorporated voice and text acquisition. Although this study yielded good results, classification method implemented in [4] is exclusively binary.

Another related investigation focused on brain signals through electroencephalograms (EEG). For this study, virtual environments are implemented to subject patients to emotional thresholds, which are categorized through activation and valence. For classification, signals are first characterized by partitioning their power, resulting in two characterization methods called bipartition and tripartition. Support vector machines (SVM) and a decision tree model are used for classification [5].

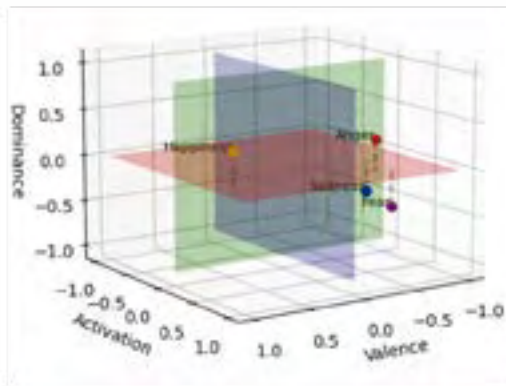


## 2 Methodology

For this study, a database collected in another work titled "Automatic emotion detection through biosignals and Virtual Environments" is used. This database compiles three different physiological signals: heart rate, temperature, and skin impedance. The database contains information from 30 patients subjected to four different emotions (happiness, anger, sadness, and fear) through virtual environments generated using images from IAPS [7] and sounds from IADS [6].

Physiological signals are measured in voltage and then processed to convert them into interpretable units: beats per minute (bpm), degrees Celsius ( $^{\circ}\text{C}$ ) and impedance ( $\Omega$ ). Once the database information is preprocessed, a final transformation is performed, where these interpretable units are converted to values ranging from -1 to 1, corresponding to the three-dimensional space proposed by Mehrabian and Russell [3]. In this space, each signal corresponds to one of the axes (as shown in Figure 1):

- Valence: Degree of pleasure or displeasure associated with the emotion.
- Activation: Level of arousal or physiological excitement.
- Dominance: Sensation of control or submission in response to emotion.



**Fig. 1.** Representation of the three-dimensional space defined by dominance, valence and activation.

### 2.1 Signal Characterization

To label emotions, an algorithm based on Euclidean distance is used as:

$$d(P, Q) = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad (1)$$

| Emotion   | X     | Y    | Z     |
|-----------|-------|------|-------|
| Happiness | 0.76  | 0.48 | 0.35  |
| Anger     | -0.43 | 0.67 | 0.34  |
| Fear      | -0.64 | 0.60 | -0.43 |
| Sadness   | -0.63 | 0.27 | -0.33 |

**Table 1.** Coordinates for each emotion.

Each signal is compared to predefined reference points in the three-dimensional space (Table 1), representing emotions of happiness, sadness, fear, and anger. Signal is classified with emotion corresponding to the closest point in terms of Euclidean distance, thus obtaining usable data for emotional classification.

## 2.2 Neural Network Design

Two neural network models are designed to observe their behavior with different activation functions.

First neural network is designed with 3 inputs, one hidden layer containing 20 neurons with a hyperbolic tangent (*tanh*) activation function, and finally an output layer with 4 neurons and a linear activation function. This design aims to generate 4 hyperplanes capable of correctly separating emotions.

$$f(x) = x \quad (2)$$

$$\tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \quad (3)$$

The second model followed the same pattern as the first, with 3 inputs, a hidden layer of 5 neurons with a tanh activation function, and a final output layer with a Softmax activation function and 4 outputs to classify the 4 different emotions present in this study to predict both neural networks are trained using data transformed into dominance-activation-valence space, with the goal of predicting the corresponding emotion.

$$\text{Softmax}(x_i) = \frac{e^{x_i}}{\sum_j e^{x_j}} \quad (4)$$

Inputs to use are the three values obtained in characterization phase. Values are dominance for temperature, valence for heart rate and activation for skin impedance.

Selection of these activation functions is based on the type of data that is being used. Function selected for the hidden layer (*tanh*) is chosen because of data being handled is normalized between -1 and 1 and this function can work with both negative and positive values. As for activation functions for output layer (linear and Softmax), this choice is made to compare results in classification

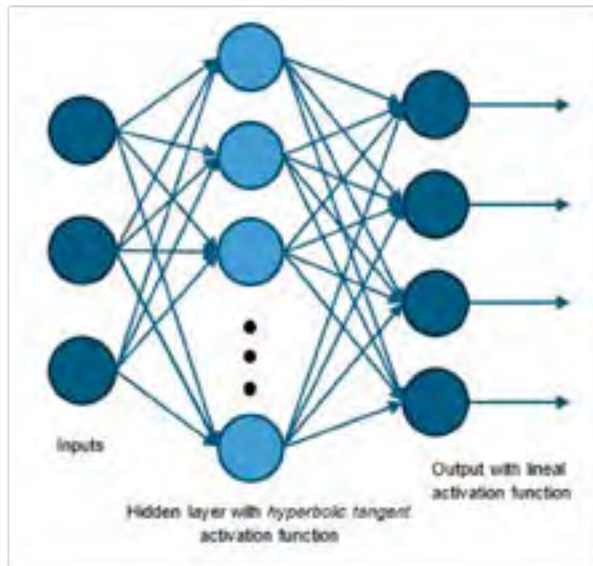


Fig. 2. Architecture design with linear output.

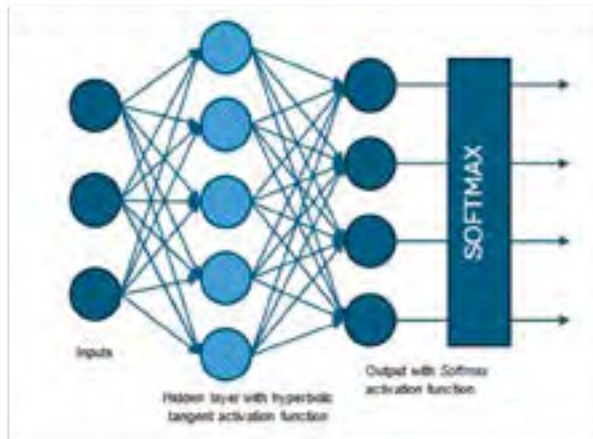


Fig. 3. Architecture design with Softmax output.

using hyperplanes in case of linear function and by probability in the case of Softmax function.

Simulation is carried out in a virtual Python environment on the Google Colab server, using the TensorFlow library to generate neural network models. By implementing this library, the Adam optimizer model is used and loss (Mean

square error for lineal out and categorical cross entropy for Softmax) and accuracy (f1-score) metrics are assigned. The training process is planned to start with a low number of epochs and gradually increase them based on the behavior of the neural network.

### 2.3 Implementation of Backpropagation

Training neural networks is carried out using backpropagation algorithm, which adjusts the weights of neural network to minimize loss function. This process consists of two main phases: forward pass and backward pass.

**Forward Pass:** In this step, input data is propagated through neural network, calculating outputs of each layer until final prediction is obtained. For each neuron, corresponding activation function is applied. **Backward Pass:**

In this phase, error between neural network's prediction and actual value is calculated. This error is propagated backward through network, updating weights of each neuron using chain rule to compute gradients. General updating weight is:

$$w_{ij} = w_{ij} - n \frac{\partial L}{\partial w_{ij}} \quad (5)$$

1.  $w_{ij}$  represents the weight between neuron  $i$  and neuron  $j$ .
2.  $n$  is the learning rate, which controls the size of the weight updates.
3.  $\partial L$  is the gradient of the error  $L$  for the weight  $w_{ij}$ .

## 3 Results

### 3.1 Analysis of Physiological Signals

Analysis of the physiological signals in dominance-activation-valence space revealed clear patterns associated with each emotion:

Happiness: High valence, moderate activation, and high dominance.

Sadness: Low valence, low activation, and low dominance.

Fear: Low valence, high activation, and low dominance.

Anger: Low valence, high activation, and dominance.

These patterns align with findings reported in literature, validating effectiveness of proposed approach.

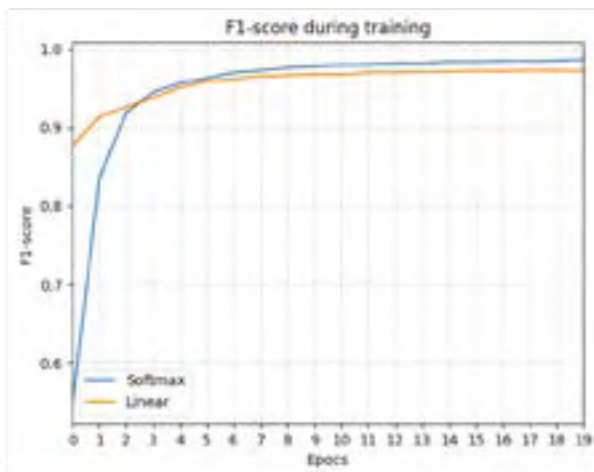
### 3.2 Performance of the Neural Networks

Both implemented neural networks performed well in classification tasks. Main difference between them is number of iterations required to achieve obtained result.

As shown in Table 2, differences F1-score result are minimal, suggesting that both networks have high classification potential. Now, it is possible to conclude about both models:

| Model                  | F1-score |
|------------------------|----------|
| Linear Neural Network  | 0.96     |
| Softmax Neural Network | 0.99     |

**Table 2.** Results of Neural Network Training.



**Fig. 4.** Evolution of the Softmax neural network and Linear neural network training for validation dataset.

**Linear Neural Network:** Despite having a larger hidden layer (20 neurons), this model showed similar performance to Softmax Neural Network, suggesting that additional complexity is not necessary for this dataset.

**Softmax Neural Network:** With a smaller hidden layer (5 neurons) and a Softmax activation function in output layer, this model also achieved exceptional performance, highlighting effectiveness of Softmax function for multiclass classification problems.

Tests are conducted using a wide variety of configurations to determine which setup provided the best performance and optimal learning time. The best training results for both networks were achieved with a batch size of 10, leading to fast training and good performance, as observed in Fig. 4.

To ensure that these results are not merely due to overfitting to the training data, tests were conducted by adding a small perturbation to test data, ranging from -0.1 to 0.1. Such a small noise level is chosen because emotions to be classified are located at short distances in the three-dimensional space. If perturbation exceeded  $\pm 0.2$ , points belonging to one emotion would cross threshold of the hyperplanes classifying the emotions.



## 4 Discussion

Experimental results showed high performance for both neural networks, suggesting that three-dimensional space governed by dominance, activation, and valence has a strong capacity to effectively represent emotions based on physiological signals. Additionally, it demonstrates that this representation is effective for training neural networks. Ability of neural networks to achieve a high F1-score value indicates that implemented physiological signals contain sufficient information to discriminate among four emotions studied.

Similarity in the performance of both models suggests that, for the dataset used, simple architecture can achieve good and accurate classification. This is highly relevant for future research, as using simpler architecture makes their implementation in real-time systems more straightforward, where computational efficiency is crucial.

## Conclusion

This study shows feasibility of using neural networks to classify emotions based on physiological signals transformed into a dominance-activation-valence space. Results highlight the importance of representing emotions in a multidimensional space and effectiveness of neural networks in learning complex patterns from physiological data. Future research could explore generalization of these models to other datasets or incorporation of additional signals, such as brain activity (EEG) or facial expressions, to further improve classification accuracy.

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# Artificial Intelligence for monitoring water pollutants

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**Abstract.** This project aims to develop an innovative model based on neural networks and differential equations (DEs) to analyze, simulate, and predict the dynamics of pollutants in water bodies. The approach focuses on mixing problems, where the concentration of substances changes over time due to the inflow and outflow of pollutants within the system. Through mathematical modeling, the project seeks to accurately represent the physical and chemical processes affecting water quality, while neural networks provide the capability to learn complex patterns and make precise predictions based on observed data. The proposed methodology enables the identification of critical pollution peaks, predicts their evolution over time, and assesses their environmental impact, offering essential information for preventing and mitigating risks associated with water quality. By integrating advanced artificial intelligence techniques with the rigor of mathematical modeling, this project addresses the growing need for innovative tools to support sustainable water management. Moreover, the developed model can serve as a key decision-making tool for environmental authorities and water resource managers. It facilitates strategic planning and the design of public policies aimed at ensuring the sustainability of natural resources. This approach not only promotes environmental conservation but also positively impacts economic and social development by securing access to clean water for present and future generations.

**Keywords:** Artificial Intelligence, education, applied physics, neural network, DEs, environmental sciences

## 1 Introduction

Rivers, as natural streams of freshwater flowing from higher elevations to lower areas, play essential roles within the hydrological cycle by transporting water and sediments through diverse ecosystems. These fluvial systems not only serve as critical habitats for a wide range of aquatic and terrestrial species but have also been fundamental for the development of human civilizations throughout history, providing sources of water, transportation routes, and economic drivers (Ward & Tockner, 2001).

The importance of rivers spans multiple dimensions, as they are vital for supplying water for human consumption, agricultural production, and industrial activities, in addition to being key sources for hydroelectric power generation. Rivers also support

<https://doi.org/10.61728/AE20255206>



ecosystems with remarkable biodiversity and provide essential ecosystem services, such as climate regulation and natural water purification. Several studies highlight that rivers and lakes are facing unprecedented pressures due to human activities, which jeopardize their ecological and socio-economic functions (Grill et al., 2019).

Today, rivers face significant threats stemming from pollution, the overexploitation of water resources, and the effects of climate change. Industrial and agricultural discharges have severely compromised water quality, impacting aquatic ecosystems and posing risks to human health. Additionally, interventions such as dam construction and excessive water extraction for irrigation have altered natural flow regimes, negatively affecting fluvial ecosystems. Recent research has identified the presence of heavy metals and persistent organic compounds in rivers as a serious threat to both aquatic biodiversity and human communities that rely on these resources (Tóth et al., 2016).

The degradation of rivers has far-reaching consequences. Impacts on water quality and availability directly affect food security, public health, and economic activities, especially for communities that depend on these resources for their livelihoods. Moreover, the loss of biodiversity and changes in ecosystem services linked to rivers can undermine the capacity of ecosystems to adapt and recover from future disturbances. To mitigate these effects, it is crucial to implement conservation policies and sustainable management strategies that protect the integrity of fluvial systems and promote the well-being of human communities that rely on them (Grill et al., 2019).

In the present context, the ability to anticipate and manage water quality is essential for safeguarding water resources and ensuring community well-being. The growing need for innovative tools to effectively monitor water pollution has driven the adoption of advanced approaches, such as combining mathematical modeling with artificial intelligence (AI), which offer accurate, real-time solutions to address this challenge (Pellenz et al., 2020).

This project combines the solution of differential equations (DEs) and artificial neural networks to model and predict the dynamics of pollutants in water bodies. By integrating AI techniques and mathematical modeling, the system allows for the analysis of how pollutants spread and dilute based on factors such as flow rate, pollutant load, and environmental conditions. Trained with historical water quality data, the model can identify complex patterns, predict pollution peaks, and assess environmental impacts, providing a precise tool for the management and protection of water resources.

This project not only aims to understand how pollution levels in Michoacán's rivers vary based on environmental and human factors but also seeks to generate concrete, scalable solutions that contribute to more sustainable water management.



## 2 Background

Artificial Intelligence (AI) has become an essential tool in environmental management, standing out for its ability to analyze large volumes of data and detect complex patterns. In pollutant dispersion modeling, AI enables the prediction of trajectories and concentrations of harmful substances in the air, water, and soil by integrating variables such as meteorological and geospatial data. These capabilities have significantly improved decision-making and the implementation of public policies, protecting both ecosystems and human communities. Additionally, AI plays a key role in responding to ecological disasters such as oil spills, wildfires, and floods. With predictive systems based on historical and real-time data, AI allows for the simulation of critical scenarios and the optimization of response and mitigation strategies. Integrated with tools like remote sensors and satellite imagery, AI facilitates constant ecosystem monitoring and early detection of environmental changes, significantly contributing to environmental protection and human well-being (Kolasa-Więcek, 2011).

Using predictive models based on machine learning, advanced simulations have been developed to understand and predict how hydrocarbons disperse in water. These simulations incorporate complex variables such as ocean currents, water temperature, winds, and other climatic conditions, enabling accurate predictions of spill trajectories and spread. This information is crucial for prioritizing response areas, identifying high-risk zones, and preventing severe damage to vulnerable ecosystems like coral reefs, mangroves, and marine habitats. AI applications have significantly optimized cleanup and mitigation strategies. By analyzing real-time data, models can suggest ideal locations for deploying containment barriers or initiating recovery operations, maximizing resource efficiency. They also assist in assessing the environmental impact post-event, facilitating the design of ecological restoration programs. These advancements not only minimize the environmental and economic consequences of oil spills but also reduce response times, protecting both biodiversity and the communities that rely on marine environments for their livelihoods. The integration of AI in this field represents a significant shift toward more precise and effective management of ecological disasters (Termitope Yekeen & Balogun, 2020).

One relevant work in this field is by Quirónes Huatingari et al. (2020), who developed a neural network to estimate the Water Quality Index using various environmental monitoring variables. Their research highlighted the benefits of neural networks in processing large volumes of data, such as pollutant concentrations, pH, temperature, and other critical parameters that determine water quality. The proposed approach not only provided an effective tool for estimating water quality but also allowed for more accurate predictions of potential changes in water conditions over time, which is essential for efficient water resource management.

Additionally, a study conducted by Flores et al. (2023) on the water quality of the Loa River in the Atacama Desert, Chile, used machine learning models to classify water quality status and predict its variations over time. This research focused on water quality classification and the identification of potential pollutants, using both

historical data and specific environmental parameters of the area. The study demonstrated how AI techniques can identify and predict the effects of pollution in rivers under extreme climatic conditions, which has direct implications for other regions with similar environmental characteristics.

Similarly, the study by Conejeros Molina et al. (2021) addressed water quality monitoring in rural drinking water systems. Using an AI-based approach, this work provided effective tools for water management in rural areas, where water quality is crucial for public health and local development. A neural network model was used to predict contamination levels based on variables such as pollutant load, flow rate, and characteristics of the water distribution system. This approach demonstrates the viability of neural networks as tools for predicting water quality and optimizing available resources in rural drinking water systems.

Collectively, these studies highlight the potential of neural networks to accurately and efficiently monitor water quality. However, few studies have combined the use of differential equations (DEs) with neural networks to model and predict pollutant dynamics in water bodies, especially in regions with environmental complexities like Michoacán. This project aims to advance this field by integrating these approaches, providing a predictive tool that not only simulates pollution evolution but also supports the implementation of concrete solutions for sustainable water management.

### 3 Problem Statement

**Research Question.** How can a model based on neural networks, combined with differential equations, improve the analysis, simulation, and prediction of contaminant dynamics in water bodies, enabling the identification of critical pollution peaks, the anticipation of its future evolution, and the assessment of its environmental impact?

**Clarity and Focus.** The central point of the research is to design and validate a hybrid model that integrates artificial intelligence and mathematical modeling to address mixing problems in water bodies. This includes analyzing how the inflow and outflow of pollutants affect their temporal concentration, predicting future behaviors, and generating useful information to mitigate environmental risks and optimize water management. The research specifically focuses on the applicability of the model to identify critical pollution events and facilitate real-time decision-making.

**Contribution to the Field.** This proposal provides an innovative approach to environmental management and water monitoring systems by integrating artificial intelligence techniques with traditional mathematical models. The impact of this research lies in its ability to provide advanced predictive tools, which not only enable a more effective response to pollution events but also improve long-term planning. Additionally, by linking artificial intelligence with environmental modeling, the theoretical and methodological framework is expanded to address complex problems in natural resource conservation, positioning this research as a reference in the application of emerging technologies for environmental sustainability.

### **3.1 Relevance and Pertinence**

#### **Social Relevance**

Water is a vital resource for life and sustainable development. In a global context where water pollution poses a significant threat to public health, ecosystems, and food security, efficient monitoring of contaminants in water bodies becomes a priority. This project addresses a critical issue by developing advanced technological tools that allow for the anticipation and management of pollution events. Ensuring water quality directly contributes to the well-being of communities, environmental sustainability, and the achievement of the Sustainable Development Goals (SDGs), particularly SDG 6: Clean Water and Sanitation.

#### **Practical Implications**

The development of a neural network-based model for pollutant analysis has immediate practical applications. It allows environmental authorities, water resource managers, and companies to identify critical pollution peaks, assess their impact in real-time, and design effective mitigation strategies. Additionally, the model's predictive capacity strengthens long-term water management and planning, reducing environmental and economic risks. The implementation of this system can be integrated into real-time monitoring platforms, optimizing resources and preventive actions.

#### **Theoretical Value**

The project combines two fundamental disciplines: mathematical modeling using DEs and artificial intelligence, specifically neural networks. This interdisciplinary approach generates new knowledge about the dynamics of pollutants in complex water systems and their behavior under different conditions. The integration of these methods not only enriches the existing theory on mixing and dispersion processes but also opens pathways for their application in other environmental systems, fostering research in related areas.

#### **Methodological Usefulness**

The proposed methodology stands out for its versatility and scalability. By modeling pollutant dynamics with DEs and neural networks, a tool adaptable to different geographical contexts and types of water bodies is developed. The ability to predict future scenarios and assess impacts strengthens the design of public policies and environmental management strategies. Furthermore, this approach can be replicated for other environmental issues, positioning it as a methodological reference for the use of artificial intelligence in natural resource conservation.

Altogether, our proposal not only addresses an urgent need that affects us all but also provides innovative and sustainable solutions that benefit both the natural environment and human communities.

### 3.2 Goals

#### General Goal

To develop a model based on neural networks and differential equations to analyze, simulate, and predict the dynamics of pollutants in water bodies, in order to identify critical pollution peaks, anticipate their evolution, and assess their environmental impact, contributing to informed decision-making and the sustainable management of water resources.

#### Specific Goals

- To design a mathematical model based on differential equations that describes the mixing processes and concentration variations of pollutants as a function of inflow and outflow flows in water bodies.
- To implement and train a neural network that, using data generated by the mathematical model and empirical observations, allows predicting future pollution scenarios and evaluating their impact over time.
- To validate the proposed model by comparing its predictions with real water monitoring data, to optimize its accuracy and ensure its applicability in environmental risk management and public policy planning.

## 4 Methodology

This project uses a non-experimental approach based on computational simulations to model and predict the dynamics of pollutants in bodies of water. The methodology focuses on the development and training of artificial neural networks designed to solve ordinary (ODE) and partial (PDE) differential equations, which describe the mixing and diffusion of pollutants in aquatic systems.

### 4.1 Procedure

#### Definition of the model

The ODE that models the inflow and outflow of pollutants in a water reservoir is:

$$\frac{dq}{dt} = r_e - r_s \quad (1)$$

where:  $r_e = c * a$  represents the rate of entry of pollutants, with  $c$  being the concentration and  $a$ , the rate of water entry. Moreover,  $r_s = q * v * b$  models the exit of pollutants, where  $q$  is the current flow,  $v$  is the system volume, and  $b$  is the exit rate.

On the other hand, the PDE that models the diffusion of a contaminant substance of certain density in a medium is

$$\frac{\partial u}{\partial t} = k (\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}) + f(x,y) \quad (2)$$

where:  $u=u(x,y,t)$  represents the concentration of pollutants,  $k$  is the diffusion coefficient and  $f(x,y)$  is a source term dependent on the spatial coordinates.

```
import torch
import torch.nn as nn
import torch.nn.functional as F
import torch.optim as optim

# Parameters
input_size = 1
hidden_size = 10
output_size = 1

# Layers
input_layer = nn.Linear(input_size, hidden_size)
hidden_layer = nn.Linear(hidden_size, hidden_size)
output_layer = nn.Linear(hidden_size, output_size)

# Loss function
loss_fn = nn.L1Loss()

# Optimizer
optimizer = optim.Adam(model.parameters())

# Training loop
for epoch in range(1000):
    # Forward pass
    model.train()
    for i in range(100):
        # Input
        x = torch.randn(1, input_size)

        # Forward pass
        h1 = F.relu(input_layer(x))
        h2 = F.relu(hidden_layer(h1))
        y = output_layer(h2)

        # Loss
        loss = loss_fn(y, target)

        # Backward pass
        loss.backward()

        # Optimizer step
        optimizer.step()

        # Zero the parameter gradients
        optimizer.zero_grad()

    # Print the loss
    print('Epoch: %d, Loss: %f' % (epoch, loss))

# Save the model
torch.save(model.state_dict(), 'model.pth')
```

Fig. 1. Architecture of the network to model the inflow and outflow of contaminants.

```
import torch
import torch.nn as nn
import torch.nn.functional as F
import torch.optim as optim

# Parameters
input_size = 1
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        # Backward pass
        loss.backward()

        # Optimizer step
        optimizer.step()

        # Zero the parameter gradients
        optimizer.zero_grad()

    # Print the loss
    print('Epoch: %d, Loss: %f' % (epoch, loss))

# Save the model
torch.save(model.state_dict(), 'model.pth')
```

Fig. 2. Architecture of the network with the equation that models diffusion.

## Neural network architecture

In order to solve the ODE, the proposed architecture is as follows:

*Input layer:* Receives time ( $t$ ).



**Hidden layer:** Three layers, each with 128 neurons and Tanh activation, introducing non-linearity.

**Output layer:** Returns the pollutant amount  $q$ . A specific formulation is incorporated to satisfy the boundary condition

$$q(0) = 100; \quad q(t) = q(0) + t * NN(t), \quad (3)$$

where  $NN(t)$  is the output of the neural network,

For the PDE (DiffusionNet), the selected architecture was as follows:

*Input Layer:* Receives  $(x, y, t)$ .

*Hidden Layer:* Three hidden layers with 64 neurons each and Tanh activation function.

**Output Layer:** Returns  $u(x,y,t)$ , the concentration of pollutants.

```

1 x = 0.01 # initial value of  $\theta$ 
2 w = 200. # initial value of  $w$ 
3 b = 250. # initial bias
4 z = 0.0001 # initial value of  $\eta$ 
5 initial_value = torch.tensor([w, b]) # initial weights and bias
6
7 def train_step(optimizer, network):
8     # For 100 epochs
9     for i in range(100):
10         # w = w -  $\eta \cdot \nabla w$ 
11         # b = b -  $\eta \cdot \nabla b$ 
12         optimizer.step()
13
14 # After 100 epochs
15 def test_step(network):
16     # Test the network
17     test_loss, test_acc = test_step(network)
18     print('Test Loss: %f, Test Accuracy: %f' % (test_loss, test_acc))
19
20 # Main function
21 def main():
22     # Create the network
23     net = torch.nn.LSTM(1, 1)
24     # Create the optimizer
25     optimizer = optim.Adam(net.parameters())
26     # Create the data loader
27     data_loader = torch.utils.data.DataLoader(
28         torch.utils.data.TensorDataset(
29             torch.rand(1000, 1),
30             torch.rand(1000, 1)
31         ),
32         batch_size=10,
33         shuffle=True
34     )
35     # Train the network
36     for i in range(100):
37         train_step(optimizer, net)
38     # Test the network
39     test_step(net)
40
41 if __name__ == '__main__':
42     main()

```

Fig. 3. Parameter definitions and the loss function that enforces boundary conditions

[illegible]

Fig. 4. Definition of the PDE, loss, boundary and initial conditions, and the generation of training data using a spatial and temporal mesh.

### Generation of training data

For the ODE, values of  $t$  were generated in an interval from 0 to 50 minutes, with higher point density near  $t=0$  to ensure compliance with the boundary condition.

For the PDE, a uniform spatial mesh was used over the domain  $[0, L_x] \times [0, L_y]$  and temporal  $[0, T]$  with  $n=50$  points.

The data was scaled and prepared to maximize the model accuracy.

## 4.2 Training the network

### Loss

A loss function was used that combines: Error in solving the ODE. Penalization for violating the initial condition.

### Optimization

The RAdam optimizer was used with a learning rate scheduler (StepLR) that dynamically adjusts the rate to stabilize training.

The model was trained for 2500 and 2000 epochs.

```

4. def train():
    # Create the model and the loss function
    model = Net()
    loss = Loss()
    # Create the optimizer
    optimizer = optim.Adam(model.parameters())
    # Create the scheduler
    scheduler = optim.lr_scheduler.StepLR(optimizer, step_size=1000, gamma=0.1)
    # Training loop
    for epoch in range(2500):
        # Train the model
        train_loss = 0
        for batch in range(100):
            # Forward pass
            output = model(input)
            # Compute the loss
            loss_value = loss(output, target)
            # Backward pass
            loss_value.backward()
            # Update the parameters
            optimizer.step()
            # Clear the gradients
            optimizer.zero_grad()
        # Compute the average loss
        train_loss += loss_value
    # Print the final loss
    print('Final training loss: %f' % train_loss)

```

Fig. 5. Training of the first network (ODE)

```

def train_diffusion_network():
    # Define model architecture
    model = DiffusionNetwork()
    # Define loss function
    loss_fn = nn.L2Loss()
    # Define optimizer
    optimizer = optim.Adam(model.parameters())
    # Training loop
    for epoch in range(100):
        # Generate synthetic data
        x_train, y_train = generate_synthetic_data(10000)
        # Forward pass
        y_pred = model(x_train)
        # Calculate loss
        loss = loss_fn(y_pred, y_train)
        # Backward pass
        optimizer.zero_grad()
        loss.backward()
        # Update parameters
        optimizer.step()
        # Print progress
        if epoch % 10 == 0:
            print(f'Epoch {epoch}, Loss: {loss.item():.4f}')
    # Save the trained model
    torch.save(model.state_dict(), 'diffusion_model.pth')
    print('Training completed. Model saved.')

```

Fig. 6. Training of the diffusion network

### Model validation

After training, the model was evaluated by generating predictions over a time range  $t$  and comparing the results with the expected solution to verify consistency.

## 4.3 Equipment and Tools

### Software

Python 3.9 with libraries: torch for neural network implementation, matplotlib for result visualization, numpy for mathematical operations

### Data collection

Data used for training is artificially generated based on the parameters of the defined differential equations. In future applications, the model could integrate with sensor systems for real-time data collection from local rivers.

### Data analysis

The mean squared error (MSE) between the derivatives calculated by the model and the theoretical derivatives was measured. Prediction graphs of pollutants were analyzed to evaluate behavior patterns and detect.

#### 4.4 Discrepancies and Schematics

##### Neural Network Architecture

Diagram of the network layers, showing connections and activations.

##### Training Flow

Flowchart detailing the steps from data generation to model evaluation.

##### Result Graphs

Loss curves during training.

Network predictions compared to the theoretical solution.

With this methodology, the model is expected to predict the dynamics of contaminants with high accuracy, facilitating the monitoring and sustainable management of water in the rivers of Michoacán.

### 5 Results

The results obtained validate the predictive capability of both models in different scenarios.

#### 5.1 ODE

The neural network accurately predicted the temporal evolution of the contaminant quantity  $q(t)$ . Stable loss curves were observed, reaching minimum values after 1500 epochs, as seen in Fig. 7. Figure 8 depicts the numerical solution and the theoretical prediction, that are on top of each other.

#### 5.2 PDE

The DiffusionNet accurately captured diffusion and mixing patterns of contaminants across spatial and temporal domains, as can be seen in Fig. 9. Plots of the concentration  $u(x,y,T)$  at the final time showed strong alignment with expected conditions, highlighting critical areas of accumulation.

#### 5.3 Patterns and Analysis

The models identified contamination peaks and anticipated long-term trends, demonstrating their applicability in water management. The experiment replicability offers a tool adaptable to different water bodies, validating its use in diverse contexts. These results reaffirm the feasibility of the proposed hybrid approach, combining neural networks with differential equations for monitoring and predicting contaminants in water bodies.

|                                   |                                   |
|-----------------------------------|-----------------------------------|
| Epoch [100/2500], Loss: 0.819138  | Epoch [100/2000], Loss: 0.958695  |
| Epoch [200/2500], Loss: 0.805113  | Epoch [200/2000], Loss: 0.892608  |
| Epoch [300/2500], Loss: 0.803816  | Epoch [300/2000], Loss: 0.777427  |
| Epoch [400/2500], Loss: 0.800739  | Epoch [400/2000], Loss: 0.798633  |
| Epoch [500/2500], Loss: 0.800987  | Epoch [500/2000], Loss: 0.928899  |
| Epoch [600/2500], Loss: 0.800386  | Epoch [600/2000], Loss: 0.834312  |
| Epoch [700/2500], Loss: 0.800054  | Epoch [700/2000], Loss: 0.731645  |
| Epoch [800/2500], Loss: 0.800418  | Epoch [800/2000], Loss: 0.743299  |
| Epoch [900/2500], Loss: 0.800171  | Epoch [900/2000], Loss: 0.642562  |
| Epoch [1000/2500], Loss: 0.800343 | Epoch [1000/2000], Loss: 0.494870 |
| Epoch [1100/2500], Loss: 0.800127 | Epoch [1100/2000], Loss: 0.512128 |
| Epoch [1200/2500], Loss: 0.800138 | Epoch [1200/2000], Loss: 0.548058 |
| Epoch [1300/2500], Loss: 0.800182 | Epoch [1300/2000], Loss: 0.595927 |
| Epoch [1400/2500], Loss: 0.800092 | Epoch [1400/2000], Loss: 0.575160 |
| Epoch [1500/2500], Loss: 0.800082 | Epoch [1500/2000], Loss: 0.615761 |
| Epoch [1600/2500], Loss: 0.800070 | Epoch [1600/2000], Loss: 0.686164 |
| Epoch [1700/2500], Loss: 0.800078 | Epoch [1700/2000], Loss: 0.632732 |
| Epoch [1800/2500], Loss: 0.800078 | Epoch [1800/2000], Loss: 0.582592 |
| Epoch [1900/2500], Loss: 0.800066 | Epoch [1900/2000], Loss: 0.542198 |
| Epoch [2000/2500], Loss: 0.800062 | Epoch [2000/2000], Loss: 0.531965 |
| Epoch [2100/2500], Loss: 0.800064 |                                   |
| Epoch [2200/2500], Loss: 0.800070 |                                   |
| Epoch [2300/2500], Loss: 0.800070 |                                   |
| Epoch [2400/2500], Loss: 0.800074 |                                   |
| Epoch [2500/2500], Loss: 0.800074 |                                   |

Fig. 7. Loss Per Epoch

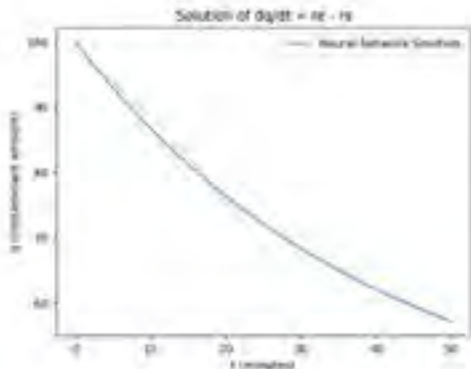


Fig. 8. Solution Plot

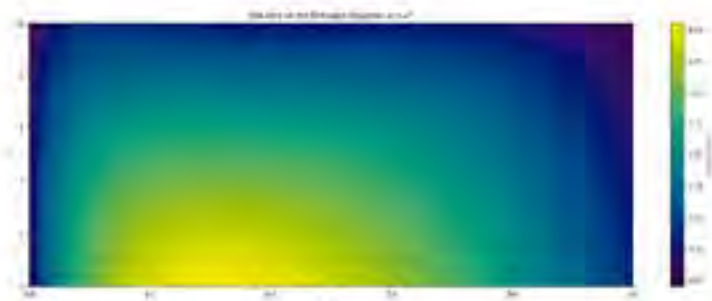


Fig. 9. Diffusion Equation Solution Plot



## 6 Conclusions

A hybrid model has been proposed that combines the power of neural networks with the rigor of differential equations, providing an accurate and adaptable tool for analyzing the dynamics of pollutants in bodies of water. The model has demonstrated its ability to predict the evolution of pollutants over time with high precision, making it a valuable tool for informed decision-making. The analysis of the results has allowed the identification of patterns in the evolution of pollution, facilitating the understanding of underlying processes and the anticipation of future events.

The model can be used by environmental authorities and water resource managers to design more efficient monitoring and management strategies, reducing the risks associated with pollution and ensuring the availability of clean water for future generations. By predicting and preventing pollution events, the project contributes to the protection of aquatic ecosystems and the conservation of biodiversity. The proposal has driven the development of advanced technological tools, such as neural networks, in the field of environmental management, opening new possibilities for research and innovation.

The combination of knowledge from mathematics, computer science, and environmental science has been fundamental to the success of the project, highlighting the importance of an interdisciplinary approach to address complex problems. The developed model can be adapted and applied to different types of water bodies and pollutants, demonstrating its potential to be a general tool in water management. In future research, integrating real-time water quality monitoring data will be crucial to validate and refine the model, as well as exploring the possibility of using real-time sensor data to enhance the system response capabilities. Other AI techniques, such as deep learning and reinforcement learning, can be explored to further improve the accuracy of the model and generalization capabilities.

This proposal directly contributes to ensure availability and sustainable management of water and sanitation for all. By providing tools to improve water quality and manage water resources, it contributes to public health, food security, and economic development in communities. The development of this model represents a significant advancement in the field of environmental management and the application of artificial intelligence to solve real-world problems. The results demonstrate the potential of this technology to improve water quality and protect aquatic ecosystems. However, it is essential to continue researching and developing such tools to address the complex challenges faced in water resource management in an increasingly changing world.

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# Neural Identifier Training with Particle Filters

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**Abstract.** Nonlinear system identification is essential for modeling complex dynamics where analytical approaches fail. Recurrent high-order neural networks (RHONNs) excel in this task but require robust training methods. Traditional approaches like the Extended Kalman Filter (EKF) struggle with non-Gaussian noise and local linearization constraints. This paper proposes Particle Filter (PF) based training for RHONNs, enabling flexible and accurate state estimation. Simulations on a pendulum and a Duffing oscillator show that PF significantly reduces identification errors compared to EKF, especially under non-Gaussian noise. The results confirm PF's potential for robust and adaptive neural training, enhancing nonlinear system identification for applications in control and robotics.

**Keywords:** Neural identification · Nonlinear systems · Recurrent high-order neural networks · Particle filter · Online training.

## 1 Introduction

In control systems, a robust understanding of the target system is paramount for designing effective control strategies [10, 14, 15, 18]. Without this understanding, the resulting control inputs may lack robustness or fail entirely. Nonlinear system identification addresses this need by replicating the dynamic behavior of the original system in a mathematical model, enabling precise control design. Among the various approaches, neural networks have emerged as a powerful resource for nonlinear system identification due to their exceptional capacity to model complex nonlinearities [9, 13].

Recurrent Neural Networks (RNNs) and their advanced variants, RHONNs, are particularly effective [2, 17]. These architectures surpass traditional multi-layer perceptrons by leveraging recurrent connections, which introduce memory into the model, enabling superior dynamic representation. High-order connections further enhance efficiency by reducing the number of required neurons, making RHONNs highly suitable for real-time applications [1].

The EKF has been one of the most widely used methods for training neural networks [16]. It extends the Kalman Filter's (KF) capability to manage nonlinear systems through local linearization. However, EKF's reliance on linearization

<https://doi.org/10.61728/AE20255213>





can result in the loss of significant nonlinear behaviors. Additionally, both the KF and EKF assume Gaussian noise distributions, a limitation in scenarios involving robotics or mobile systems where noise characteristics often deviate from Gaussian assumptions [4].

To address these limitations, this work explores the use of PFs as an alternative training method for RHONNs. PFs have demonstrated superior performance in highly nonlinear systems, often surpassing the KF and its variants [3, 7]. Unlike EKF, PFs are not constrained by Gaussian noise assumptions and can approximate arbitrary probability distributions, making them a versatile choice for nonlinear system identification [6].

This paper introduces the foundational concepts of neural network-based identifiers and provides the mathematical preliminaries of the Particle Filter. Furthermore, simulation results are presented to demonstrate the identification of nonlinear systems. The structure of this work is as follows: First, Recurrent High-Order Neural Networks are introduced as one of the most effective methodologies for addressing the system identification problem. Next, the generic Particle Filter algorithm is explained, along with its application to state estimation. The discussion then shifts to the use of the Particle Filter for training Recurrent High-Order Neural Networks, highlighting its advantages in handling non-Gaussian noise and strong nonlinearities. Finally, the results of two simulations are presented, comparing the performance of the Extended Kalman Filter and the Particle Filter in terms of their identification Mean Squared Error. The results are analyzed, and the superiority of the Particle Filter over the Extended Kalman Filter is established.

## 2 Recurrent High-order Neural Networks

For control tasks, RHONNs present numerous advantages, including their exceptional approximation capabilities and robustness to noise [1].

Consider a nonlinear system in discrete-time:

$$\chi(k+1) = F(\chi(k), u(k)) \quad (1)$$

where:

- $\chi \in \mathbb{R}^n$  is the state vector of the plant.
- $u \in \mathbb{R}^m$  is the external input vector.
- $F: \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^n$  is a nonlinear function.
- $k \in \mathbb{Z}^+$  represents discrete-time steps.

To identify the system shown in Equation (1), we consider the following discrete-time RHONN:

$$x_i(k+1) = w_i^T A_i(\chi(k), u(k)), \quad i = 1, \dots, n \quad (2)$$

where:

- $x_i$  is the state of the  $i$ -th neuron.
- $w_i$  is the vector of online-adjusted weights.
- $n$  is the state dimension.
- $A_i$  is described by Equation (3).

$$A_i(\chi(k), u(k)) = \begin{bmatrix} \prod_{j \in I_1} \lambda_{ij}^{d_{ij}(1)} \\ \prod_{j \in I_2} \lambda_{ij}^{d_{ij}(2)} \\ \vdots \\ \prod_{j \in I_L} \lambda_{ij}^{d_{ij}(L)} \end{bmatrix} \quad (3)$$

with:

$$\lambda_i = \begin{bmatrix} \lambda_{i_1} \\ \vdots \\ \lambda_{i_n} \\ \lambda_{i_{n+1}} \\ \vdots \\ \lambda_{i_{n+m}} \end{bmatrix} = \begin{bmatrix} S(\chi_1) \\ \vdots \\ S(\chi_n) \\ u_1 \\ \vdots \\ u_m \end{bmatrix} \quad (4)$$

where:

- $m$  is the number of external inputs.
- $L$  is the number of higher-order connections.
- $\{I_1, I_2, \dots, I_n\}$  is a collection of non-ordered sets of dimensions  $\{1, 2, \dots, n+m\}$ .
- $d_{ij}$  are nonnegative integers.

The function  $S(\cdot)$  is a monotonic increasing, differentiable sigmoidal function defined as

$$S(\varsigma) = \alpha \frac{1}{1 + e^{-\beta \varsigma}} - \gamma, \quad (5)$$

where  $\alpha$  and  $\beta$  are positive real numbers, and  $\gamma$  is a real number. A special case arises when  $\alpha = \beta = 1$  and  $\gamma = 0$ , which results in the logistic function. Similarly, setting  $\alpha = \beta = 2$  and  $\gamma = 1$  yields the hyperbolic tangent function [2, 13, 17].

### 3 Particle Filter

The PF is a *Sequential Monte Carlo (SMC)* method used to estimate the posterior distribution of a state given noisy measurements by representing it as a set of weighted particles [4]. This approach is particularly effective in highly non-linear and non-Gaussian state estimation problems, where traditional filtering

techniques such as the KF and its extended version struggle due to their reliance on Gaussian noise assumptions and local linearization [3].

In a PF, the posterior distribution of the state given the sequence of measurements  $z(1:k)$  is approximated as:

$$p(\rho(k)|z(1:k)) \approx \sum_{s=1}^N \omega_s(k) \delta(\rho(k) - \rho_s(k)) \quad (6)$$

where:

- $\rho_s(k)$  are the sampled particles, which represent possible realizations of the state.
- $\omega_s(k)$  are the importance weights, indicating the likelihood of each particle given the observations.
- $\delta(\cdot)$  is the Dirac delta function, which expresses the fact that the posterior is approximated by a set of discrete samples rather than a continuous function [7].

This formulation allows PF to approximate arbitrary probability distributions, making it more robust for real-world applications where sensor noise and environmental disturbances often exhibit multimodal or heavy-tailed distributions [8, 12].

### 3.1 PF Algorithm Steps

PF operates sequentially as follows:

1. **Initialization** Particles are randomly sampled from a uniform distribution [4]:

$$\rho_s(0) \sim U(\rho_{\min}, \rho_{\max}) \quad (7)$$

and initialized with equal weights:

$$\omega_s(0) = \frac{1}{N}, \quad p = 1, \dots, N \quad (8)$$

2. **Prediction** Each particle evolves according to an importance density function [3]:

$$\rho_s(k) \sim q(\rho(k)|\rho_s(k-1), z(k)) \quad (9)$$

In practice, this is often chosen as the system's transition model:

$$\rho_s(k) = f(\rho_s(k-1), u(k), v(k-1)) \quad (10)$$

3. **Weight Update** Each particle weight is adjusted based on the measurement likelihood [7]:

$$\omega_s(k) = \omega_s(k-1)p(z(k)|\rho_s(k)) \quad (11)$$

To maintain a valid probability distribution, weights are normalized [8]:

$$\omega_s(k) = \frac{\omega_s(k)}{\sum_{j=1}^N \omega_j(k)} \quad (12)$$

The weights are normalized to ensure they form a valid probability distribution, satisfying the condition that their sum equals unity. This normalization is essential for maintaining the probabilistic interpretation of the particle weights in the filtering process.

4. **Resampling** To address the weight degeneracy problem, resampling is performed when the effective sample size falls below a predefined threshold [5]:

$$N_{\text{eff}} = \frac{1}{\sum_{s=1}^N (\omega_s(k))^2} \quad (13)$$

Particles with low weights are discarded, while those with higher weights are duplicated:

$$\rho_s(k) = \rho_r^*(k) \quad (14)$$

Resampling prevents particle impoverishment, where a small subset of particles dominates the estimation, reducing diversity. Common resampling techniques include systematic resampling, multinomial resampling, and stratified resampling each balancing trade-offs between computational efficiency and variance reduction [3].

5. **State Estimation** The estimated state is obtained as the weighted sum of the particles:

$$\hat{\rho}(k) = \sum_{s=1}^N \omega_s(k) \rho_s(k) \quad (15)$$

This expectation-based estimation ensures a statistically representative approximation of the state [8].

## 4 The PF Training Algorithm

Each particle in the PF represents a potential configuration of the RHONN weights. The training process consists of iteratively updating these particles based on system observations, ensuring an accurate approximation of the nonlinear system dynamics. The PF training algorithm follows a sequential Bayesian estimation approach, as outlined in Algorithm 1.

**Algorithm 1** Particle Filter-based Online Training for RHONN

**Require:** Number of particles  $N$ , initial RHONN weights  $\{w_s(0)\}_{s=1}^N$ , number of time steps  $K$ , system measurements  $\{\chi(k)\}_{k=1}^K$ , process noise variance  $\sigma_v^2$ , observation noise variance  $\sigma_n^2$

1: **Initialization:**

2: **for**  $s = 1$  to  $N$  **do**

3:   Sample initial RHONN weights:  $w_s(0) \sim p(w_0)$

4:   Assign equal particle weights:  $\omega_s(0) = \frac{1}{N}$

5: **end for**

6: **for**  $k = 1$  to  $K$  **do**

7:   **Prediction Step:**

8:   **for**  $s = 1$  to  $N$  **do**

9:     Sample predicted RHONN weights:

$$w_s(k) \sim \mathcal{N}(w_s(k-1), \sigma_v^2)$$

10:    Compute RHONN output:

$$x_s(k) = f_{\text{RHONN}}(w_s(k), \chi(k-1))$$

11:   **end for**

12:   **Weight Update:**

13:   **for**  $s = 1$  to  $N$  **do**

14:     Compute measurement likelihood:

$$p(\chi(k)|w_s(k)) = \mathcal{N}(\chi(k); x_s(k), \sigma_n^2)$$

15:     Update particle weights:

$$\omega_s(k) = \omega_s(k-1)p(\chi(k)|w_s(k))$$

16:   **end for**

17:   **Normalize Particle Weights:**

18:   **for**  $s = 1$  to  $N$  **do**

19:     Normalize:

$$\omega_s(k) = \frac{\omega_s(k)}{\sum_{j=1}^N \omega_j(k)}$$

20:   **end for**

21:   **Resampling (if needed):**

22:    Compute effective sample size:

$$N_{\text{eff}} = \frac{1}{\sum_{s=1}^N \omega_s(k)^2}$$

23:    **if**  $N_{\text{eff}} < N/2$  **then**

24:     Resample particles  $\{w_s(k)\}_{s=1}^N$  using systematic resampling.

25:     Reset particle weights (if using systematic resampling):

$$\omega_s(k) = \frac{1}{N}, \quad \forall s$$

26:   **end if**

27:   **Weight Estimation:**

28:    Compute the estimated RHONN weights:

$$\hat{w}(k) = \sum_{s=1}^N \omega_s(k) w_s(k)$$

29: **end for**

30: **Return** final estimated RHONN weights:  $\hat{w}(K)$



#### 4.1 Initialization

The training process begins by initializing a population of  $N$  particles, where each particle represents a candidate set of RHONN weights. These initial weights are sampled from a prior distribution to ensure a diverse search space, following common practices in Particle Filters for system identification [3, 4]:

$$w_s(0) \sim p(w_0), \quad s = 1, \dots, N \quad (16)$$

where  $p(w_0)$  is typically chosen as a uniform or Gaussian distribution, ensuring that the search space is sufficiently explored. Each particle is assigned an initial importance weight:

$$\omega_s(0) = \frac{1}{N} \quad (17)$$

This uniform weighting represents an equal prior belief in all candidate solutions before any observations are made, a common initialization approach in Sequential Monte Carlo methods [5, 8].

Using the sampled weights, the RHONN generates an initial estimate of the system state:

$$x_s(0) = f_{\text{RHONN}}(w_s(0), x(0)) \quad (18)$$

where  $x_s(0)$  is the predicted system state corresponding to the  $s$ -th particle. This initialization provides the foundation for the iterative refinement of RHONN weights through the Particle Filter process. The diversity of initial particles is essential to avoid premature convergence and ensure an adequate exploration of the weight space [12].

#### 4.2 Prediction

Once the particles are initialized, the next step is the prediction phase, where each particle is propagated according to an importance density function. A common choice for this function is the system's transition model [3]:

$$w_s(k) \sim q(w(k) | w_s(k-1), x(k)) \quad (19)$$

This step introduces diversity by perturbing the particles, ensuring that the weight distribution can adapt as new observations are received. Using the predicted weights, the RHONN generates a state estimate for each particle:

$$x_s(k) = f_{\text{RHONN}}(w_s(k), x(k-1)) \quad (20)$$

where  $x_s(k)$  is the predicted system state obtained using the RHONN with the sampled weights  $w_s(k)$ . This prediction will be evaluated against the true system state in the next step.

### 4.3 Weight Update

The weight update step refines the probability distribution over the RHONN weights by assigning higher weights to particles that better match the observed system behavior. The measurement likelihood is computed using a Gaussian distribution [5, 8]:

$$p(x(k)|w_s(k)) = \mathcal{N}(x(k); x_s(k), \sigma_n^2) \quad (21)$$

where  $\sigma_n^2$  represents the variance of the measurement noise. The weights are then updated using Bayes' rule:

$$\omega_s(k) = \omega_s(k-1)p(x(k)|w_s(k)) \quad (22)$$

Finally, the weights are normalized to ensure they sum to unity:

$$\omega_s(k) = \frac{\omega_s(k)}{\sum_{j=1}^N \omega_j(k)} \quad (23)$$

This normalization step maintains a valid probabilistic interpretation of the particle weights [7].

### 4.4 Resampling

Resampling is performed to prevent degeneracy, a common issue in particle filters where most particles end up with negligible weights [3, 4]. The effective sample size is computed as:

$$N_{\text{eff}} = \frac{1}{\sum_{s=1}^N \omega_s(k)^2} \quad (24)$$

If  $N_{\text{eff}}$  falls below a predefined threshold (e.g.,  $N/2$ ), resampling is triggered. This step removes particles with low weights and duplicates those with higher weights, ensuring that the weight distribution remains well-represented:

$$w_s(k) = w_{\tau(s)}(k) \quad (25)$$

where  $\tau(s)$  is an index mapping function that selects particles based on their weights. Systematic resampling is commonly used due to its computational efficiency and reduced variance [6].

### 4.5 Weight Estimation

After resampling, the RHONN weights are estimated by computing the weighted average over all particles:

$$\hat{w}(k) = \sum_{s=1}^N \omega_s(k) w_s(k) \quad (26)$$

This estimation represents the most probable RHONN weight configuration at time  $k$  given the observations up to that point. By iterating through the Particle Filter process, the RHONN gradually adapts its weights to accurately model the nonlinear system dynamics [12].

## 5 Simulation Results

To assess the performance of the PF as an online training method for the RHONN in system identification, multiple simulations were conducted. These simulations covered a range of models, from simple mathematical systems to highly nonlinear dynamics, incorporating both Gaussian and non-Gaussian noise distributions to evaluate robustness. However, the results presented focus on a simple pendulum and a Duffing oscillator. Both systems were identified using the same RHONN architecture and experimental conditions, with training performed via the EKF and, in contrast, the proposed PF-based approach. The Mean Squared Error (MSE) was used as the primary performance metric to quantify identification accuracy.

To demonstrate the superiority of the PF over the EKF in training RHONNs, Laplacian noise was added in both the process dynamics and measurement outputs. Unlike Gaussian noise, which is commonly assumed in classical estimation techniques, Laplacian noise has a sharp peak and heavy tails, making it more representative of real-world disturbances such as sensor faults, sudden perturbations, and outliers in robotic and engineering applications [3, 7, 11]. While the EKF relies on local linearization and assumes Gaussian noise [14, 19], the PF estimates the full posterior distribution using a set of weighted particles, making it well-suited for handling non-Gaussian noise and strong nonlinearities [4, 8, 12].

### 5.1 Pendulum System

To evaluate the effectiveness of the PF in training the RHONN, we first consider the identification of a simple pendulum system. The pendulum exhibits nonlinear dynamics due to the presence of the sine function, making it an ideal test case for assessing the robustness of different identification techniques under noisy conditions.

The system dynamics are governed by the following differential equation:

$$\frac{d^2\theta}{dt^2} + \frac{b}{\mu} \frac{d\theta}{dt} + \frac{g}{l} \sin\theta + \phi = 0 \quad (27)$$

where:

- $\theta$  represents the angular displacement of the pendulum.
- $\mu$  is the mass of the pendulum.
- $l$  is the length of the pendulum.
- $g$  denotes the acceleration due to gravity.

- $b$  is the damping coefficient, representing energy loss due to friction or air resistance.
- $\phi$  represents process noise, which introduces stochastic perturbations to the system dynamics.

For system identification, we employ a RHONN model, which approximates the system's behavior through adaptive weight updates. The discrete-time RHONN model is defined as:

$$\begin{aligned}x_1(k+1) &= w_{11}S(\chi_1(k)) + w_{12}S(\chi_2(k))^2 \\x_2(k+1) &= w_{21}S(\chi_1(k))^2 + w_{22}S(\chi_2(k))\end{aligned}\tag{28}$$

where  $S(\cdot)$  was chosen as the hyperbolic tangent function, and  $w_{ij}$  are the online trained weights.

The initial conditions for both the pendulum system and the RHONN models trained with the PF and EKF are identical:

$$\chi_1(0) = x_{1PF}(0) = x_{1EKF}(0) = \frac{\pi}{4}\tag{29}$$

$$\chi_2(0) = x_{2PF}(0) = x_{2EKF}(0) = 0\tag{30}$$

This ensures a fair comparison between the two training approaches.

The training was performed using:

- EKF: This method assumes Gaussian noise and relies on local linearization, potentially limiting its effectiveness in highly nonlinear settings.
- PF: This method estimates the posterior distribution of the RHONN weights using a set of particles, allowing it to handle non-Gaussian noise and strong nonlinearities.

**Results and Performance Analysis** The system response, estimated by both RHONN models, is shown in Figure 1. The PF-trained RHONN demonstrates superior accuracy in tracking the pendulum's motion, particularly in the presence of Laplacian noise. This is further validated through quantitative analysis of the MSE, presented in Table 1.

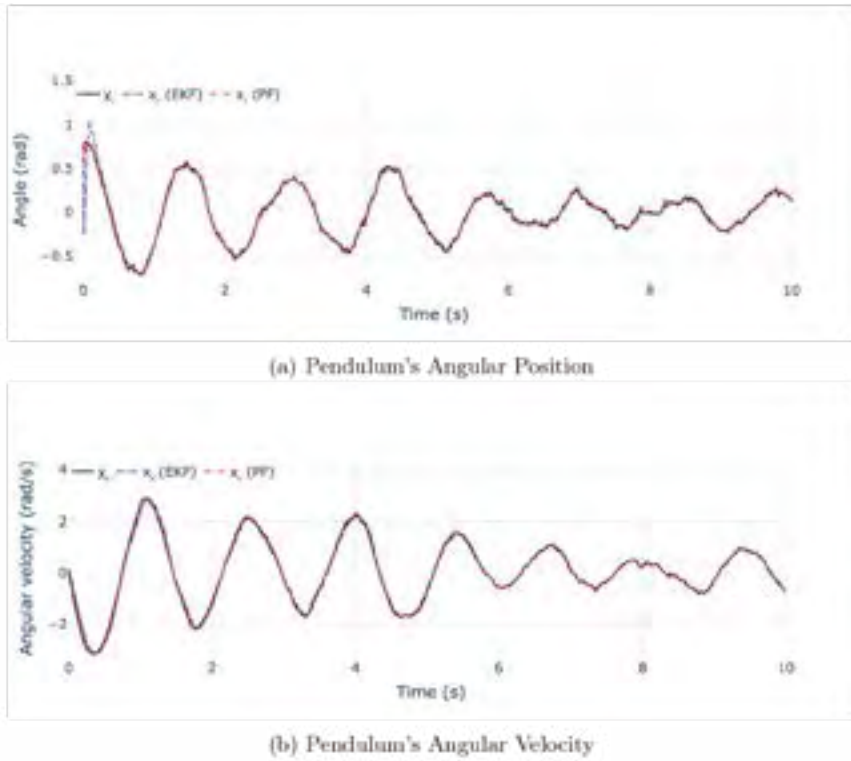


Fig. 1: Comparison of PF-trained RHONN and EKF-based training for pendulum system identification. The PF method achieves more accurate tracking in both position and velocity, particularly under non-Gaussian noise conditions.

Table 1: Mean Squared Errors (MSE) for Different Training Methods - Pendulum System

| Training Method        | MSE for $x_1$ (Position) | MSE for $x_2$ (Velocity) |
|------------------------|--------------------------|--------------------------|
| Particle Filter        | <b>0.00065</b>           | <b>0.00602</b>           |
| Extended Kalman Filter | 0.00291                  | 0.01298                  |



**KeyObservations:**

- The PF-based RHONN achieves significantly lower MSE values compared to the EKF-based RHONN, with a 77.8% reduction in position estimation error and a 53.6% reduction in velocity estimation error.
- The difference in performance is more pronounced in velocity estimation, where EKF struggles due to its reliance on local linearization.
- The presence of Laplacian noise degrades EKF performance more severely than PF, reinforcing the latter's advantage in handling non-Gaussian uncertainties.

**5.2 Duffing Oscillator System**

The Duffing oscillator is a well-known nonlinear system used to model oscillatory phenomena in physics and engineering. It is commonly employed to study chaotic behavior, bistable dynamics, and resonance effects. The Duffing equation describes the motion of a damped, periodically driven oscillator with a nonlinear restoring force and is given by:

$$\frac{d^2x}{dt^2} + \delta \frac{dx}{dt} + \alpha x + \beta x^3 = \gamma \cos(\omega t) + \phi \quad (31)$$

where:

- $x$  represents the system's displacement.
- $\delta$  is the damping coefficient, governing energy dissipation.
- $\alpha$  and  $\beta$  define the nonlinear restoring force, with  $\beta x^3$  introducing nonlinearity.
- $\gamma$  represents the external forcing amplitude.
- $\omega$  is the forcing frequency.
- $\phi$  is the process noise, modeling external perturbations.

This system exhibits both periodic and chaotic motion, depending on parameter values, making it a challenging benchmark for system identification.

To approximate the Duffing oscillator's dynamics, it is employed a RHONN, following the discrete-time representation:

$$\begin{aligned} x_1(k+1) &= w_{11}S(\chi_1(k))^3 + w_{12}S(\chi_2(k)) \\ x_2(k+1) &= w_{21}S(\chi_1(k))^2 + w_{22}S(\chi_2(k))^3 \end{aligned} \quad (32)$$

where:

- $S(\cdot)$  is a sigmoidal activation function ensuring smooth, bounded outputs.
- $w_{ij}$  are the adaptive weights, updated during training.

The initial conditions for both the Duffing system and the RHONN models trained with PF and EKF are set to:

$$\chi_1(0) = x_{1PF}(0) = x_{1EKF}(0) = 0.2 \quad (33)$$

$$\chi_2(0) = x_{2PF}(0) = x_{2EKF}(0) = 0 \quad (34)$$

This ensures consistency in evaluating both training approaches under identical conditions.

**Results and Performance Comparison** The system response estimated by the RHONNs trained via both methods is shown in Figure 2. The PF-trained RHONN achieves noticeably improved accuracy in tracking both position and velocity, particularly in regions where nonlinearities dominate the system dynamics.

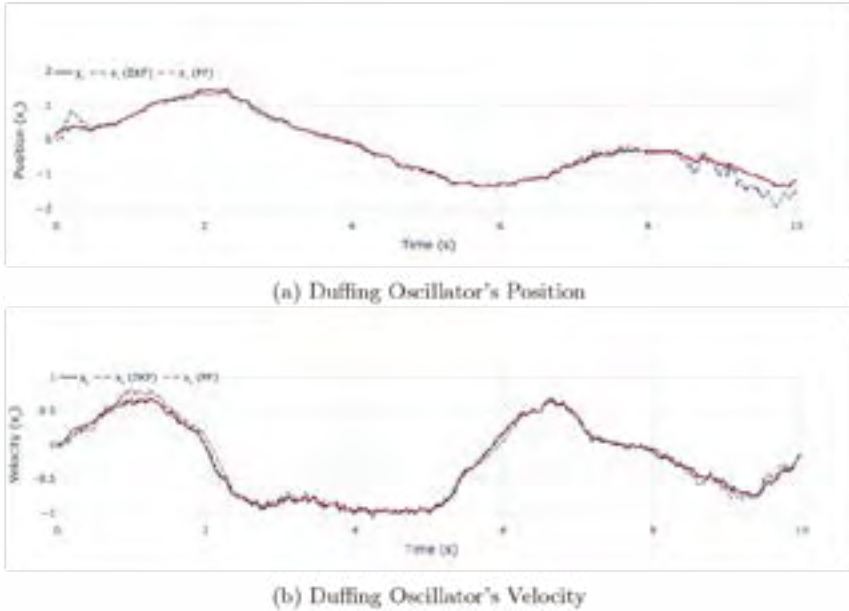


Fig. 2: Comparison of PF-trained RHONN and EKF-based training for Duffing oscillator identification. The PF method provides more accurate state estimation, particularly in capturing the system's nonlinear behavior.

Table 2: Mean Squared Errors (MSE) for Different Training Methods - Duffing Oscillator

| Training Method        | MSE for $x_1$ (Position) | MSE for $x_2$ (Velocity) |
|------------------------|--------------------------|--------------------------|
| Particle Filter        | 0.00184                  | 0.00098                  |
| Extended Kalman Filter | 0.02284                  | 0.00477                  |

#### Key Observations:

- The PF-based RHONN significantly outperforms EKF, yielding lower MSE values for both position and velocity.

- The PF achieves a 91.93% reduction in position estimation error and a 79.40% reduction in velocity estimation error compared to the EKF.
- The EKF struggles with velocity estimation, likely due to its reliance on local linearization, which may not sufficiently capture the oscillator's chaotic behavior.
- The PF training method better handles Laplacian noise, leading to more robust identification results.

The superior performance of the PF-trained RHONN can be attributed to its ability to better approximate complex probability distributions, enabling more precise weight adaptation even in the presence of strong nonlinearities and stochastic perturbations. These results further support the use of PF-based training for nonlinear system identification where conventional approaches like EKF may be insufficient.

## 6 Conclusion

This study investigated the use of PFs as an alternative training method for RHONNs in nonlinear system identification. The proposed approach was tested with comparisons against the traditional EKF training method.

The results demonstrate that the PF-trained RHONN outperforms the EKF approach in terms of accuracy, particularly when handling non-Gaussian noise. The MSEs indicate that the PF-based method achieves lower identification errors, making it a more robust and reliable training strategy for highly nonlinear and uncertain systems. These findings align with previous studies highlighting the advantages of particle filters in Bayesian state estimation for nonlinear systems [3, 4, 7].

One of the main advantages of PF-based training is its ability to approximate arbitrary probability distributions, unlike EKF, which relies on Gaussian noise assumptions and local linearization [8, 16]. This makes PF particularly effective for real-world applications, where sensor noise and environmental disturbances often follow heavy-tailed distributions [7].

Despite these advantages, computational complexity remains a challenge, as PFs require resampling steps and a large number of particles to maintain accuracy [5, 12]. Future research will focus on optimizing particle resampling techniques and improving computational efficiency to enable real-time implementations in embedded control systems while exploring hybrid approaches like PF-EKF fusion.

Overall, the results suggest that Particle Filter-based training is a promising alternative to conventional methods, offering improved robustness, accuracy, and adaptability for training RHONNs in nonlinear system identification.

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# Innovations in Uroflowmetry: Ergonomic, Cost-Effective, and AI-Powered Solutions for Sustainable Healthcare

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**Abstract.** Lower Urinary Tract Symptoms (LUTS) affect 40% of male adults over the age of 40, with this percentage increasing as they age. These symptoms impact quality of life and require frequent evaluations in clinical settings. However, access to timely diagnostic tests may be limited, delaying detection and appropriate treatment. To address this issue, a home uroflowmetry was developed to assess and monitor urinary flow from home. This device integrates advanced biosignal processing techniques, offering an innovative and accessible methodology for collecting and analyzing urodynamic data. In addition to enabling continuous monitoring, the tool provides preliminary diagnoses, enhancing autonomous management of urological health and optimizing clinical decision-making.

**Keywords:** Uroflowmeter, Lower Urinary Tract Symptoms, Diagnosis, Prevention.

## 1 Introduction

Symptoms of the Lower Urinary Tract (LUTS) encompass a set of clinical manifestations that significantly affect the male population, especially men over the age of 40. These alterations are primarily characterized by three types of manifestations: bladder storage issues, changes in urination, and post-micturition symptoms [1].

Among the most common pathologies associated with LUTS is benign prostatic hyperplasia (BPH), a condition affecting 50% of men over 60 in Mexico [2], characterized by the non-cancerous growth of the prostate, which causes obstruction in urinary flow. Prostate cancer, the second leading cause of cancer-related death in Mexican men, can also initially manifest with LUTS. Additionally, conditions affecting the urethra, such as stenosis or inflammatory processes, contribute to obstructive symptoms [3].

The timely diagnosis and management of LUTS are crucial, as up to 30% of untreated cases develop significant complications within five years, including recurrent urinary tract infections, stone formation, and progressive renal function deterioration

<https://doi.org/10.61728/AE20255220>



[4]. A complete urodynamic evaluation, considered the gold standard for diagnosis, requires specialized equipment with costs ranging from \$40,000 to \$180,000 MXN, in addition to highly trained personnel [5]. This economic barrier, coupled with the invasive nature of certain diagnostic procedures, contributes to approximately 45% of patients delaying their medical evaluation, postponing the diagnosis and treatment of underlying conditions such as benign prostatic hyperplasia (BPH) [6].

The objective of this research was to examine the challenges currently faced by the healthcare sector in diagnosing Lower Urinary Tract Symptoms, and how the current diagnostic mechanisms present specific issues. To this end, a search was conducted for various products on the market, as well as developing technologies, to identify flaws and potential innovations in diagnostic equipment. The analysis helped pinpoint crucial areas where innovations are needed and provided insight into how these improvements can enhance the healthcare system. As part of the analysis, a proposed solution to the identified flaws in diagnostic equipment is presented, along with how they can be implemented in a medium-level device. In this context, the integration of innovative technologies emerges as a promising solution to develop more accessible and less invasive diagnostic tools.

### **1.1 Problem Statement**

The current problem of Lower Urinary Tract Symptoms (LUTS) is exacerbated by multiple interconnected factors. Limited access to specialized tests, with waiting times that can exceed six months in public health systems, is combined with a low culture of prevention, where 67% of men consider urinary symptoms as a normal part of aging [7]. These figures describe the U.S. population; however, this trend is repeated globally due to the taboo surrounding discomfort related to the genital area.

In addition to the low culture of prevention, some of the current diagnostic methods are invasive (urethral catheterization), which causes reluctance to undergo these procedures, with records showing that approximately 40% of patients avoid periodic evaluations [8]. It is important to note that this percentage of patients is found in those over 50 years of age, the target population for the timely diagnosis and management of LUTS. This suggests an increased urgency regarding the methodologies implemented for this purpose[9].

It is imperative to transform the current diagnostic paradigm by eliminating access barriers and improving accuracy in monitoring urinary function. This improvement focuses on integrating an affordable home device with advanced data processing algorithms for the early detection of urological alterations and continuous patient monitoring.

## **2 Literature Review**

This literature review overviews the different methods used in the market for the construction of a uroflowmeter, as well as the current use of new technologies such as Machine Learning in the development of a diagnosis based on the data acquired by the device.

## 2.1 Operation and Mechanism of Uroflowmeters in Clinical Practice

Currently, the construction of the mechanism for a uroflowmeter is based on four main operating mechanisms for sample collection [10]. The first recorded uroflowmetry instrument is attributed to Rehfisch in 1897; this device operated based on the principle of air displacement [11]. However, the most used mechanisms on the market today are Weight Transducers, Rotating Disks, Capacitance Transducers, and Volume-based systems.

### *Weight Transducer Flowmeter*

This type of uroflowmeter involves weighing the voided urine, thereby measuring the volume of urine expelled. It also calculates the urine flow rate by differentiation with respect to time. This operating principle is also known as the Gravimetric Principle [12].

This type of uroflowmeter is the most widely used on the market due to its ease of construction. Additionally, it offers the advantage of precise measurement of the evacuated volume. However, it has several disadvantages due to its operating principle, including a slow response time, the density of the urine affecting the results, and any external impact or movement potentially causing artifacts [13].

### *Rotating-disc Flowmeter*

The uroflowmeter involves a spinning disc onto which the urine falls. The disc is kept rotating at a constant speed by a servomotor, despite variations in urine flow rate; the weight of the urine tends to slow the disc's rotation. The additional power required to maintain a constant rotation is proportional to the urine flow rate [12].

This type of uroflowmeter offers advantages such as precise flow measurement and a fast response time, thanks to the Momentum Flux Principle. However, its disadvantages include the interpretation of traces, as artifacts can arise from the "wag effect." Additionally, results are affected by urine density, and the device is difficult to clean [13].

### *Capacitance Flowmeter*

This uroflowmeter uses the Bimetallic Strip principle, where the electrical capacitance of a dipstick, mounted in the chamber, changes as the height of the urine column in a standard-sized container varies [12].

Its advantages include lower construction costs and the presence of mechanical components. However, the urine density must be set, and it is prone to artifacts caused by external impacts [13].

## 2.2 Analyzing Uroflowmetry Curves with Machine Learning

The analysis of uroflowmetry curves has significantly evolved since the introduction of the first mechanical uroflowmeter by Drake in 1948 [15], becoming a fundamental diagnostic tool in modern urological practice. This non-invasive technique provides crucial quantitative information about the function of the lower urinary tract, allowing for the detection and monitoring of various urological pathologies [16].



The standardization of measurement parameters by the International Continence Society (ICS) has established a universal reference framework for interpreting uroflowmetry studies [17]. The key parameters include maximum flow ( $Q_{max}$ ), average flow ( $Q_{ave}$ ), flow time, and total volume, with  $Q_{max}$  being particularly relevant in the evaluation of lower urinary tract obstructions, with reference values established for both genders.

Schafer et al. [18] systematized the morphological analysis of flow curves, identifying characteristic patterns including the normal bell-shaped pattern, the intermittent pattern associated with neurological dysfunctions, the flat pattern indicative of severe obstructions, and the asymmetric pattern suggesting anatomical or functional alterations. This morphological classification continues to be the basis of current clinical analysis.

The incorporation of computerized techniques has revolutionized the analysis of uroflowmetry curves. Spectral analysis using Fourier transform, developed by Yang et al. [19], allows the decomposition of curves into their frequency components, facilitating the identification of subtle pathological patterns and the elimination of artifacts. Advances in machine learning, such as artificial neural networks, have achieved accuracies above 90% in the automatic classification of patterns [20].

Kumar et al. [21] implemented support vector machine algorithms, which have significantly improved discrimination between normal and pathological patterns, while Wang et al. [22] demonstrated the effectiveness of random forests in the multiparametric analysis of flow curves. These advances in artificial intelligence have enabled a more objective and reproducible evaluation of uroflowmetry studies.

Modern real-time analysis systems, described by Park et al. [23], have introduced instantaneous data processing during the study, enabling early artifact detection and dynamic parameter adjustment. Integration with complete urodynamic studies, investigated by Yamanishi et al. [24], has significantly improved the understanding of micturition pathophysiology and diagnostic accuracy.

Current trends in the field are moving towards the development of portable monitoring systems, the implementation of more sophisticated artificial intelligence algorithms, and integration with telemedicine platforms. These advances promise to improve the accessibility and diagnostic accuracy of uroflowmetry studies, enabling more continuous and personalized monitoring of patients with lower urinary tract pathologies.

### 3 Methodology

Currently, in the healthcare market, the diagnosis of Lower Urinary Tract Symptoms is carried out using a series of methodologies focused on Urodynamics, with Uroflujometry being the main non-invasive diagnostic method due to its simplicity. However, the execution of this study has various external factors that affect the results and the accessibility of this procedure.

To create a potential solution to the diagnostic problem of Lower Urinary Tract Symptoms, we analyzed the main issues that these face, considering the economic accessibility of the study, the social paradigm surrounding diseases related to the genital

area, the process of conducting the study both methodologically and functionally, and the delay in the use of new technologies in the equipment.

### **Ergonomics: Challenges in the Design of Uroflowmetry Equipment**

These devices typically require patients to urinate in a specific position, which is not always comfortable or suitable for everyone. The shape of the urine funnel, for example, may not fit the anatomy of all patients, leading to discomfort and affecting the accuracy of the measurement. Additionally, the incorrect shape of the funnel can cause splash accidents [25].

Moreover, the environment in which the test is performed also influences the patient's experience. Many patients feel anxious when having to undergo a test related to urination, due to the perception of invasiveness and the associated shame. This phenomenon, known as "white coat syndrome," can interfere with the proper execution of the procedure and, therefore, the results obtained. Anxiety and discomfort can also result in a decrease in the quality of the data collected, affecting the effectiveness of the diagnosis [26].

### **Costs: A Barrier to Accessing Uroflowmetry**

The cost of a uroflowmetry test and the price of uroflowmetry equipment represent a significant barrier for many patients, especially in regions with limited resources. Current devices, although effective, are expensive in terms of both acquisition and maintenance. Additionally, the tests must be performed in specialized facilities, which further increases the expenses associated with the procedure. This economic factor limits access to timely diagnoses, leading many people not to undergo the necessary tests or to receive a delayed diagnosis [6].

### **Use of New Technologies: Artificial Intelligence and the Revolution in Diagnostics**

In the field of uroflowmetry, the incorporation of new technologies like artificial intelligence (AI) has begun to make a significant difference in diagnostics. However, its adoption is still limited, mainly due to the lack of proper infrastructure and the conservatism of some sectors of medicine. AI has the potential to improve the accuracy of urinary flow measurements, enabling faster and less invasive diagnoses [27].

Moreover, AI could help analyze large volumes of patient data, allowing the identification of patterns that might otherwise go unnoticed. The use of advanced technologies could also facilitate the development of smaller, more accessible, and efficient devices, reducing the need for expensive equipment and enhancing the patient's experience.

### **Future of Uroflowmetry: Home Use Devices and Continuous Monitoring**

The future of uroflowmetry could be marked by the creation of home-use devices, which would allow patients to perform tests in the comfort of their own home. These devices could integrate with mobile applications, enabling more continuous and accessible monitoring of urological conditions [28].



In conclusion, the challenges faced by uroflujometry in terms of ergonomics, costs, social context, and the adoption of new technologies are numerous, but they also present opportunities for improvement. As medicine progresses, the implementation of innovative technologies could transform the patient's experience and make diagnoses more accessible and accurate.

## 4 Results

As a result of the analysis of the current issues in uroflowmetry diagnosis, our goal is to develop a comprehensive biomedical system for uroflowmetry that includes the creation of a device with an ergonomic and durable casing to ensure accuracy in measuring urine volume and flow without interference, the development of an advanced algorithm for data processing that allows the identification of patterns indicative of lower urinary tract disorders, and the implementation of programming tools to generate clear and understandable graphical reports for patients.

FlowCare for U is a male uroflowmeter prototype designed as a home-based tool for the detection of Lower Urinary Tract Symptoms (LUTS), providing continuous monitoring and offering information that gives an integrated context of the patient and reliable clinical data. The first part is based on the weight measurement principle using piezoelectric transducers, highly sensitive sensors to mechanical distortions, while the second part involves the processing of the biosignal to obtain clinically relevant data, creating an easily accessible and understandable graphical report for users/patients, and the classification of this data through artificial intelligence for the potential early detection of pathologies primarily related to the prostate and the male urinary tract.

This proposed idea can be seen in Fig. 1, which presents a representation of the ongoing development of the FlowCare device. Currently, the development of this solution is still in progress; however, the research conducted on the current issues has enabled the creation of this prototype. Each stage carried out throughout the development of this proposed solution is detailed in the following points:

### Phase 1: Literature Review

In the first stage, a comprehensive search of existing studies was conducted to identify key points, their significance, and their relationship with men's sexual, functional, and reproductive health.

As a result, the current issue in detecting Lower Urinary Tract Symptoms (LUTS) was identified, as well as how these symptoms are linked to more severe urinary conditions in adult men [29]

Additionally, a literature review was conducted on innovations in the field of medical devices for LUTS diagnosis, revealing various products aimed at home-based screening but at excessively high prices for the target audience.

The conclusion of this research led to establishing the objectives and components that would be integrated into the final prototype, aiming to develop a comprehensive and holistic project that fulfills its purpose as an easy-to-use medical device.



**Fig. 1** Visual representation of the development flow of the FlowCare For U device, designed for the early detection of Lower Urinary Tract Symptoms (LUTS) from home. This process encompasses the review of literature to observe what has already been recorded, the creation of a low-cost circuit for data collection, the design of the prototype, the integration of AI for early diagnosis, and the completion of the device along with the patient's status report.

### Phase 2: Circuit

The second part of the project involved designing the electronic circuit for data acquisition, specifically measuring the patient's urine flow. This circuit consists of three key components:

1. **ESP32 Microcontroller** – Responsible for collecting and processing sensor data.
2. **Load Cell** – Measures variations in urine flow using strain gauges, based on the Wheatstone bridge configuration. The selected load cell has a 5 kg limit and generates a small voltage signal when deformed by an applied load.
3. **HX711 Module** – Amplifies and converts the analog signal from the load cell into a digital format using a 24-bit ADC. It then transmits the data to the ESP32 via a two-wire serial interface (Clock and Data), ensuring precise weight readings.

For wireless communication, the ESP32 was configured as a Bluetooth device, allowing real-time data transmission to a mobile device or computer. Depending on the application, Bluetooth Low Energy (BLE) or Serial Bluetooth (SPP) was used, enabling users to receive, visualize, and analyze the data through a compatible app or software.

### Phase 3: Prototyping

The uroflowmeter was composed of several parts that together function as the hardware. First, it was designed with an ergonomic approach for personalized home use,

requiring no technical knowledge and being easy to clean for the user. This design was 3D-printed to achieve the goal of being a low-cost device.

This process focused on a support structure for capturing urination with two objectives: preventing splashing accidents during urination and ensuring that the flow correctly falls into the collection cup. Additionally, during this prototyping stage, efforts were made to create a small and user-friendly uroflowmeter, considering its intended home use.

#### **Phase 4: Database and AI Classification**

Once the data was acquired and transmitted via the Bluetooth communication protocol, it was processed and conditioned to quantify the six most important values of our curves, according to the ICS.

In addition to being processed to obtain these values, the data was fed into an AI system that classified it to provide a possible diagnosis of the patient's lower urinary tract health.

The AI is trained using a database previously provided by a urologist. With the goal of improving urological diagnostic equipment, the specialist contributed a dataset of adult male patients who had consulted him for abnormalities in their natural urination patterns.

This AI system was developed using an algorithm capable of classifying patient data for the detection of potential pathologies related to the urinary tract and prostate.

#### **Phase 5: Uroflowmetry Report**

The goal is to generate a report for each urination, allowing the user to visualize both the processing and their flow and volume curves, as well as the six key metrics obtained from these graphs. Additionally, the report will include a diagnosis of their Lower Urinary Tract condition, enabling personalized monitoring.

#### **Phase 6:**

Thus, with the completion of the project methodology design and the prototyping of four deliverables, the system includes: the uroflowmeter ready for measuring changes in urine flow, the support structure along with the collection urinal to ensure accident-free collection without altering the flow, a collection cup, and a final report on the patient's urination.

## **5 Discussion**

The current landscape of diagnosing Lower Urinary Tract Symptoms (LUTS) reveals several significant barriers that hinder early detection and treatment. As highlighted in the introduction, LUTS is a common issue among adult men, especially those over 40, and often points to underlying conditions such as benign prostatic hyperplasia (BPH) and prostate cancer. However, the traditional diagnostic methods, including urodynamics, face challenges such as cost, invasiveness, and accessibility, which delay timely



diagnosis and treatment. These barriers ultimately lead to worsening health conditions and increased healthcare costs due to the development of complications.

One of the main findings of this study is the identification of the limitations in current diagnostic devices. While uroflowmetry remains a widely used non-invasive diagnostic tool, the mechanisms of existing uroflowmeters often suffer from inaccuracies due to external interference, ergonomic limitations, and high costs. Additionally, many patients are deterred from undergoing the necessary tests because of anxiety, discomfort, and the perceived invasiveness of certain procedures. The low cultural awareness of the importance of preventing urinary disorders further exacerbates these challenges, with a significant proportion of men regarding urinary symptoms as a normal part of aging, thus avoiding seeking medical attention until symptoms become severe.

Given these issues, the proposed home-use uroflowmeter presents a novel solution that addresses multiple aspects of the diagnostic process. The integration of a user-friendly, low-cost device that allows for continuous monitoring of urinary flow represents a significant improvement over traditional method. By enabling patients to collect their own data at home, the device not only enhances convenience and comfort but also reduces the stigma often associated with clinical visits for urinary health.

Moreover, the incorporation of advanced technologies such as artificial intelligence (AI) holds the potential to revolutionize how uroflowmetry data is analyzed. The application of machine learning algorithms to identify patterns indicative of urinary tract disorders offers the advantage of higher diagnostic accuracy and objectivity. The development of AI-based systems for early detection allows for quicker and more accurate identification of potential issues, reducing the need for costly and invasive procedures in the future. In addition to improving diagnostic speed, AI can also help identify at-risk individuals earlier, enabling preventive care that reduces the likelihood of complications such as recurrent infections or kidney damage.

In conclusion, this research highlights the need for innovation in the diagnostic tools available for LUTS. The integration of home-use devices with AI for data analysis presents a transformative opportunity to overcome existing barriers such as cost, accessibility, and patient reluctance. By addressing these challenges, this solution could pave the way for a more efficient, affordable, and patient-centered approach to managing urinary tract health. Ultimately, this innovation will contribute to a more proactive healthcare model that emphasizes prevention, early detection, and continuous monitoring, benefiting both patients and healthcare systems alike.

## **6 Conclusion**

Through the search for improvements in the diagnostic processes of Lower Urinary Tract Symptoms, this study allows us to develop a possible solution to the current problems in the healthcare sector, specifically in the urology field.

According to our research, innovation in medical diagnosis can lead to improvements in patient care, cost savings in both diagnosis and the consequences of later-diagnosed diseases, as well as enhanced management of the data obtained from each diagnostic study.

Furthermore, it was discovered that the current development of new technologies, such as Machine Learning for issuing a potential diagnosis, presents a huge opportunity for implementation in new devices. The study also shows that this potential diagnostic aid is being developed through multiple modalities for analyzing the data, whether through the analysis of the curves formed or simply by the uroflowmeter parameters collected by the device.

Finally, the proposed solution will not only optimize the diagnostic process, reducing detection times through the creation of a culture of urinary disease prevention and the development of a clinical history related to the patient's urination, but it would also reduce costs associated with managing complications. In doing so, a more efficient, accessible, and preventive care model is promoted, aligned with the current needs of the healthcare system.

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# Neural Network-Based Digital Twin for Hypertension Simulation

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**Abstract.** Hypertension, a significant cardiovascular disease, necessitates continuous monitoring and precise predictive models to optimize treatment strategies. This research proposes a Digital Twin for Hypertension, integrating a mathematical model based on Olufsen's differential equations with artificial neural networks to dynamically adjust vascular resistance, arterial compliance, and blood flow inertia. This model is implemented in MATLAB®, utilizing the Runge-Kutta method to solve 11 differential equations. In contrast with conventional blood pressure monitoring techniques, which rely on discrete measurements, this approach provides real-time estimation of blood pressure fluctuations, allowing for improved risk stratification and personalized treatment recommendations. Expected results suggest that the use of the digital twin can enhance hypertension management by adapting to individual physiological conditions and predicting pressure variations more accurately than conventional methods. Compared to existing compartmental models, this approach leverages neural networks to optimize parameter estimation, improving prediction accuracy and adaptability. However, challenges remain about acquiring real-time data and achieving adequate computational efficiency, issues which will be addressed in future research. Potential applications include integrating wearable devices for continuous blood pressure monitoring and simulation of pharmacological interventions. It is submitted that this research makes a significant contribution to electronics and communication by demonstrating how mathematical modelling and artificial intelligence can be combined to enhance medical simulations. Future research will focus on real-time validation, optimization of computational performance, and extending the model's applicability to personalized medicine. The digital twin framework has been identified as a valuable instrument for enhancing hypertension diagnosis, treatment, and research in cardiovascular health.

**Keywords:** Digital Twin · Hypertension · Mathematical Modeling · Neural Networks · Blood Pressure Simulation · Cardiovascular System

<https://doi.org/10.61728/AE20255237>



## 1 Introduction

Hypertension is the predominant risk factor for cardiovascular diseases and is recognized as a global public health issue. Current estimates suggest that more than 1.28 billion adults worldwide live with hypertension, while approximately 46 percentage of them are unaware of their diagnosis, according to the World Health Organization (WHO) [1]. In recent years, this has led to a growing need to monitor and control blood pressure to prevent complications such as heart attacks, strokes, and kidney failure. In this scenario, computational modelling methods based on tool development have enabled the creation of digital twins, which are virtual systems capable of modelling a patient's physiological behaviour and being actively updated with real-time individual data [2]. In instances of hypertension, for illustration, mathematical models have been shown to be conducive to the combination with artificial intelligence, thereby enhancing the capacity for prediction of physiological states and facilitating more informed medical decision-making. In this article, the development of a digital twin for hypertension monitoring is the focal point. This digital twin incorporates artificial neural networks, which are employed to predict blood pressure. Additionally, a detailed exposition is provided of the underlying mathematical model utilized for this purpose, in addition to a description of how it is implemented in MATLAB® environment. Furthermore, an examination of potential implications for early detection and personalized treatment of hypertension is undertaken. It also analyzes how relevant and beneficial such a method is in comparison to traditional blood pressure monitoring and control approaches. Following that, other sections provide an overview of relevant literature on the applicability of digital twins in healthcare, existing hypertension research, and artificial neural networks in this field. Then, there is a presentation of how the methodology was adopted, including a mathematical model, implementation process, evaluation methods, and validation. Subsequently, it shows the anticipated results and discusses their implications for medical practice. Finally, conclusions and future research directions in this field are outlined.

## 2 Literature Review

Advanced technology development in recent years has driven the rapid creation of digital twins across various fields, including medicine. A digital twin is a real-time virtual model representing a physical system, achieved through data collection and continuous self-updating to simulate and predict performance [4].

In medicine, these models offer valuable applications for personalizing diagnosis and treatment of chronic diseases, as deep learning has consistently improved clinical strategies' accuracy and preventive measures. In cardiology, orthopaedics, and neurology, recent studies have explored heart behaviour modelling, joint crush simulation, and prediction of neurodegenerative disease progression [5,6], respectively. Digital twin applications can help hypertension predict hypertensive episodes, assess real-time treatment impact, and offer a more adaptable, personalized approach to patient care.



Despite potential benefits, the complexity of the cardiovascular system—shaped by physiological, environmental, and genetic factors—makes hypertension modelling one of the most challenging tasks in biomedical research. Over recent decades, various mathematical models have been proposed to replicate blood pressure dynamics, using differential equations or analogue circuits to resemble electrical systems [7]. Among these, the Windkessel model has become a widely adopted approach for modelling blood pressure dynamics, drawing an analogy to a simple hydraulic system with resistive and capacitive components [8]. However, classical models struggle to capture interindividual variability and long-term treatment effects. Artificial neural networks have been suggested for hypertension modelling to address these limitations, as they can recognize nonlinear patterns in blood pressure data and enhance prediction accuracy [8,9].

So far, artificial neural networks have been applied in studies for clinical data analysis and cardiovascular disease (CVD) prediction. Recent research has demonstrated their ability to predict blood pressure from electrocardiography (ECG) and photoplethysmography (PPG) signals with greater accuracy than traditional models [10]. Additionally, deep learning algorithms have been introduced to detect patterns in data from hypertensive patients, enabling early risk factor recognition and optimized therapeutic strategies [11]. However, these advancements are rarely integrated into digital twin models based on neural networks for hypertension. Most studies rely solely on historical data analysis, lacking capability for dynamic simulation and real-time patient-specific treatment adaptation.

Although significant progress has been made in leveraging artificial intelligence for hypertension management, integrating these models into a digital twin capable of providing real-time insights into individual physiology remains challenging [8]. Current studies have primarily developed neural networks that predict trends based on historical data, yet they do not dynamically interact with patients or adjust treatments according to physiological responses. Additionally, many established models rely on population-based datasets, limiting their ability to personalize predictions and reducing their practical applicability in clinical settings. While numerous studies have demonstrated feasibility of implementing one or more components of a digital twin, lack of comprehensive clinical validations and challenges in merging multiple biomedical data sources into a unified framework continue to hinder adoption of a fully operational digital twin for hypertension management [11]. This study aims to bridge this gap by introducing a digital twin based on artificial neural networks. This twin simulates blood pressure evolution in hypertensive patients while optimizing treatment based on individual physiological responses. This approach enhances prediction accuracy by integrating a validated mathematical model with state-of-the-art machine learning algorithms. It offers an innovative tool for personalized hypertension treatment. I will schedule some time for us to connect.



### 3 Methodology

#### 3.1 Description of Mathematical Model

Olufsen et al. (2005) proposed a compartmental system of ordinary differential equations (ODEs) to describe blood pressure and flow dynamics across multiple segments of the cardiovascular system. Developed to capture interindividual variability in hypertensive patients better, this model integrates cardiac contraction dynamics with portal and arterial circulation to reflect interactions between vessel dynamics and distribution [13].

Human cardiovascular function operates as a highly complex circuit, exhibiting pulsatile blood flow and variable blood pressure due to necessary cardiac contraction and relaxation, peripheral vascular resistance, and arterial capacitance. Olufsen's model extends classical approaches, such as Windkessel-based representations, by describing coupled arterial segments through differential equations.

As a compartmental model, it divides cardiovascular circulation into distinct arterial and venous compartments, each governed by a differential equation that describes pressure and blood volume evolution over time. This approach captures how pressure waves propagate through blood vessels and highlights the impact of arterial stiffness in individuals with hypertension.

**Model Components** Olufsen's model includes three main elements to represent the cardiovascular system: Resistance  $R$  represents opposition to blood flow due to friction between blood and arterial walls. Blood within the system behaves according to Hagen-Poiseuille's law, where vessel resistance is inversely proportional to the fourth power of vessel radius [12]. Slight variations in vessel diameter can lead to significant changes in flow resistance. This relationship is modelled using differential equations in Olufsen's model, which describe pressure drop along arterial circulation and allow assessment of how pressure changes in response to peripheral resistance [13].

Arterial capacitance  $C$  represents the ability of blood vessels to store blood and their elasticity, directly influencing blood pressure dynamics [14]. In Olufsen's model, this parameter is crucial for estimating pressure variations caused by changes in blood volume, which is particularly relevant in pathological conditions such as hypertension, where vessel stiffening prevents proper vascular adjustment to blood flow variations. Blood flow inertia  $L$  models the delay in flow response caused by blood mass. These factors are key in studying pressure wave propagation in large arteries, affecting circulatory dynamics and interaction between blood ejection and vascular resistance. In Olufsen's model, inertia is incorporated into the equation governing flow dynamics to characterize how pressure and flow react swiftly to changes in heart rate and structural properties of blood vessels across arterial circulation [17].

**Differential Equations for Blood Pressure:** Each equation signifies this progression, delineating a distinct segment of the cardiovascular system.

$$\frac{dP_a}{dt} = \frac{\frac{(P_v - P_a)}{R_{av}} - \frac{(P_a - P_{au})}{R_{au}} - \frac{(P_a - P_{ae})}{R_{ae}} - \frac{(P_a - P_{af})}{R_{af}}}{C_a} \quad (1)$$

$$\frac{dP_{au}}{dt} = \frac{\frac{(P_a - P_{au})}{R_{au}} - \frac{(P_{au} - P_{ad})}{R_{ad}} - \frac{(P_{au} - P_{aup})}{R_{aup}}}{C_{au}} \quad (2)$$

$$\frac{dP_{ad}}{dt} = \frac{\frac{(P_{au} - P_{ad})}{R_{ad}} - \frac{(P_{ad} - P_{adp})}{R_{adp}}}{C_{ad}} \quad (3)$$

$$\frac{dP_{af}}{dt} = \frac{\frac{(P_a - P_{af})}{R_{af}} - \frac{(P_{af} - P_v)}{R_{afp}}}{C_{af}} \quad (4)$$

$$\frac{dP_{ae}}{dt} = \frac{\frac{(P_a - P_{ae})}{R_{ae}} - \frac{(P_{ae} - P_{aep})}{R_{aep}}}{C_{ae}} \quad (5)$$

$$\frac{dP_v}{dt} = \frac{\frac{(P_{vup} - P_v)}{R_{vu}} + \frac{(P_{vc} - P_v)}{R_{vc}} + \frac{(P_{af} - P_v)}{R_{afp}} - \frac{(P_v - P_{va})}{R_v}}{C_v} \quad (6)$$

$$\frac{dP_{vu}}{dt} = \frac{\frac{(P_v - P_{vu})}{R_{vu}} + \frac{(P_{au} - P_{vu})}{R_{aup}} - \frac{(P_{vu} - P_v)}{R_v}}{C_{vu}} \quad (7)$$

$$\frac{dP_{ad}}{dt} = \frac{\frac{(P_{ad} - P_{adp})}{R_{adp}} - \frac{(P_{ad} - P_{au})}{R_{ad}}}{C_{ad}} \quad (8)$$

$$\frac{dP_{vc}}{dt} = \frac{\frac{(P_{aep} - P_{vc})}{R_{aep}} - \frac{(P_{vc} - P_v)}{R_{vc}}}{C_{vc}} \quad (9)$$

Compartmental models, such as Olufsen's model, represent a system of 9 ordinary differential equations describing blood pressure evolution across different compartments of cardiovascular circulation. These equations establish relationships between pressure, flow, and resistance in specific arterial or venous regions. Nine differential equations governing how pressure influences blood circulation are described below. Differential equation (1) represents arterial pressure in systemic arterial circulation (aorta). This equation accounts for blood entering through the left ventricle and distributing into significant arteries. Resistance across the aortic valve  $R_{av}$  influences pressure at this stage, with blood flow redirected toward upper body arteries, capillary beds, and femoral arteries  $R_{au}$ ,  $R_{ae}$ ,  $R_{af}$ . Variations in these parameters help regulate overall blood pressure, increasing susceptibility to hypertension [13].

Second differential equation (2) corresponds to pressure in arteries supplying the upper body, specifically subclavian and carotid arteries. Blood is directed into this region from the aorta through resistance  $R_{au}$  and exits via  $R_{ad}$  toward head and arm circulation.  $R_{aup}$  regulates arterial pressure in this region and influences redistribution of blood flow into superior venous circulation [13].

Equation (3) describes pressure in narrower upper-body arteries, which exhibit increased resistance due to progressive vessel constriction. This moist lung region lacks pressure in either pulmonary ventricle, where suction is determined by blood flow exiting  $P_{au}$  and entering superior venules  $P_{st}$ , regulated by  $R_{alp}$ . Increased vessel stiffness in this region can result in localized hypertension in upper circulation [13].

Fourth differential equation (4) involves pressure in arteries supplying the lower body, specifically femoral arteries and branches. Blood flow from the aorta reaches this site through resistance  $R_{af}$ , while venous return from this area is regulated by  $R_{afp}$ . Reduced arterial compliance in this segment may contribute to increased systolic pressure in lower extremities [13].

Equation (5) governs transition toward capillary beds through filtration and fluid reabsorption mechanisms between arteries and veins. At this stage, blood pressure decreases significantly due to capillary resistance  $R_{ac}$  and outflow toward capillary venules  $R_{ac}$ . Microcirculatory disruptions can alter the fluid balance and contribute to pathologies such as capillary hyper flow [13].

Sixth differential equation (6) represents pressure in central venous circulation. Veins from various compartments, including upper circulation  $P_{vu}$ , capillary circulation  $P_{cc}$ , and femoral veins  $P_{af}$ , return blood to the heart through VNC, influenced by venous resistances  $R_{vu}$ ,  $R_{cc}$ ,  $R_{fp}$ . Central venous pressure is a key indicator of cardiac preload status and impacts cardiac function [13].

Seventh differential equation (7) describes pressure in superior veins, responsible for draining venous return from the head and arms. Flow rates from  $P_{st}$  and  $P_{au}$  into  $P_{vu}$  are regulated by  $R_{st}$  and  $R_{aup}$ , while outflow into systemic circulation occurs through  $R_{vu}$ . Alterations in venous return within this region can affect cerebral blood flow and venous pressure dynamics, influencing cerebral compliance [13].

Eighth differential equation (8) defines pressure in upper-body venules. Pressure in this region is determined by blood entering  $P_{al}$  and exiting through  $P_{vu}$ , where  $R_{alp}$  and  $R_{st}$  regulate inflow and outflow, respectively. Variations in these resistances impact blood redistribution and venous pressure within the thoracic region [13].

Ninth differential equation (9) describes pressure in capillary venous circulation. Blood moves from  $P_{ac}$  to  $P_{cc}$  through  $R_{acp}$ , with venous return to  $P_c$  regulated by  $R_{cc}$ . Pressure within this compartment plays a crucial role in fluid balance, tissue perfusion, and systemic blood pressure regulation [13].

Each equation is fundamental in defining hemodynamic dynamics and arterial pressure distribution throughout circulation. Variations in  $R$ ,  $C$ , or flow characteristics lead to alterations in overall hemodynamics, reinforcing Olufsen's model as a valuable tool for testing hypertension predictions and control strategies.



**Equations for Ventricular Volume:** Ventricular volume changes over time in response to pressure and resistance of the cardiac compartments:

$$\frac{dV_{lv}}{dt} = \frac{P_a - P_{lv}}{R_{mv}} - \frac{P_{lv} - P_a}{R_{av}} \quad (10)$$

$$\frac{dV_{la}}{dt} = \frac{P_v - P_{la}}{R_v} - \frac{P_{la} - P_{lv}}{R_{mv}} \quad (11)$$

Differential equation (10), which describes variations in left ventricular volume, is the primary driver of systemic blood pressure. The dynamic balance between inflow from the left atrium and outflow toward the aorta determines this. Blood flow occurs through the mitral valve, where resistance  $R_{mv}$  regulates the amount of blood transferred from the left atrium into the left ventricle. Consequently, blood ejection into systemic circulation occurs through the aortic valve, where resistance  $R_{av}$  determines the volume successfully delivered by the ventricle with each heartbeat [13].

Blood flow happens during this phase (ventricular filling) when left atrial pressure  $P_{la}$  exceeds ventricular pressure  $P_{lv}$ . Conversely, systole is when ventricular pressure rises sufficiently to open the aortic valve, allowing blood to be expelled into the aorta. This process is crucial for maintaining blood pressure and ensuring cardiac output, meaning that valvular resistance or ventricular contractility variations can influence stroke volume and organ perfusion [13].

On the other hand, differential equation (11) describes volume changes in the left atrium, a critical compartment for regulating blood pumping into the left ventricle. Atrial volume depends on inflow from PTX and outflow into the ventricle via MV. Resistance to blood returning from peripheral circulation  $R_v$  represents systemic venous resistance, while resistance to blood entering the left ventricle  $R_{mv}$  corresponds to mitral valve resistance [13].

During diastole, when  $P_{lv}$  decreases, the mitral valve opens, allowing the atrium to empty. However, increased mitral valve resistance or ventricular dysfunction can impair ventricular filling, reducing cardiac output and leading to pulmonary hypertension [13].

### 3.2 Integration with Artificial Neural Networks

Considering the complexity of cardiovascular function and interpatient variability in hypertension, an artificial neural network is integrated to enhance model performance in terms of mathematical model accuracy and real-time adaptability in management methods. This work has not yet determined the specific neural network type. However, different architectures will be explored to maximize blood pressure prediction and system response to representative physiological variations [14].

A neural network was trained to adapt parameters of Olufsen's model, including structural parameter elements related to vascular resistance  $R$ , arterial capacitance  $C$ , and blood flow inertia  $L$ . These parameters can be individualized, changing with age, arterial stiffness, or autonomic response. Consequently,

relying solely on a static model built with differential equations may not be sufficient to describe hypertension dynamics accurately [16].

While the specific architectural design may exhibit slight variations depending on the type of neural network, it is generally understood that input variables such as previous blood pressure readings, heart rate, and other clinical parameters are essential. These data facilitate the neural network's capacity to personalize Olufsen's model by adjusting its parameters, thereby producing enhanced flow predictions for each patient, tailored to their unique conditions [16].

During neural network training, the error function will be defined based on minimizing differences between experimentally obtained blood pressure values and those predicted by the hybrid model. This difference will be calculated using a mean squared error (MSE) metric [17].

$$\mathcal{L} = \sum_{i=1}^N (P_i - \hat{P}_i)^2 \quad (12)$$

Where  $P_i$  represents measured blood pressure, and  $\hat{P}_i$  denotes blood pressure predicted by the system. Adjusting this multiple-input multiple-output (MIMO) process will refine the model, enhancing prediction accuracy and simulating physiological and pathological scenarios. These neural networks will be tested in different configurations:

- multilayer perceptron (MLP)
- recurrent neural network (RNN)
- convolutional neural network (CNN)
- deep neural network

during upcoming development stages.

Selection of the final architecture will be selected based on each model's performance in accuracy, stability, and generalization in blood pressure prediction [17]. Recent studies suggest that integrating classical mathematical methods with deep learning can help identify non-invasive patterns in blood pressure oscillations and improve health data mining to continuously monitor patients with hypertension [18].

### 3.3 MATLAB® Implementation

For simulation of a digital twin for hypertension, a model was developed based on 11 differential equations describing blood pressure evolution and volume changes across different compartments of cardiovascular circulation. MATLAB® was implemented using the ode45 integrator, which is suitable for solving first-order ordinary differential equation systems. The following section details the implementation process and analyzes the behaviour of the obtained results. [13]

Cardiovascular model was built following the mathematical formulation of Olufsen et al. (2005), incorporating physiological parameters that represent blood flow dynamics across different arterial and venous segments. Initial conditions were defined based on systemic blood pressure values, venous pressure, and volumes in the left ventricle and left atrium. [13]



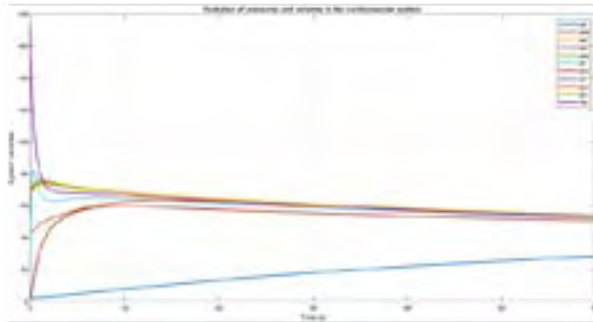
**Definition of Model and Physiological Parameters:** This cardiovascular model presented in this study was developed based on a compartmental representation of arterial and venous circulation, divided into multiple physiological compartments (aorta, upper and lower arteries, capillary bed, and veins) [15]. Physiologically realistic values were assigned to initial conditions for arterial and venous pressures and volumes in the left ventricle and left atrium. Simulated parameters include vascular resistance, which represents hydrostatic opposition during blood flow through each compartment, and arterial and venous capacitance, which define the distensibility of vascular walls and the blood reservoir capacity itself. These parameters work together to establish cardiovascular load and simulate resting behaviour by relating pressures and volumes as a function of time [13].

**Solving differential equations:** Ode45, a differential equation integrator suitable for biological dynamic systems [12], was used to calculate the evolution of pressures and volumes over time. This method provided approximate solutions for each differential equation, illustrating how pressures in different compartments interact in response to changes in blood flow. Each differential equation describes how pressure in a compartment is influenced by inflows and outflows, which are regulated by vascular resistances. Similarly, equations for ventricular and atrial volumes show how these change based on blood entry from venous circulation and ejection into arterial circulation [13].

**Viewing Results:** Results were graphically represented as an evolution of pressures and volumes over time. Initial changes in pressure and volume dynamics at the beginning of the simulation, preceding eventual stability in the generated graph, indicate an adjustment period. During this phase, blood flow redistributes in response to the model's initial conditions. Pressure and volume curves stabilise over time as the system reaches a steady state. This behaviour is attributed to the absence of a periodic source of variability (e.g., heartbeats), resulting in pressures and volumes converging to constant values when no external stimuli are applied to the model [13].

**System Behavior Analysis:** This behaviour reflects a resting cardiovascular system, where vessel pressure and circulating blood volume reach equilibrium without external forces acting upon them [16]. In reality, blood pressure in a living biological system is not constant but oscillates with each ventricular contraction [12]. For a more realistic Coronary Blood Flow (CBF) simulation, a pulsatile signal is required to mimic the cardiac cycle. This generates oscillations that replicate human physiological blood pressures and enhance simulation accuracy. Using an artificial neural network to adjust model characteristics based on accurate data dynamically further personalizes the model, enabling more precise blood pressure predictions for hypertensive patients [18].

In order to facilitate numerical resolution of the differential equations, a cardiovascular model was implemented in MATLAB, thus enabling researchers to



**Fig. 1.** Evolution of pressures and volumes in the cardiovascular system

obtain the evolution of pressures and volumes across different compartments. It was demonstrated by simulation results that, in the absence of external variations, the system tends to stabilise in a steady state. In a subsequent study, a periodic function representing heartbeats will be included, along with artificial neural networks, to enhance the model's accuracy and adaptability in clinical applications [17].

**Evaluation and Validation Methods for Model:** Ensuring the accuracy and applicability of a digital twin for hypertension requires evaluation and validation techniques that compare model predictions with clinical data or reference simulations. Olufsen's model, adapted with neural networks, will be validated at two levels: mathematical validation and physiological validation. Mathematical validation will focus on verifying that numerical solutions of the 11-equation differential system remain stable and consistent with known cardiovascular dynamics. Numerical stability of solutions obtained with ode45 will be analyzed, ensuring that the model does not exhibit divergences or non-physiological oscillations under minor variations in initial conditions or system parameters [12]. Additionally, model results will be compared with previously established solutions from studies on compartmental blood pressure models, ensuring that general simulation trends align with existing literature [13]. Model convergence will also be evaluated by analyzing whether arterial pressures and ventricular volumes reach a physiologically plausible steady state without external variations, indicating that the model accurately reflects cardiovascular homeostasis [14].

For physiological validation, model predictions will be compared with blood pressure recordings from prior simulations and databases of hypertensive patients. Evaluation will be performed using quantitative metrics such as mean squared error (MSE), which will measure differences between model-predicted blood pressures and reference values. A low MSE will indicate that the model accurately replicates expected values under normal and pathological conditions [15]. Pearson correlation coefficient  $R$  will also be analyzed to assess linearity between model predictions and reference data, ensuring that relationships be-

tween variables remain significant [16]. Additionally, Bland-Altman concordance index will be applied to evaluate error distribution and detect systematic biases in model predictions compared to actual data [17]. Since the model integrates an artificial neural network to adjust physiological parameters dynamically, assessing the impact of this integration on system accuracy is necessary. MSE values will be compared before and after neural network incorporation to determine whether parameter optimization enhances simulation accuracy [18]. Model adaptability to different hypertension profiles will also be evaluated, testing performance under varying vascular resistance and arterial stiffness to determine whether the neural network can adjust parameters in a physiologically coherent manner [13].

Computational efficiency of the system will be measured by comparing processing times for each simulation before and after artificial intelligence integration, ensuring feasibility for real-time applications or clinical simulations [14]. In order to assess model robustness under different clinical conditions, various pathological scenarios will be simulated, and system responses analyzed. Primary hypertension will be represented by increasing peripheral resistance, observing whether the model predicts a sustained rise in systolic and diastolic blood pressure, as seen in hypertensive patients [15]. Model behaviour under induced hypotension will also be analyzed by reducing vascular resistance and ventricular contractility to determine whether pressure drops similar to those observed in orthostatic hypotension episodes are simulated [16]. Additionally, administration of antihypertensive drugs, such as calcium channel blockers and vasodilators, will be simulated, verifying whether the model responds with a progressive reduction in blood pressure consistent with pharmacological effects reported in literature [17].

A digital twin for hypertension will be validated at multiple levels, ensuring that the model remains accurate and physiologically realistic. Integration with neural networks will be evaluated using quantitative metrics, determining its impact on prediction error reduction and system adaptability to different hypertension profiles. These processes will improve model reliability and potential application in treatment simulation and personalization for hypertensive patients.

## 4 Expected Results

A digital twin for hypertension promises to fundamentally transform how this condition is evaluated and managed by simulating blood pressure and cardiovascular system responses to various physiological and therapeutic scenarios. In this developed model, hypertension progression in patients is expected to be better predicted, enabling risk factor identification and personalized treatment [14]. An implemented digital twin has a significant advantage over static numerical modelling by dynamically adjusting vascular resistance, arterial capacitance, and blood flow inertia. These parameters change dynamically using artificial intelligence to reflect an individual's physiological state [15]. This approach captures



real-time variability and predicts responses to stimuli and treatments, unlike traditional blood pressure monitoring methods that rely primarily on discrete measurements and static models [16]. With integration into artificial neural networks, this model will adapt to specific data, providing more accurate simulations and representing a significant advancement over traditional compartmental models used in cardiovascular studies [17].

From a clinical perspective, the next step in utilizing a digital twin would be to improve risk stratification in hypertensive patients, aiding in more informed decisions regarding lifestyle modifications or pharmacological therapy adjustments [12]. Additionally, this tool supports research on therapeutic interventions by allowing evaluation of antihypertensive drug effects and blood pressure control strategies without requiring invasive procedures [13]. A digital twin would offer more predictive and adaptive capabilities than traditional hypertension measurements, such as ambulatory blood pressure monitoring (ABPM) or office-based sphygmomanometers [18]. Conventional methods rely on discrete readings that fail to capture blood pressure variability throughout the day accurately. However, differential equations and a machine learning framework embedded in this model will provide continuous and personalized estimates of cardiovascular dynamics [14]. This represents a crucial advantage, particularly in blood pressure management, where variability is key in cardiovascular event risk [16]. Furthermore, this proposed approach is unique in integrating artificial neural networks, allowing system parameter optimization and improving predictive accuracy compared to other compartmental mathematical models found in literature [13]. Unlike traditional models that require manual adjustments of physiological parameters to simulate variable pathological states, a digital twin can autonomously learn from clinical data, making it more adaptable for research and clinical environments [17].

Therefore, a digital twin for hypertension is envisioned as a far more precise, flexible, and predictive approach for evaluating this disease. It would enable continuous blood pressure monitoring and optimize therapy beyond classical methods [15]. This advancement could significantly impact clinical practice and hypertension research, enhancing patient quality of life and increasing efficiency in medical decision-making [18].

## 5 Discussion

Expected outcomes of a digital twin for hypertension suggest that this approach will provide a more precise and dynamic representation of blood pressure compared to traditional models, enabling a more detailed assessment of disease progression and personalized treatment strategies. The model's ability to dynamically adjust its parameters through artificial neural networks makes it an innovative tool with the potential to enhance hypertension behaviour prediction across different clinical scenarios. By considering interactions between vascular resistance, arterial capacitance, and blood flow inertia, this model will analyze the current state of cardiovascular function and anticipate physiological changes

under various conditions and treatments [12]. Despite its advantages, this study presents limitations that must be addressed in future research. One of the main limitations is the need for extensive and high-quality clinical data to train the artificial neural network, which may pose a challenge regarding availability and variability in physiological records. Model accuracy will largely depend on the diversity and quality of data used for calibration, making it essential to have representative databases that include patients with different hypertension levels and associated cardiovascular conditions [13]. Additionally, the current model does not incorporate a pulsatile source to represent heartbeats realistically. This may limit its applicability in studies where blood pressure variability throughout the cardiac cycle is a key factor. To improve cardiovascular dynamics representation, integrating a periodic signal that reflects pressure changes induced by left ventricular activity would be recommended [14].

Another significant limitation is computational complexity when integrating the model with artificial neural networks. While automatic parameter adjustment improves simulation accuracy, it also increases processing time and computational requirements, potentially complicating implementation in clinical settings where rapid and efficient responses are needed. Optimizing the model for real-time execution remains a challenge, and future research should focus on enhancing computational efficiency without compromising prediction accuracy [15]. Implications for future research span various aspects of cardiovascular modelling and artificial intelligence applications in healthcare. First, integrating a digital twin with continuous blood pressure monitoring devices could enable more precise and real-time calibration, improving its ability to adapt to patient profiles. This implementation would facilitate model validation in real clinical scenarios by comparing predictions with real-time measurements from wearable sensors or implantable devices [16]. Additionally, future studies could explore model applications in evaluating antihypertensive drug responses, analyzing how different medication classes influence vascular resistance and blood flow dynamics. Using a digital twin as a simulation tool for treatment personalization could lead to more effective therapeutic strategies and reduce the need for dosage adjustments through a mathematically driven predictive approach [17]. Another relevant research avenue involves improving the neural network architecture used for parameter adjustment. Exploring more advanced models, such as recurrent neural networks or hybrid frameworks combining deep learning with equation-based optimization, could further enhance prediction accuracy and computational efficiency [18].

Consequently, a digital twin for hypertension signifies a substantial advancement in cardiovascular system modelling and treatment personalisation. Nevertheless, challenges that necessitate future research persist. Enhancing data quality, optimising computational performance, and integrating with continuous monitoring devices will be pivotal for consolidating its clinical and research applications. Implementing this model in prospective studies could yield valuable insights into hypertension progression and its response to various therapeutic



strategies, thereby contributing to developing more effective disease management approaches.

## 6 Conclusions

This study integrates differential equations and artificial neural networks to develop a Digital Twin for Hypertension, marking a new cardiovascular simulation and prediction era. Extending Olufsen's framework, the model accurately represents interactions between vascular resistance, arterial capacitance, and blood flow inertia across cardiovascular compartments. Dynamically adjusting parameters via artificial intelligence enhances adaptability to individual conditions, improving personalized hypertension treatment [12].

A key contribution is its ability to provide real-time, informative blood pressure estimations compared to traditional static models. Unlike conventional monitoring methods, this approach integrates discrete measurements with continuous pressure evolution, offering superior predictive capabilities for cardiovascular risk stratification and clinical decision-making [14]. Additionally, its application in electronic and communication systems advances intelligent physiological modelling, fostering the development of software-based medical devices that integrate with monitoring sensors for continuous blood pressure estimation. AI-driven autonomous systems could further aid early diagnosis and treatment of cardiovascular diseases.

Future research should focus on integrating the digital twin with continuous monitoring devices for real-time validation, refining physiological parameterization, and incorporating pulsatile sources to improve simulation accuracy. Optimizing computational performance will enable its use in clinical environments requiring rapid decision-making [17]. Furthermore, evaluating its response to antihypertensive treatments and non-pharmacological interventions will provide deeper insights into cardiovascular dynamics, with prospective clinical validation confirming its potential in medical practice [18].

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# VigilEye: System for Prevention of Accidents Caused by Changes in State of Alertness while Driving

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**Abstract.** This project presents the development of VigilEye, a prototype system for continuous monitoring of alertness in drivers on long journeys. This monitoring is performed by means of a camera through the analysis of eye movement patterns, with purpose of preventing automobile accidents. Implementation includes a gradual response protocol that includes sound alerts, visual signals and, in critical cases, controlled intervention of vehicle systems. VigilEye proposes a prototype of a two-stage system to respond to detection of decreased alertness in long-distance drivers. This system uses a detailed analysis of eye movements to detect signs of fatigue. In first stage, upon identifying that driver is showing signs of decreased alertness, system emits an acoustic signal to alert driver and stimulate an immediate reaction. If driver does not respond to this warning, system activates second stage of response in which vehicle turns on flashing lights to warn other drivers and simultaneously reduces speed progressively, in order to minimize risk of accidents and ensure safety on the road.

**Keywords:** Alertness detection, Accident prevention, Eye monitoring, Road safety, Warning systems.

## 1 Introduction

Previous research demonstrates existence of fatigue detection systems, however, they may present significant limitations that compromise their effectiveness, as some of methods using electroencephalograms (EEG) require connection of electrodes, which is invasive, impractical and costly to implement in real driving environments [1].

<https://doi.org/10.61728/AE20255244>



In context of technological advances in automotive industry, systems implemented in current vehicles are capable of detecting if a person is asleep at wheel and system will also alert driver in order to avoid a greater harm. Among these systems developed in recent years are:

### **1.1 Driver Alert Control (Volvo®)**

Volvo® developed Driver Alert system, designed to reduce accidents caused by fatigue and distraction. It uses a camera and sensors to analyze vehicle behavior, issuing alerts if it detects erratic driving patterns. Although it does not intervene in the control of car, it helps drivers to react in time and improve their performance on the road [2].

### **1.2 Attention Assist (Mercedes-Benz®)**

Attention Assist is a system that monitors steering wheel and analyzes 70 parameters to detect signs of fatigue in drivers traveling between 50 and 112 mph. If erratic movements are identified, system issues alerts and suggests taking a break [3].

### **1.3 Driver Monitoring System (Toyota®)**

Toyota® has improved its Pre-Crash Safety System by including technology that analyzes whether the driver's eyes are open and attentive. Using a camera and an image processor, system issues warnings in case of distraction or drowsiness, contributing to the reduction of accidents [4].

### **1.4 Detection of eye fatigue through machine learning based on single-channel electrooculography**

This method focuses on excessive use of electronic devices, which has increased eye fatigue, making its objective and scientific measurement urgent. It proposes an innovative system based on single-channel electrooculography (EOG) signal, which is convenient, inexpensive and compatible with mobile devices. Research explores link between EOG and eye fatigue, optimizing detection and facilitating its practical application [5].

Together, these technologies can be very useful in accident prevention; however, they do not offer a comprehensive solution to significantly reduce risk of road accidents.

Faced with these limitations, our proposal presents an innovative approach based on two levels of progressive intervention. First level, of a preventive nature, activates audible and/or visual alerts to warn driver of a decrease in his state of alertness. Second level, critical intervention, implements activation of emergency lights and initiates a gradual reduction in speed. This approach not only alerts driver, but also takes proactive measures to ensure safety on the road.



## 2 Methodology

VigilEye system is developed using a processing that ensures an efficient and organized flow of data from initial capture to alert generation. This work structure allows each stage of process to be optimized independently, ensuring optimal performance and seamless integration of components (see Fig.1).

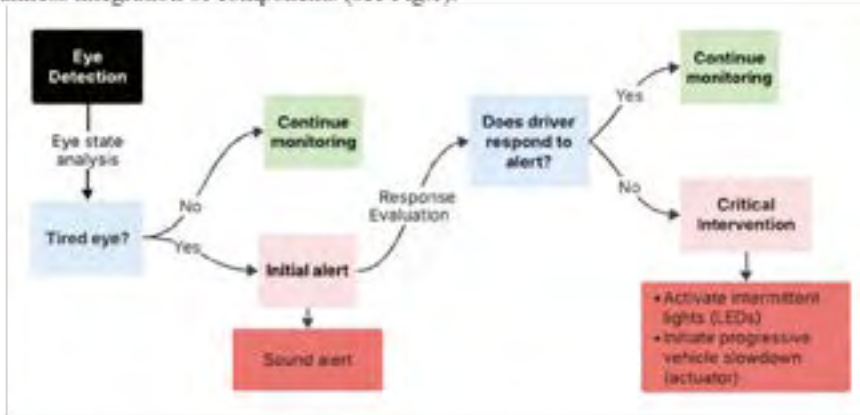


Fig. 1. Decision Flow of the VigilEye Detection and Response System.

### 2.1 Data Acquisition

Data acquisition is the first step in system's *pipeline*. Using a high-definition *webcam*, system captures continuous video of driver's face at 30 frames per second (FPS). Camera is strategically positioned on vehicle dashboard in front of driver to ensure an optimal field of view, allowing accurate capture of eye movements without interfering with driving.

Each frame is processed to extract coordinates of points that define contour of eyes. This accurate facial mapping is essential to determine state of eyes at each moment, providing basis for blink pattern analysis (see Fig. 2). This accurate facial mapping is essential to determine state of eyes at every moment, providing basis for blink pattern analysis. Image quality and capture stability are critical, so preprocessing techniques are implemented to enhance contrast and reduce noise, ensuring that data are consistent and accurate.



Fig. 2. Facial landmarks generated by MediaPipe Face Mesh [6].

## 2.2 Implementation of Detection System

Detection system is based on a continuous processing *pipeline* using *MediaPipe Face Mesh* for accurate detection of facial markers. Calculation of Eye Aspect Ratio (EAR) (see Fig. 3) is performed by ratio between vertical and horizontal distances of points defining eye contour. This value provides an accurate measure of eye opening state, allowing reliable detection of blinks and their temporal features.



Fig.3. Mathematical principle of the Eye Aspect Ratio (EAR) applied to blinker detection using facial landmarks [7].

Processing of data obtained implements a real-time classification system that determines driver's state of alertness. Algorithm analyzes three fundamental parameters:

blink frequency, duration of each blink and PERCLOS (percentage of eye closure). These data are processed through a 60-second sliding window, allowing detection of temporal patterns indicative of decreased alertness. Implementation of detection system is optimized to minimize latency, ensuring that alerts are generated in a timely and accurate manner.

### 2.3 Response System

Based on the analysis of detected states, system implements two response levels proposing number 1, as value of closed eye, and value 0 as value of open eye designed to intervene effectively upon detection of reduced alert states:

**Stage 1 response.** Upon detection of prolonged state 1 sequences ( $>400\text{ms}$ ), the system activates a 2000Hz audible alert via a buzzer, seeking to regain the driver's attention in an immediate and non-intrusive manner. This alert is designed to be loud enough to capture attention without causing additional distraction.

**Stage 2 response.** When a maintained state 1 ( $>500\text{ms}$ ) is detected, the system activates a series of more intense responses, including:

*Emergency Lights.* LEDs that simulate emergency flashing lights, alerting both driver and other road users. This visual signal is crucial to warn other drivers of a potential problem.

*Braking Actuator.* Activation of an actuator that simulates the ability to stop vehicle safely, demonstrating potential for direct intervention in vehicle control. This actuator is designed to integrate with vehicle's braking systems, providing controlled deceleration.

*Audible Alert.* Maintenance of audible alert to ensure that driver receives warning. Combination of audible and visual signals maximizes likelihood that driver will respond appropriately.

## 3 Discussion, Application, Trends and Opportunities

### 3.1 Innovation

This work aims to introduce an innovative solution in automotive industry, focusing on road safety and driver well-being. Through processing of biomedical signals, it seeks to revolutionize the way in which vehicles monitor driver's health and condition, allowing these systems to predict and react to risk situations.

As part of this innovation, aim is to encourage more effective human-vehicle interaction, thus improving driving conditions and promoting healthy habits, as well as importance of adequate rest. In addition, company plans to collaborate with automotive

industry to take speed reduction prototype beyond its initial phase, with aim of implementing it in a wide range of vehicles. This initiative not only aims to improve road safety, but also to contribute to general well-being of drivers.

### 3.2 Social Impact

**Road Safety.** Our main objective is to reduce accidents and fatalities by implementing systems that monitor drivers' health to prevent road incidents. This not only increases confidence in public transportation, but also ensures the safety of passengers when driving with health monitoring. By monitoring drivers, public transport users will feel safer, which will encourage their use.

The decrease in social costs associated with accidents will be notable, as preventing accidents reduces medical and rehabilitation costs and lost productivity, generating economic benefits and improving the healthcare system.

**Public Health.** Implementation of our system will help reduce work-related stress for drivers, who often face high levels of tension. Monitoring their health indicators allows us to identify when they need rest, thus improving their physical and mental health. In addition, better rest habits will be encouraged: monitoring sleep helps avoid fatigue, which improves concentration and reduces the risk of accidents. Promoting adequate rest increases road safety.

### 3.3 Development or Market Potential

Project of detecting driver fatigue by analyzing eye movement patterns and using biometric technologies presents considerable development and market potential due to significant number of car accidents, growing public and government awareness about road safety has generated a growing demand for solutions that help prevent these incidents.

This creates a receptive market for technologies that address this critical problem. Project also benefits from growing awareness of health and wellness, especially in context of mental health and fatigue. By aligning with these broader trends, system can promote healthy habits and highlight importance of adequate rest. Going forward, and with the possibility of collaborating with automakers to integrate this system into new vehicles represents a significant opportunity: creation of mobile apps or platforms that complement fatigue detection system, providing information on sleep habits, personalized recommendations and alertness tracking, can increase value of product and appeal to a wider audience.

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# Adaptive Outer-Loop Neural PID Control for Quadcopters Trained with EKF in a HIL Environment

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**Abstract.** Quadcopters require robust and adaptive control systems to ensure stability and trajectory tracking under dynamic environmental conditions. Traditional Proportional-Integral-Derivative (PID) controllers offer simplicity and effectiveness but lack adaptability to external disturbances such as wind gusts. This study proposes an Adaptive Neural PID controller trained using the Extended Kalman Filter (EKF) to dynamically adjust control gains in real time, enhancing trajectory tracking and disturbance rejection. The proposed approach is implemented as an outer-loop controller to regulate vehicle motion via velocity setpoints. The method is validated in a Hardware-in-the-Loop (HIL) simulation environment using a PX4-based quadcopter and Gazebo, assessing performance under nominal, moderate (6-8 m/s), and gusty wind conditions (8-14 m/s). Results demonstrate that Neural PID reduces settling time by up to 70.8% in Z-axis, improves mean squared error (MSE) by 34.2% in moderate wind, and decreases overshoot by 35.7% in lateral axes compared to conventional PID. Under gusty wind conditions, Neural PID provides enhanced stability in Y-axis, reducing deviations by 35.9%, though conventional PID maintains slightly lower error in X and Z. Overall, the findings highlight the effectiveness of adaptive neural control for improving quadcopter resilience against environmental disturbances, making it a viable alternative for real-world applications.  
**Keywords:** UAV Control, Neural PID Control, Extended Kalman Filter, Hardware-in-the-Loop, Wind Disturbance Rejection.

## 1 Introduction

Unmanned Aerial Vehicles (UAVs) have experienced an accelerated growth in popularity due to advances in propulsion technologies and the development of lightweight, low-cost, and energy-efficient components. These systems have opened significant opportunities in military and civilian applications, including surveillance, fire detection, precision agriculture, traffic monitoring, and other activities with high social impact [1]. Among these platforms, quadcopters stand

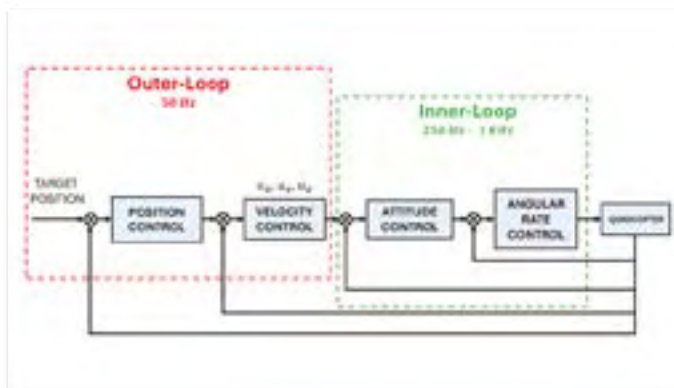
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out due to their Vertical Take-off and Landing (VTOL) capabilities, maneuverability, stable hovering, and adaptability to indoor and outdoor environments [2]. However, their complex, non-linear, and underactuated dynamics often demand sophisticated control methods to handle parameter uncertainties, external disturbances, and potential failures [3].

The design of a quadcopter control system presents significant challenges. Although Proportional-Integral-Derivative (PID) controller remains the most widely employed in UAVs due to its simplicity, ease of implementation, and effectiveness in structured environments [4], it relies on fixed parameter tuning, which limits its adaptability in real-world scenarios. When wind gusts or load variations occur, this approach may become inadequate, leading to oscillations, excessive overshoot, or instability [5]. These issues highlight the need for more adaptive and robust methods capable of adjusting in real time to changing flight conditions without requiring manual reconfiguration. In response, several advanced control strategies have been introduced, such as sliding mode control [6], backstepping control [7], and neural inverse optimal control [8] to improve the robustness and adaptability of UAVs. While these techniques have proven effective at directly tackling non-linearities of the system, they often require extensive modeling of low-level dynamics or significant tuning efforts.

A layered control strategy has become increasingly popular in practical applications, where an outer loop controller focuses on generating reference commands such as velocity or position setpoints, rather than directly regulating attitude or motor inputs [16]. Since  $u$  is not directly applied to actuators in this approach, it is referred to as velocity setpoints, as supported by previous research [17]. The resulting architecture enables modular and scalable control design by operating the outer loop at lower frequencies (e.g., 50 Hz), while an inner-loop manages attitude stabilization and motor actuation at higher frequencies (250 Hz–1 kHz), as illustrated in Fig. 1 [14].



**Fig. 1.** Quadcopter Cascaded Control Architecture.

In this study, an outer loop position controller is implemented to regulate quadcopter motion via velocity setpoints. These setpoints are processed by a dedicated autopilot, such as Pixhawk<sup>1</sup>, which executes inner-loop control for attitude stabilization and actuator signals. To evaluate the effectiveness of this approach, a conventional PID controller is compared against a Neural PID controller trained with Extended Kalman Filter (EKF) algorithm, aiming to improve trajectory tracking under parameter uncertainties and external disturbances. The proposed method is validated using Hardware-in-the-Loop (HIL) simulation integrating Gazebo<sup>2</sup> for realistic physics-based evaluation.

This paper is organized as follows: Section 2 describes methodology, including quadcopter kinematic model and proposed control approaches (conventional PID and Neural PID with EKF). Section 3 details experimental setup and implementation aspects. Section 4 presents results and performance metrics. Finally, Section 5 summarizes conclusions and discusses possible future research directions.

## 2 Methodology

### 2.1 Quadcopter Kinematic Model

The proposed quadcopter system is analyzed as a six-degree-of-freedom (DoF) system within the North-East-Down (NED) reference frame, which is commonly used in aerial robotics due to its alignment with navigation and mapping conventions [18], as shown in Fig. 2.

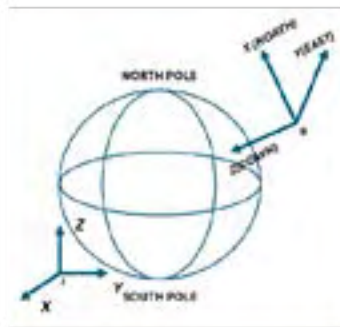


Fig. 2. North-East-Down Configuration.

Based on [19], the general motion of a quadcopter is defined in terms of the inertial reference frame  $\mathcal{C}_I(x_I, y_I, z_I)$  and the body-fixed reference frame

<sup>1</sup> Pixhawk is a registered trademark of Dronecode Project, Inc.

<sup>2</sup> Gazebo is an open-source robotics simulator developed by the Open Source Robotics Foundation (OSRF).

$\varepsilon_B(x_B, y_B, z_B)$ , with origin located at the center of mass. The orientation of the body-fixed reference frame  $\varepsilon_B$  on vehicle with respect to the inertial reference frame  $\varepsilon_I$  is determined by the rotation angles  $\mu = [\phi, \theta, \psi]^T$  using Euler angles or roll-pitch-yaw.

The body-fixed reference frame  $\varepsilon_B(x_B, y_B, z_B)$  is rigidly attached to the quadcopter. The coordinates of the origin of  $\varepsilon_B(x_B, y_B, z_B)$  with respect to  $\varepsilon_I(x_I, y_I, z_I)$  are determined by Cartesian coordinate vector  $\xi = [\xi_{xI}, \xi_{yI}, \xi_{zI}]^T \in \varepsilon_I(x_I, y_I, z_I)$ .

The mathematical structure that describes the general motion of orientation and position in three-dimensional space for a quadcopter, considering the analysis in moving reference frames using Euler angles, is given by:

$$p_I = \xi + R_{zyx}^e(\psi, \theta, \phi)p_B \quad (1)$$

where the term  $p_I$  represents the position of a point in the inertial frame, while  $p_B$  denotes the same point expressed in the body-fixed frame. The vector  $\xi$  defines the position of the body-fixed frame origin relative to the inertial frame. The rotation matrix  $R_{zyx}^e(\psi, \theta, \phi)$  transforms coordinates from the body-fixed frame to the inertial frame using a ZYX Euler angle convention, where  $\psi$  corresponds to yaw,  $\theta$  to pitch, and  $\phi$  to roll.

In this research, the outer-loop controller operates on desired velocity set-points expressed in the NED frame. These commands are then processed by the onboard autopilot, which generates the necessary thrust and attitude angles to achieve the commanded motion.

## 2.2 Velocity Control Approaches

**Conventional PID Control.** Appropriate velocities are computed to achieve position tracking. Consequently, the controller determines velocities  $u_x(t)$ ,  $u_y(t)$  and  $u_z(t)$  at time step  $t$  to guide quadrotor from its current position (2) to desired position (3).

$$[x(t) \ y(t) \ z(t)]^T \quad (2)$$

$$[x_d(t) \ y_d(t) \ z_d(t)]^T \quad (3)$$

Error between desired and current positions is defined as

$$\begin{bmatrix} x(t) \\ y(t) \\ z(t) \end{bmatrix} = \begin{bmatrix} x_d(t) - x(t) \\ y_d(t) - y(t) \\ z_d(t) - z(t) \end{bmatrix} \quad (4)$$

Discrete PID control laws [11] at step  $t$  are provided in equations (5)–(7). In this control scheme, there is a dedicated PID module for each error signal  $u_x(t)$ ,  $u_y(t)$ , and  $u_z(t)$ . The parameters  $K_p^x$ ,  $K_i^x$ , and  $K_d^x$  correspond to proportional, integrative, and derivative gains for error  $x_e$ , respectively. Similarly, the parameters  $K_p^y$ ,  $K_i^y$ , and  $K_d^y$  are applied to error  $y_e$ , while  $K_p^z$ ,  $K_i^z$ , and  $K_d^z$  are used for error  $z_e$ .



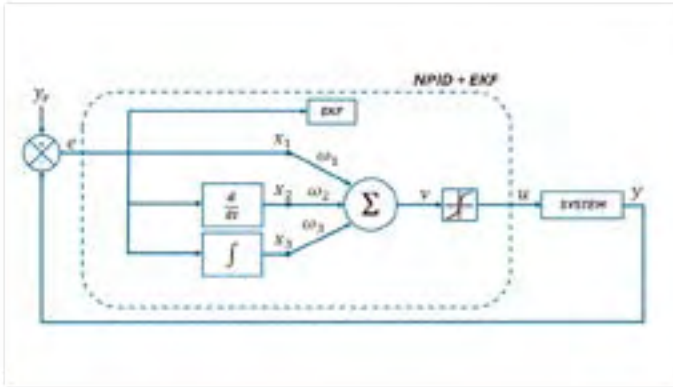
$$u_x(t) = K_P^x x_e(t) + K_I^x \sum_{j=1}^t x_e(j) + K_D^x [x_e(t) - x_e(t-1)] \quad (5)$$

$$u_y(t) = K_P^y y_e(t) + K_I^y \sum_{j=1}^t y_e(j) + K_D^y [y_e(t) - y_e(t-1)] \quad (6)$$

$$u_z(t) = K_P^z z_e(t) + K_I^z \sum_{j=1}^t z_e(j) + K_D^z [z_e(t) - z_e(t-1)] \quad (7)$$

The gains are manually adjusted to ensure a stable response under nominal conditions. However, a main limitation of this method is the need for recalibration whenever the system experiences variations in its dynamics or flying conditions.

**Adaptive Neural PID Control.** The Adaptive Neural PID controller dynamically adjusts control gains in real time to enhance trajectory tracking and disturbance rejection. It replaces fixed PID parameters with a single-neuron architecture that learns and updates its proportional, integral, and derivative gains. Contrary to conventional PID control, which requires manual tuning, this adaptive approach improves system robustness by continuously refining control actions based on real-time error feedback.



**Fig. 3.** Scheme of the Proposed Adaptive Neural PID Controller Trained With the EKF Algorithm.

$$\hat{y} = \Theta(\omega^T x) \quad (8)$$

where  $\omega$  is a weight vector,  $x$  input vector,  $\hat{y}$  is output of neuron and  $\Theta$  is an activation function. Training can be perform using different paradigms [10].

*Neural PID Architecture.* In Fig. 3 illustrates proposed Adaptive Neural PID controller. In this configuration,  $e$  denotes system error (9), defined as difference between reference  $y_r$  and output of the system  $y$ . The neuron receives  $x_1$ ,  $x_2$  and  $x_3$  as inputs, representing proportional error (10), integral of error (12), and derivative of error (11), respectively. The weights  $\omega_1$ ,  $\omega_2$ , and  $\omega_3$  are adapted on-line through EKF, and they correspond to  $K_P$ ,  $K_I$  and  $K_D$  gains. The weighted sum  $v$  is defined in (13), and neuron output  $u$  is given in (14). The activation function  $\tanh(\cdot)$  is employed, and  $\alpha$  scales amplitude of  $\tanh$ .

$$e(t) = y_r(t) - y(t) \quad (9)$$

$$x_1(t) = e(t) \quad (10)$$

$$x_2(t) = e(t) - e(t-1) \quad (11)$$

$$x_3(t) = \sum_{j=1}^t e(t) \quad (12)$$

$$v(t) = \sum_{i=1}^3 \omega_i(t) x_i(t) \quad (13)$$

$$u(t) = \alpha \tanh(v(t)) \quad (14)$$

The activation function  $\tanh(\cdot)$  operates within the interval  $[-1, 1]$ . In addition, parameter  $\alpha$  must be chosen based on the level of control action necessary for the corresponding tasks.

*EKF-Based Online Training.* The EKF training algorithm is given by Equations (15)–(17)[9]:

$$\mathbf{K}(t) = \mathbf{P}(t) \mathbf{H}^T(t) [\mathbf{R}(t) + \mathbf{H}^T(t) \mathbf{P}(t) \mathbf{H}(t)]^{-1} \quad (15)$$

$$\omega(t+1) = \omega(t) + \eta \mathbf{K}(t) [y(t) - \hat{y}(t)] \quad (16)$$

$$\mathbf{P}(t+1) = \mathbf{P}(t) - \mathbf{K}(t) \mathbf{H}(t) \mathbf{P}(t) + \mathbf{Q}(t) \quad (17)$$

$$\mathbf{H}_j(t) = \left[ \frac{\partial u(t)}{\partial \omega_j(t)} \right] = \left[ \frac{\partial u(t)}{\partial v(t)} \frac{\partial v(t)}{\partial \omega_j(t)} \right] = \alpha [1 - \tanh^2(v(t)) x_j(t)] \quad (18)$$

where  $\mathbf{K}$  denotes the Kalman gain, while  $\mathbf{P}$ ,  $\mathbf{Q}$ , and  $\mathbf{R}$  are the covariance matrices for weight estimation errors, estimation noise, and output noise, respectively. The matrix  $\mathbf{H}$  encapsulates the partial derivatives of the neuron output with respect to each weight,  $\eta$  denotes the learning rate, and  $u$  is the neuron output. The error  $e$  corresponds to the difference between the desired output and the neuron output. Collectively, these elements form an iterative procedure that updates the neural network parameters, ensuring stable and efficient adaptation of the Single Neuron PID controller.

The training objective is to find a weight vector  $\omega$  such that  $u$  minimizes the error between the reference signal and the system output, as shown in (9).

### 3 Experimental Setup

#### 3.1 Hardware-in-the-Loop Configuration

The HIL configuration allows Pixhawk to process simulated sensor data and execute control commands in a virtual environment, replicating real-flight conditions. The system components include:

- Pixhawk 2.4.8 running PX4 firmware (v15.1.0).
- Host Computer: Intel Core i5 processor, 8GB RAM, Ubuntu 20.04.
- Simulator: Gazebo 11 with PX4 SITL.



Fig. 4. Setup HIL.

#### 3.2 Control System Implementation

To establish this configuration, Pixhawk is connected to host computer via USB, and QGroundControl<sup>3</sup> is used to activate HIL mode. Under this setup, physical sensors such as the Inertial Measurement Unit (IMU), Global Positioning System (GPS), and barometer are bypassed, and all measurements are generated by the simulation. These simulated sensor values are transmitted to autopilot via MAVLink<sup>4</sup> messages. The flight controller processes these commands, executes control signals, and sends actuator responses back to the simulator, creating a fully closed-loop system. [14].

Fig. 5 illustrates the data flow between the flight controller, QGroundControl, and simulation.

<sup>3</sup> QGroundControl is an open-source ground control station maintained by the Dronecode Project, Inc.

<sup>4</sup> MAVLink is an open-source communication protocol for unmanned vehicles maintained by the Dronecode Project, Inc.

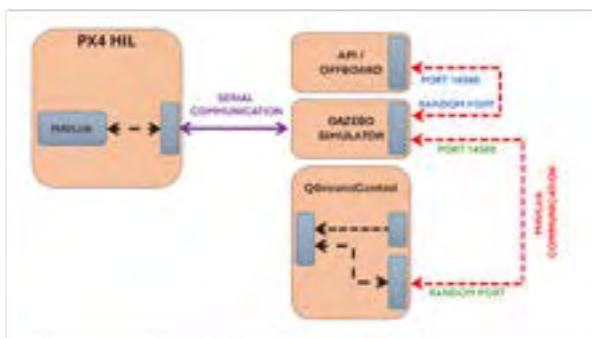


Fig. 5. Diagram of HIL Simulation Environment.

### 3.3 Control System Implementation

The outer-loop velocity controller is implemented in Python using the pymavlink library, which allows direct communication with the PX4 autopilot. The control system computes velocity setpoints based on position errors and transmits them to the Pixhawk via the MAVLink message `SET_POSITION_TARGET_LOCAL_NED`, configured with a mask that enables only velocity control in the NED frame.

To ensure real-time performance and reliability, the following optimizations are applied:

- Communication Baud Rate: MAVLink at 921600 bps.
- Controller Update Frequency: 50 Hz for velocity setpoints.
- Gazebo Physics Update Rate: 250 Hz to match real-time dynamics.

Additionally, MAVProxy is used to monitor and log MAVLink messages for debugging and analysis.

The closed-loop system operates by continuously receiving state feedback from Gazebo, which includes position, velocity, and attitude data. These measurements are used to correct velocity setpoints in real time, ensuring trajectory tracking even under external disturbances.

**MAVLink Message Structure: `SET_POSITION_TARGET_LOCAL_NED`.** This message specifies position, velocity, acceleration, and yaw setpoints in the local NED frame [15]. It is preferred over alternatives such as `SET_ATTITUDE_TARGET` because it allows direct velocity control while the autopilot autonomously manages attitude stabilization. The relevant dimensions are shown in Table. 1:

*Type Mask Configuration.* The `type_mask` is a 16-bit bitmap that determines which dimensions in the message are ignored by the autopilot. A value of 1 in a bit position indicates that the corresponding is ignored, while a value of 0 enables it. The specific mapping used in this implementation is shown in Table 2.



**Table 1.** Message Dimensions Used for the Implementation of Controllers.

| Field            | Type     | Description               |
|------------------|----------|---------------------------|
| target_system    | uint8_t  | System ID                 |
| target_component | uint8_t  | Component ID              |
| coordinate_frame | uint8_t  | MAV_FRAME_LOCAL_NED       |
| type_mask        | uint16_t | Bitmap                    |
| vx               | float    | X velocity setpoint (m/s) |
| vy               | float    | Y velocity setpoint (m/s) |
| vz               | float    | Z velocity setpoint (m/s) |

**Table 2.** Bitwise Definition of Type Mask for Velocity Control. The Resulting Value for this Configuration is 0b110111000111

| Bit Position | Description                       | Value |
|--------------|-----------------------------------|-------|
| 0            | Ignore position X                 | 1     |
| 1            | Ignore position Y                 | 1     |
| 2            | Ignore position Z                 | 1     |
| 3            | Ignore velocity X                 | 0     |
| 4            | Ignore velocity Y                 | 0     |
| 5            | Ignore velocity Z                 | 0     |
| 6            | Ignore acceleration X             | 1     |
| 7            | Ignore acceleration Y             | 1     |
| 8            | Ignore acceleration Z             | 1     |
| 9            | Use force instead of acceleration | 0     |
| 10           | Ignore yaw                        | 1     |
| 11           | Ignore yaw rate                   | 1     |

### 3.4 Simulation Environment

The Gazebo 11 is configured with Iris quadcopter from PX4. This model has the following properties:

- Mass: 1.5 kg.
- Inertia matrix: Defined based on standard Iris parameters.
- Motor configuration: Quadcopter X-frame with four brushless motors.
- Actuator response: Modeled based on real-world thrust-to-weight ratios.

**Wind Simulation and Test Scenarios.** To evaluate robustness of the control system under different environmental conditions, a wind disturbance model is implemented using the Gazebo Wind Plugin [14].

To establish realistic wind conditions, the Beaufort scale is used as a reference for selecting wind speeds, ensuring consistency with standardized meteorological classifications [20], [21]. Three scenarios are defined to assess the robustness of each controller under varying wind disturbances:

- Nominal Condition: No wind disturbances, evaluating reference tracking accuracy under ideal conditions (0 m/s).



- Moderate Wind: A steady wind classified as Beaufort 4 (moderate breeze), with speeds ranging from 6 to 8  $m/s$ . The disturbance is applied uniformly in all three axes ( $X, Y, Z$ ), using an azimuthal angle of  $0^\circ$  with variations up to  $\pm 5^\circ$ , simulating typical outdoor conditions.
- Gusty Wind: A continuous wind of 8 to 11  $m/s$  (Beaufort 6) combined with intermittent gusts reaching 11 to 14  $m/s$ , representing severe turbulence. The wind acts in all three axes ( $X, Y, Z$ ) to evaluate disturbance rejection capabilities.

Each scenario is repeated multiple times, and performance metrics are statistically analyzed to ensure reproducibility and reliability of results.

### 3.5 Metrics

Performance of the controllers is evaluated using several quantitative metrics:

- Mean Squared Error (MSE): Measures the average squared deviation of system response from the desired trajectory.
- Steady-State Error (SSE): Quantifies the difference between desired and actual state once system has stabilized.
- Settling Time: The time required for the response to remain within a specified tolerance of the reference trajectory.
- Overshoot (%): The maximum deviation beyond the reference before stabilization.
- Integral Absolute Error (IAE): Evaluates accumulated absolute error over time, reflecting overall tracking accuracy.
- Standard Deviation (STD): Assesses response variability and fluctuations in velocity control.

Due to the transient nature of wind disturbances in the gusty wind scenario, conventional metrics such as settling time and steady-state error are not suitable. Instead, the evaluation is based on the system's ability to recover stability after disturbances. This is assessed through qualitative observation of trajectory tracking and real-time logging of MAVLink messages.

## 4 Results

### 4.1 Comparison of Controllers

**Nominal Conditions (No Wind).** Fig. 6 and 7 illustrate the position tracking and velocity control performance of PID and Neural PID controllers in a disturbance-free scenario.

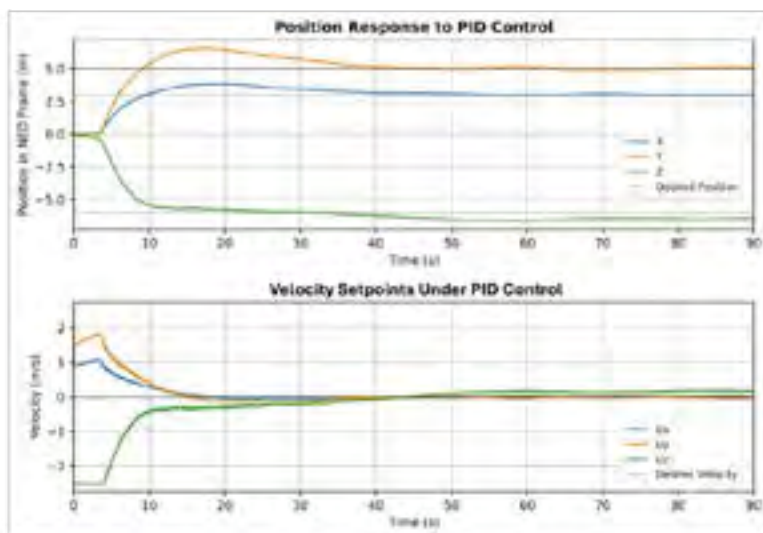


Fig. 6. Results Nominal Conditions PID.

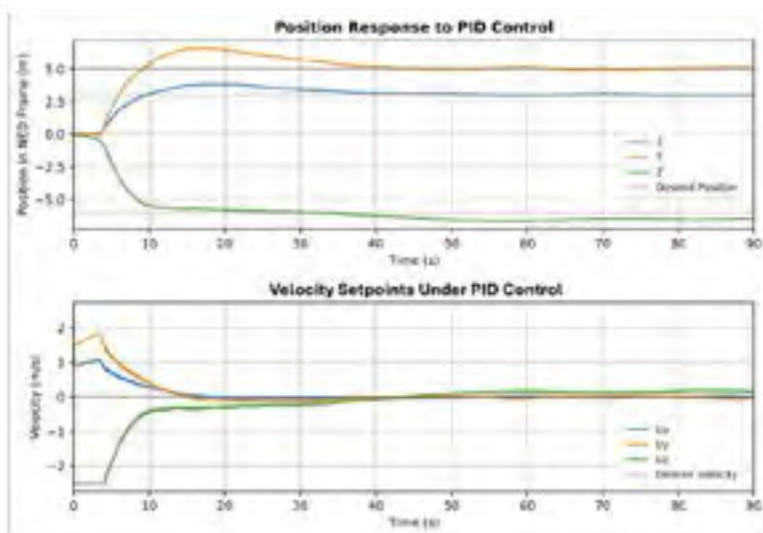


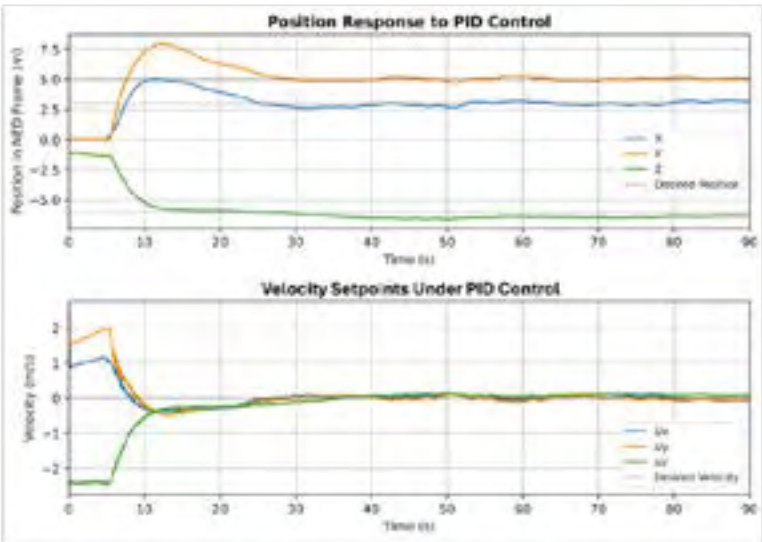
Fig. 7. Results Nominal Conditions Neural PID.

Neural PID demonstrates improved stability and reduced tracking error, particularly in the Z-axis, where settling time is significantly shorter.

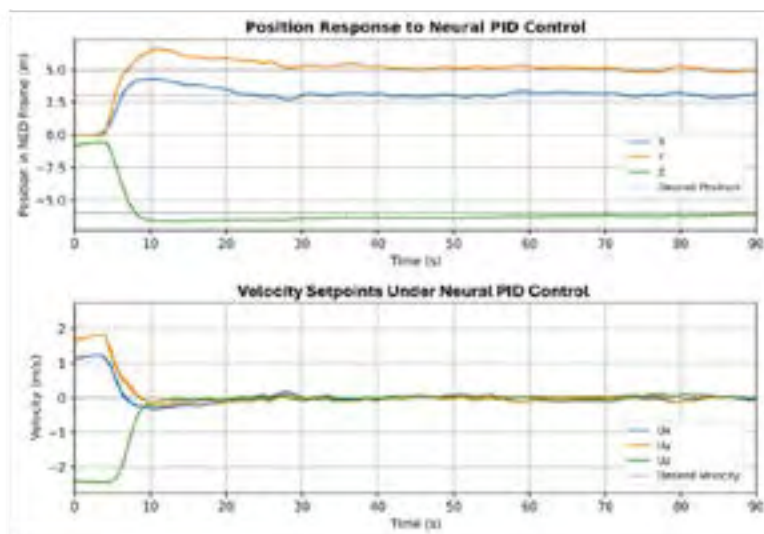
**Table 3.** Performance Metrics Under Nominal Conditions.

| Metric            | X       |                | Y       |                | Z       |                |
|-------------------|---------|----------------|---------|----------------|---------|----------------|
|                   | PID     | Neural PID     | PID     | Neural PID     | PID     | Neural PID     |
| MSE               | 0.5789  | <b>0.4174</b>  | 1.7062  | <b>1.4859</b>  | 2.0094  | <b>1.3221</b>  |
| Settling Time (s) | 9.33    | <b>5.96</b>    | 8.97    | <b>8.15</b>    | 25.70   | <b>7.49</b>    |
| Overshoot (%)     | 27.57   | <b>11.65</b>   | 31.29   | <b>25.04</b>   | 10.74   | <b>9.12</b>    |
| IAE               | 35.2736 | <b>27.0838</b> | 59.2087 | <b>55.0637</b> | 66.4549 | <b>53.3511</b> |
| STD               | 0.7609  | <b>0.6459</b>  | 1.3062  | <b>1.2189</b>  | 1.4275  | <b>1.1495</b>  |

**Moderate Wind (Beaufort 4, 6–8 m/s).** Fig. 8 and 9 depict the controllers responses under moderate wind conditions.



**Fig. 8.** Results Moderate Wind PID.



**Fig. 9.** Results Moderate Wind Neural PID.

Neural PID exhibits lower overshoot and faster stabilization, particularly in the X and Y axes, which are more affected by lateral wind disturbances.

**Table 4.** Performance Metrics Under Moderate Wind Conditions.

| Metric            | X       |                | Y       |                | Z       |                |
|-------------------|---------|----------------|---------|----------------|---------|----------------|
|                   | PID     | Neural PID     | PID     | Neural PID     | PID     | Neural PID     |
| MSE               | 0.9850  | <b>0.6224</b>  | 2.4178  | <b>1.5760</b>  | 1.8667  | <b>1.8419</b>  |
| Settling Time (s) | 7.49    | <b>6.24</b>    | 7.59    | <b>7.00</b>    | 22.96   | <b>8.00</b>    |
| Overshoot (%)     | 67.14   | <b>43.12</b>   | 59.73   | <b>32.58</b>   | 10.16   | 10.74          |
| IAE               | 50.8625 | <b>36.0855</b> | 70.7562 | <b>54.5496</b> | 65.2699 | <b>60.1176</b> |
| STD               | 0.9925  | <b>0.7888</b>  | 1.5548  | <b>1.2554</b>  | 1.3582  | <b>1.3565</b>  |

**Gusty Wind (Beaufort 6, 8–14 m/s).** Fig. 10 and 11 illustrate the controllers responses under strong and intermittent wind bursts.

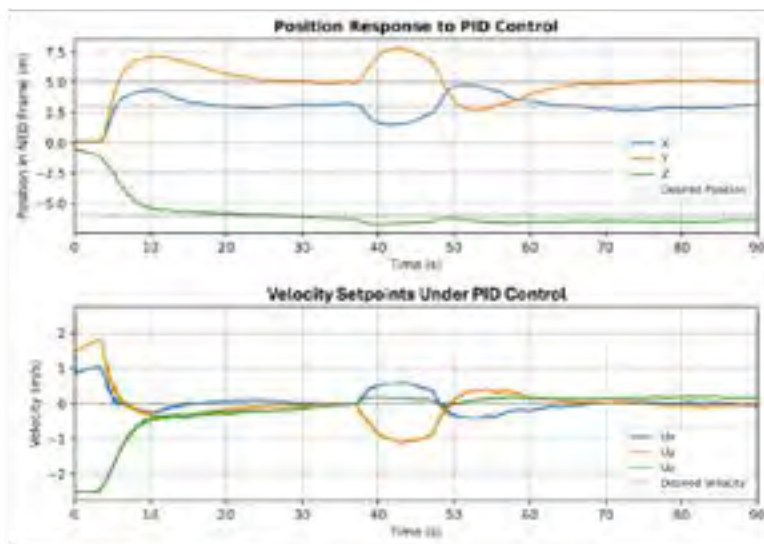


Fig. 10. Results Gusty Wind PID.

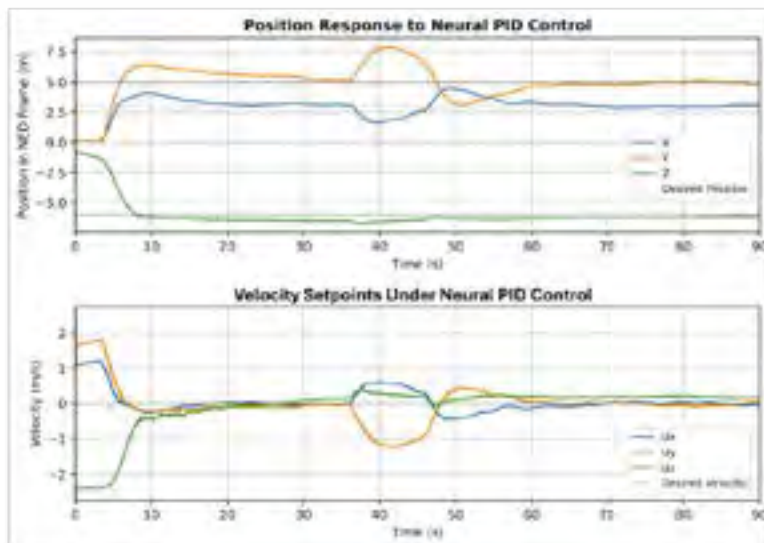


Fig. 11. Results Gusty Wind Neural PID.



The Neural PID controller demonstrates superior performance in the Y-axis, effectively reducing deviations caused by wind bursts. However, in the X and Z axes, the PID controller exhibits lower MSE and standard deviation STD, suggesting a more stable response in these directions. While the Neural PID reduces oscillations, it does not significantly enhance overall stability under extreme wind conditions.

**Table 5.** Performance Metrics Under Gusty Wind Conditions.

| Metric | X             |            | Y      |               | Z      |               |
|--------|---------------|------------|--------|---------------|--------|---------------|
|        | PID           | Neural PID | PID    | Neural PID    | PID    | Neural PID    |
| MSE    | <b>0.8541</b> | 0.8993     | 4.0517 | <b>2.5956</b> | 1.4405 | <b>1.7393</b> |
| STD    | <b>0.9241</b> | 0.9483     | 2.0129 | <b>1.6110</b> | 1.1963 | <b>1.3157</b> |

#### 4.2 Discussion

Under nominal conditions, Neural PID exhibits superior performance in reducing settling time, tracking error, and overshoot. In moderate wind conditions, it provides faster convergence and lower oscillations, improving stability. In gusty wind scenarios, the Neural PID controller shows enhanced resilience, minimizing trajectory deviations and maintaining flight stability despite external disturbances.

### 5 Conclusions and Future Work

This study demonstrates that an Adaptive Neural PID controller trained with EKF improves quadcopter trajectory tracking and stability under varying wind conditions. In nominal and moderate wind scenarios, it outperforms conventional PID by reducing overshoot, improving settling time, and minimizing tracking error. Under gusty wind conditions, the Neural PID controller enhances stability in the Y-axis but does not significantly surpass the PID controller in other axes.

Future work will focus on extending this method to incorporate fault diagnosis modules (e.g., actuator or sensor failures) and exploring additional non-linear control strategies such as sliding-mode or backstepping with neural adaptation. Additionally, more extensive hardware flight tests beyond HIL will be conducted to validate these findings in real-world operational environments.

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# Habdil - Development of an adaptive and affordable partial hand prosthesis using 3D printing

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**Abstract.** This paper introduces the design and development of an adaptive hand prosthesis that incorporates flexible materials and advanced sensors to improve user functionality and comfort. This prosthesis is designed for individuals with partial hand amputations, enabling better control and ergonomic integration with the natural hand anatomy. The methodology used for the design, simulation, and validation of the prototype is presented, as well as preliminary tests carried out in controlled environments.

**Keywords:** Prosthesis, ergonomics, design, disability, amputation, finger, partial, modular, 3D printing, rehabilitation, prototype, mechanical, flexible mechanism.

## 1 Problem Description

### 1.1 A Subsection Sample

In Mexico, out of approximately 128.5 million inhabitants, 9.25 million people have some form of disability, 17.3% of whom experience difficulties in moving or using their arms or hands. In Jalisco, which has a population of 8.82 million, around 96,333 people face challenges with arm or hand mobility, according to INEGI reports [1].

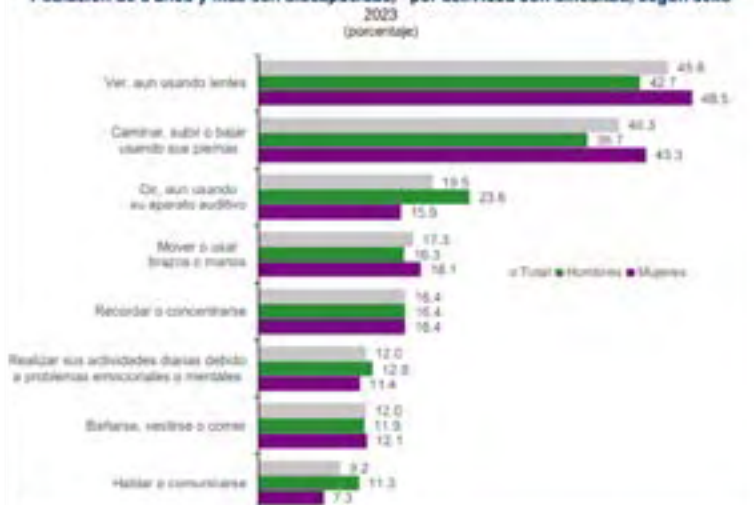
Current upper limb prostheses are often expensive, complex, and poorly adapted to users, particularly in cases of partial hand amputations. While full-arm prostheses have been extensively developed, solutions for partial hand amputations remain limited, especially in terms of functionality and affordability. Additionally, 31% of Jalisco's population lacks access to medical services [2], further restricting their ability to obtain advanced prosthetic technology and participate in rehabilitation programs.

<https://doi.org/10.61728/AE20255268>



There is a pressing need for affordable and customizable solutions, such as a modular partial hand prosthesis that offers optimal user support, enabling them to perform daily tasks and reintegrate into the workforce, ultimately improving their quality of life.

**Población de 5 años y más con discapacidad,\* por actividad con dificultad, según sexo**



*Figure 1. Population aged 5 years and over with disabilities, by activity with difficulty and by sex, 2023)*

It refers to people who have the answer "He does it with great difficulty" or "He cannot do it" in each of the activities for which the question is asked. Note: The sum of the percentages by sex is greater than 100 because a person could report difficulty in more than one activity. The percentage is calculated with respect to the total population with disabilities for each sex. Source: INEGI National Survey of Demographic Dynamics (ENADID), 2023. Database. National Statistical and Geographic Information System (SNEIG). Information of National Interest (IIN). [1].

## 1.2 Concept

The partial prosthesis is designed to operate in two modes: a purely mechanical mode that requires no power and a hybrid mode activated by electromyography (EMG) sensors, allowing for more natural control that enhances the user's independence. This system promotes intuitive and adaptive control, making the prosthesis more user-friendly.

The goal is to develop a customizable, adaptable, and easily adjustable prosthesis featuring modular components, such as interchangeable and durable attachments. This flexibility enables the prosthesis to be tailored to users with varying degrees of finger loss.



The design is inspired by the assembly of 3D-printed components integrated into a fabric or leather base, ensuring that the device can be easily worn and removed. This concept draws from the ergonomics and functionality of medieval bracers or gauntlets.

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The proposed prosthesis aims to significantly enhance the quality of life for individuals with disabilities. This functional and affordable solution addresses the need for assistive devices that are not only cost-effective but also adaptable to different anatomies and work environments.

Its intuitive design, which combines myoelectric sensors with mechanical control, enables users to perform daily activities and participate in professional settings with greater autonomy, fostering both social and economic reintegration.

The project's open-source approach enhances accessibility by allowing healthcare professionals, engineers, and organizations to collaborate on improving and customizing the design for specific regional and individual needs. This initiative democratizes access to medical technology while also encouraging continuous innovation and scalable solutions to address the challenges of prosthetic accessibility in underserved communities.

### **1.3 Market competition:**

Arm prostheses in Mexico range in price from 10,000 to 500,000 Mexican pesos or more, depending on the model and functionality. More advanced and sophisticated prostheses tend to be significantly more expensive, while simpler, more basic models are generally more affordable [3].

There are several companies in Mexico specializing in upper limb prosthetics, but most focus on transulnar or full-arm amputations. In contrast, finger prostheses are primarily aesthetic, offering limited movement and load-bearing capacity.

### **1.4 Product differentiation**

The primary mission of this product is to enhance user self-sufficiency by providing a functional and adaptable solution that restores mobility and dexterity for essential daily activities. By offering a combination of mechanical and myoelectric control, this prosthesis allows users to perform routine tasks with greater ease and confidence.



Additionally, the design aims to facilitate workforce integration, empowering individuals with partial hand amputations to engage in professional environments and skilled labor without the limitations imposed by traditional prosthetic devices. By promoting greater autonomy and independence, this prosthesis contributes to improving users' overall quality of life, enabling them to fully participate in social, economic, and personal development activities.

### 1.5 Sustainable Development Goals (SDGs)

This project aims to meet some of the Sustainable Development Goals in the following ways:

**SDG 3: Health and Well-being:** The project has the potential to improve the quality of life of people with partial amputations by providing them with a functional tool that restores motor skills and promotes their physical and psychological well-being.

**SDG 9: Industry, Innovation and Infrastructure:** It incorporates electromyography sensors and 3D printing to promote research and development of accessible and customizable prostheses.

**SDG 10: Reduced Inequalities:** Offering an accessible and functional prosthetic solution can help reduce inequalities by empowering people with disabilities, allowing them to fully participate in society and the labor market.

**SDG 12: Responsible Production and Consumption:** Promotes the efficient use of resources and reduces environmental impact with sustainable materials and additive manufacturing.

**SDG 17: Partnerships to Achieve the Goals:** A project of this nature allows for collaborations between researchers, designers, engineers and health professionals, strengthening alliances for innovation and inclusive development.

### 1.6 Reduction to practice

Currently, a prototype of the prosthesis has been developed using a public domain model as a template [4]. A custom socket was added by editing it with Blender software, using the scanned stump as a reference and guide to ensure a precise fit for the user (Fig. 2). 3D printing has proven to be highly efficient in terms of material usage. The solid parts are made of PET-G, which exhibits remarkable resistance to wear and tear, even after more than a year of use. The joints in the wrist and phalanges were printed with TPU, allowing the prototype to incorporate a compliant mechanism activated by wrist flexion. This feature enhances the ability to grip large objects, such as glasses, bottles, and boxes, and facilitates holding items that require the support of both hands.

The only component that requires regular maintenance is the fishing line (hemp), which acts as tendons and needs to be replaced approximately every two months due to wear. One of the main challenges to address is properly sizing the anatomical proportions to

ensure the device does not exceed the dimensions of the user's hand. Another key objective is to enable finger articulation, allowing for individual movement, which is currently being evaluated for practicality using the author as a test subject.

These tests include validating ergonomics, assessing the functionality of the hybrid system (mechanical and myoelectric), and evaluating ease of use. The 3D-printed components have demonstrated a good balance between cost and durability, while the integration of EMG sensors has enabled basic motor control testing. Initial iterations have focused on optimizing the design's adaptability to anatomical differences and everyday tasks, yielding promising results in terms of comfort and control. Additionally, efforts are underway to improve documentation and refine the design, facilitating the replication of the model within communities of interest.



Fig. 2 Screenshot of the unedited open source model next to the version with the socket and the scan from the test subject user.



Fig. 3 Screenshot of all the prototype parts in Blender.



Fig. 4 Photo of the prototype in use based on the test subject.

### 1.7 Pathway to implementation

1. Strategic collaborations: With the support of the Inventors Laboratory, CyberTIM-Lab, BioTimLab (from CUCEI UdeG) and the Innovation Laboratory (LIN) of the Zapopan government, there are facilities where there is advice, linkage and various equipment, specialized equipment for manufacturing (3D printers, laser cutters, etc.)

and testing of the device. These alliances will also facilitate clinical validation with real users.

2. Design optimization: Based on current tests, we will continue to iterate on the design to improve its functionality, comfort and efficiency in manufacturing.

3. Accreditation and testing: Through strategic collaborations with institutions that promote community support, tests will be carried out with different users who meet the user profile to validate the effectiveness and impact of the project.

4. Distribution and accessibility: Publishing the design as open source will ensure that communities, professionals and institutions can access the project and adapt it to their needs.

## **1.8 Conclusion.**

A design that enables users to experience the seamless functionality of a tool, as effortlessly and discreetly as putting on a glove, represents a significant step toward fostering the reintegration of individuals with functional diversity into various aspects of daily life. Often, these individuals face challenges not only in physical functionality but also in societal perceptions that can lead to exclusion from certain activities. By prioritizing comfort, accessibility, and intuitive usability, such a device has the potential to break down barriers and redefine the relationship between assistive technology and personal empowerment. Furthermore, with the correct implementations, this innovation serves as a crucial bridge between rehabilitation technology and bioengineering, demonstrating how advancements in material science, sensor integration, and ergonomic design can converge to create solutions that are not only functional but also enhance the user's overall quality of life. Beyond its technical merits, this approach highlights the importance of human-centered design in medical and assistive technologies, emphasizing that true progress in the field comes not just from improving mechanical efficiency but from fostering dignity, independence, and social inclusion.

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# Neural PID controller to improve hierarchical multitask scheme for redundant cooperative manipulators

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**Abstract.** The hierarchical multitasking scheme is a useful approach for robotic systems with multiple objectives, where each objective has a lower priority than the previous one. However, some tasks can be complex enough to require significant effort for fine-tuning. In this paper, we propose the implementation of a neural incremental proportional-integrative-derivative (NI-PID) approach to control multiple tasks within a hierarchical multitasking scheme for a dual-arm robotic system. The NI-PID adapts its weights online, significantly reducing the effort required for tuning gains. The effectiveness of the proposed approach is validated through simulations on a dual-arm system modeled with the Baxter arm, featuring 7 degrees of freedom (7DOF).

## 1 Introduction

The cooperation and collaboration of robotic manipulators remain a highly studied area, the proper functioning of two or more manipulators working together has a positive impact on various fields, such as industry, aeronautics, exploration systems, and more, reducing costs, increasing production efficiency, and enhancing automation capabilities while carrying out tasks classified as risky for humans. Both terms might be considered synonyms; however, when it refers to the topic of controlling robotic manipulators, they have important differences [1]. Cooperation refers to how two or more manipulators fulfill independent specific tasks that contribute to achieving a final common objective. Each manipulator's task is independent of the others, and while it can significantly impact the final objective, it does not affect the task of each manipulator. On the other hand, Collaboration suggests that two or more manipulators share a common objective, where each one performs a specific task that highly depends on the performance of the other manipulator [2, 3]. Coordination in cooperation and collaboration tasks suggests that the manipulators physically interact with each other, meaning their dynamics must be related. Conversely, in non-coordinated scenarios, robotic manipulators can be analyzed individually, as their dynamics do not

<https://doi.org/10.61728/AE20255275>



interact in any way [4]. In this work, we implement a hierarchical multitasking scheme for a dual-arm system in coordinating cooperative manipulation tasks.

Kinematic redundancy is important to consider when working with robotic manipulators, it refers to the robot having more degrees of freedom than necessary to perform a task. It is well known that six degrees of freedom are sufficient to execute most tasks in the Cartesian workspace. However, a higher number of degrees of freedom yield better results when performing more complex tasks or tasks requiring greater precision [5]. A robotic manipulator can be controlled to successfully execute two or more tasks depending on their complexity and the degrees of freedom it possesses; this concept is known as multitask scheme. Furthermore, if the tasks need to be executed with a certain level of priority, the concept is named as hierarchical multitask scheme. In the last one, the robotic manipulator has a control action that seeks to satisfy multiple objectives simultaneously, such as trajectory tracking, obstacle avoidance, and coordination, among others, where each task can be weighted based on its desired priority, thus establishing an order and hierarchy during execution [6].

Classical control methods often get good results when applied to robotic manipulators, but they come with certain challenges, such as the need for recalibration over time, lack of adaptability, and difficulty in adjusting gains for specific work environments. One of the proposed solutions to these challenges, which has gained popularity in recent years, is neural controllers. These controllers can modify gains either online or offline, improving results and enhancing the manipulator's adaptability to noise or external system elements [7]. The contribution of this paper is to propose a better solution when handling hierarchical multitask schemes for redundant robots.

In this work, we propose improving a hierarchical multitask scheme for coordinate cooperative manipulators. To improve adaptability against external conditions and avoid extra efforts tuning parameters, the classic controller for coordinate manipulation is going to be replaced for a NI-PID. The case of study consists of a dual-arm system of two Baxter 7DOF manipulators. The master manipulator must execute a secondary task which consists of following a trajectory, while both robots (master and slave) are fulfilling the primary task of coordination. The kinematics for both manipulators are analyzed together using a relative Jacobian. This problematic can be applied to a wide range of real-life situations, where the tasks and their priority can be modified to achieve different objectives.

The paper is organized as follows: Next section introduces the Hierarchical multitasking scheme along with the relative Jacobian. Section 3 addresses the NI-PID controller and its adaptations rules. Section 4 presented the proposed approach. The simulation results are given in section 5. Finally, the conclusions are provided in section 6.

## 2 Hierarchical multitasking scheme

Hierarchical multitasking scheme allows multiple tasks to be executed in a structured order, where each task does not interfere with the execution of the preceding one [8]. This structure continues recursively, ensuring that task  $N$  does not affect task  $N - 1$ , maintaining system stability and efficiency. In this paper, we consider implementing the hierarchical multitasking scheme for a dual-arm system for coordinate cooperation.

The dual-arm system scheme for coordinate cooperation is represented in Fig. 1. The vector  $\vec{q}_A$  contains the joint configuration for manipulator  $A$ , such that  $\vec{q}_A = [\theta_1^A, \theta_2^A, \theta_3^A, \theta_4^A, \theta_5^A, \theta_6^A, \theta_7^A]^T$ ; moreover, for manipulator  $B$  we have  $\vec{q}_B = [\theta_1^B, \theta_2^B, \theta_3^B, \theta_4^B, \theta_5^B, \theta_6^B, \theta_7^B]^T$ . Both manipulator joints are contained on  $\vec{q} = [q_A^T, q_B^T]^T$ . Matrixes  $J_A$  and  $J_B$  expressed the Jacobian matrix in the world frame for manipulator  $A$  and  $B$ , respectively.

For the coordination objective on a multitask scheme, the analysis of the robotic manipulators is done together, as shown in Fig. 1, it is defined four important reference frames: the base of manipulator  $A$  {1}, its end-effector {2}, the base of manipulator  $B$  {4}, and its end-effector {3}.

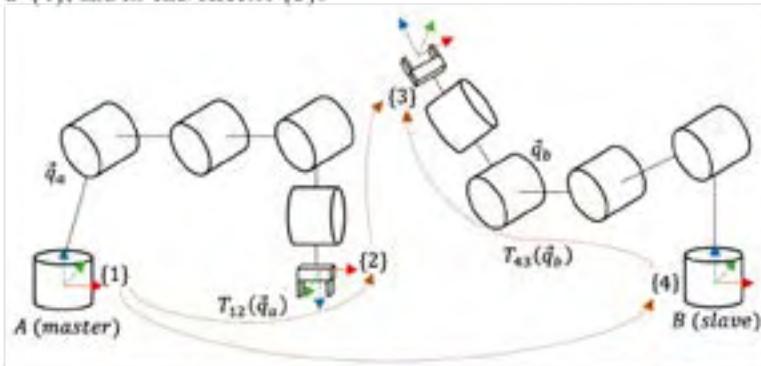


Fig. 1. Dual-arm system for coordinate cooperation.

In Fig. 1,  $T_{ij}$  is a homogenous transformation matrix that transforms frame  $\{i\}$  to frame  $\{j\}$ . This matrix is defined as

$$T_{ij} = \begin{bmatrix} R_{ij} & \vec{t}_{ij} \\ \vec{0} & 1 \end{bmatrix} \quad (1)$$

where  $R_{ij}$  is a  $3 \times 3$  rotation matrix, and  $\vec{t}_{ij}$  is a translation vector.

Following the literature [1, 4], a matrix that relates end-effector for manipulator  $A$  with end-effector for manipulator  $B$  relatively to their bases frame of reference can be defined as relative Jacobian:

$$J_R(\vec{q}) = [-\psi_{23}\Omega_{21}J_A \quad \Omega_{24}J_B] \quad (2)$$

where:

$$\psi_{ij} = \begin{bmatrix} I & -S(\tilde{t}_{ij}) \\ \tilde{0} & I \end{bmatrix} \quad \Omega_{ij} = \begin{bmatrix} R_{ij} & 0 \\ 0 & R_{ij} \end{bmatrix} \quad (3)$$

and  $S(\cdot)$  is an antisymmetric matrix generated by vector  $\tilde{t}_{ij}$ .

The classic hierarchical multitask scheme for two tasks, where the primary is coordination using the relative Jacobian is:

$$\dot{\tilde{q}} = J_R^* (\dot{\tilde{x}}_{R,d} + K_1 \tilde{e}_R) + (I - J_R^* J_R) J_k^* (\dot{\tilde{x}}_{k,d} + K_2 \tilde{e}_k) \quad (4)$$

where  $J_R^*$  is the Moore-Penrose pseudo-inverse of the relative Jacobian,  $\dot{\tilde{x}}_{R,d}$  is the desired relative end-effector motion vector,  $K_1$  and  $K_2$  are gains matrix that define the convergence,  $\tilde{e}_R$  is the relative position and rotation error, the term  $(I - J_R^* J_R)$  is the null space projection of the primary task,  $J_k$  is a Jacobian matrix designed for the secondary task,  $\dot{\tilde{x}}_{k,d}$  is the desired motion vector for secondary task, and  $\tilde{e}_k$  is the error defined for secondary task.

Gains  $K_1$  and  $K_2$  are tuned manually to achieve best performance. However, in this work we proposed to use NI-PID approach to adapt them online.

### 3 Neural incremental PID approach

The structure for the NI-PID is illustrated on Fig. 2, and the control action given by the NI-PID is defined by [9]:

$$u(t) = u(t-1) + \Delta u(t) = u(t-1) + K_{PID} \sum_{m=1}^3 \omega_m(t) y_m(t) \quad (5)$$

where  $K_{PID}$  is a scalar gain,  $\omega_m$  are the normalized weights, and  $y_m(t)$  are the neuron inputs that represent the PID errors:

$$\begin{aligned} y_1(t) &= e_{PID}(t) \\ y_2(t) &= e_{PID}(t) - e_{PID}(t-1) \\ y_3(t) &= e_{PID}(t) - 2e_{PID}(t-1) + e_{PID}(t-2) \end{aligned} \quad (6)$$



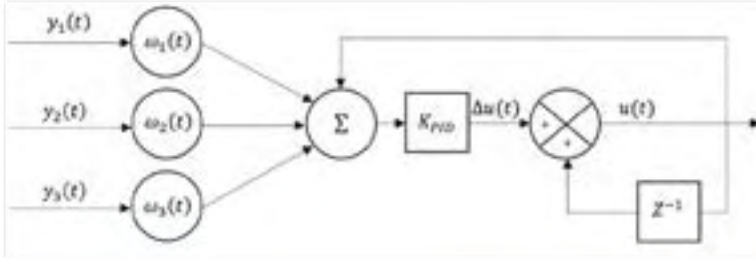


Fig. 2. Structure for NI-PID.

The input  $y_1$  represents integral term,  $y_2$  is the proportional, and  $y_3$  the derivative, while  $e_{PID}$  is the error that wants to be minimized with this controller. To prevent that weight grows without bounds, we normalize them.

Normalized weights are obtained with:

$$\omega_m(t) = \frac{w_m(t)}{\sum_{n=1}^3 |w_n(t)|} \quad (7)$$

where  $w_m$  are the regular weights for the neuron.

Update weights rule is:

$$\begin{aligned} w_1(t) &= w_1(t-1) + \eta_I e_{PID}(t) u(t) y_1(t) \\ w_2(t) &= w_2(t-1) + \eta_P e_{PID}(t) u(t) y_2(t) \\ w_3(t) &= w_3(t-1) + \eta_D e_{PID}(t) u(t) y_3(t) \end{aligned} \quad (8)$$

where the scalar values for  $\eta_I, \eta_P, \eta_D$  are the learning rates for the proportional, integral and derivative terms [9].

In summary, given an error  $e_{PID}(t)$ , the NI-PID computes the control law  $u(t)$ , which is  $u(t) = \text{NI-PID}(e_{PID}(t))$ .

## 4 Proposed approach

The hierarchical multitask scheme (4) for coordinate manipulation is considered for two tasks. We consider a primary task error  $\vec{e}_R = [\vec{e}_{23t}^T, \vec{e}_{23r}^T]^T$ , where  $\vec{e}_{23t}$  is the translational error obtained from the difference between the relative translation  $\vec{t}_{23}$  and the desired relative translation  $\vec{t}_{23}^*$ , which is  $\vec{e}_{23t} = \vec{t}_{23} - \vec{t}_{23}^*$ . The  $\vec{e}_{23r}$  is the rotational error obtained from the cross product of the relative rotation  $R_{23}$  and the desired relative translation  $R_{23}^*$  divided by half:

$$\vec{e}_{23r} = \frac{1}{2} \left( R_{23} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \times R_{23}^* \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} + R_{23} \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \times R_{23}^* \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} + R_{23} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \times R_{23}^* \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right) \quad (10)$$

Similarly, the error for neural network on following trajectory task is  $\vec{e}_k = [\vec{e}_t^T, \vec{e}_r^T]^T$ , where the translational error is  $\vec{e}_t = [\vec{t} - \vec{t}^*]$ , and the rotational error is

$$\vec{e}_r = \frac{1}{2} \left( R_{12} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \times R^* \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} + R_{12} \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \times R^* \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} + R_{12} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \times R^* \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right) \quad (11)$$

being  $\vec{t}^*$  and  $\vec{R}^*$  the translation and rotation desired for the end-effector of manipulator  $A$ .

Errors  $\vec{e}_R$  and  $\vec{e}_k$  are 6x1 vector that contains position and rotations errors for primary and secondary tasks, respectively. A NI-PID controller is applied independently for each error. Then, we have six NI-PID controllers to compute control signals for primary task  $\vec{u}_R$  based on  $\vec{e}_R$ , and other six NI-PID controllers to compute control signals for secondary task  $\vec{u}_k$  based on  $\vec{e}_k$ . Eq. (4) is rewritten to

$$\ddot{\vec{q}} = J_R^* (\ddot{\vec{x}}_{R,d} + \vec{u}_R) + (I - J_R^* J_R) J_k^* (\ddot{\vec{x}}_{k,d} + \vec{u}_k) \quad (9)$$

where  $J_k = [J_A, 0]$ .

## 5 Simulation results

The proposed approach is validated through simulations. We consider a dual-arm system composed of two Baxter arm. The Denavit-Hartenberg (DH) parameters are shown in Table 1, since both manipulators are going to have the same configuration for this paper purposes, the individual kinematics for manipulator  $A$  and manipulator  $B$  are equal [10].

**Table 1.** Baxter arm DH parameters.

| Joint | $A[m]$ | $\alpha[rad]$ | $d[m]$ | $\theta[rad]$ |
|-------|--------|---------------|--------|---------------|
| 1     | 0.069  | $-\pi/2$      | 0.270  | $\theta_1$    |
| 2     | 0      | $\pi/2$       | 0      | $\theta_2$    |
| 3     | 0.069  | $-\pi/2$      | 0.364  | $\theta_3$    |
| 4     | 0      | $\pi/2$       | 0      | $\theta_4$    |
| 5     | 0.01   | $-\pi/2$      | 0.374  | $\theta_5$    |
| 6     | 0      | $\pi/2$       | 0      | $\theta_6$    |
| 7     | 0      | 0             | 0.28   | $\theta_7$    |

As shown in Fig. 3, both manipulators are in the exact same start position, with a offset of 0.5 meters on y axis.

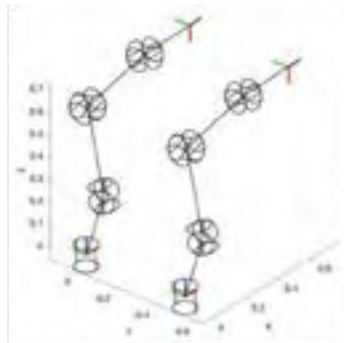


Fig. 3. Dual-arm system for simulations base on two 7DOF baxter arms.

The first experiment can be seen on Fig. 4 and Fig. 5, where both controllers were tested trying to have a coordination task for  $\vec{t}_{23d} = [0 \quad -0.5 \quad 0.2]^T$ , while the second task is the master manipulator trying to get to  $\vec{t}_d = [0.7 \quad 0 \quad 0.5]^T$ .

Fig. 4 shows the classic controller results, as can be observed, the primary task is performed, then the secondary is tried to complete. These results probably could be improved after hours of gain tuning.

Fig. 5 shows how the NI-PID approach has a similar behavior on the primary task, but results for secondary task are better, even when the weights are initialized with random numbers between 0 and 1.

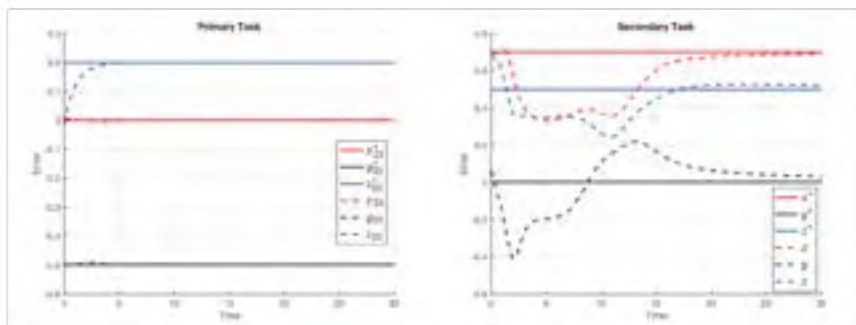
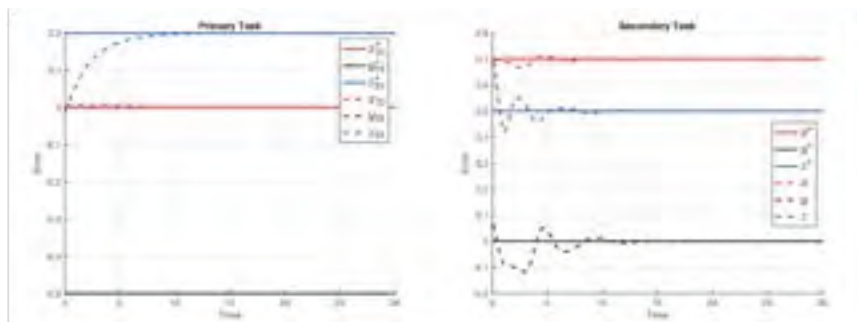
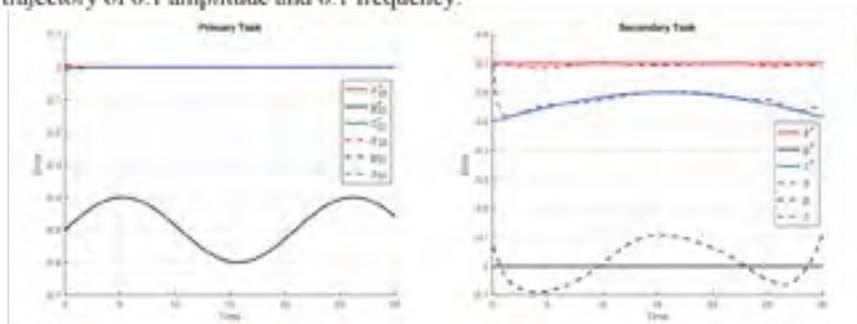


Fig. 4. Classical approach while primary and secondary task are constants.

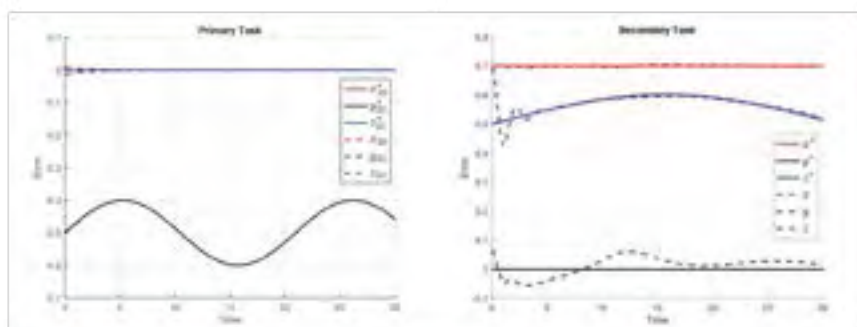


**Fig. 5.** NI-PID approach while primary and secondary task are constants.

The Fig. 6 and Fig. 7 show both approaches against task that are time variable, which is the second experiment. Primary task is trying to follow a sinusoidal signal of 0.1 amplitude and 0.3 frequency, while the secondary task tries to follow a sinusoidal trajectory of 0.1 amplitude and 0.1 frequency.



**Fig. 6.** Classic approach while primary and secondary task are time variant trajectories.



**Fig. 7.** NI-PID approach while primary and secondary task are time variant trajectories.



## 6 Conclusions

In this paper, we proposed the implementation of a NI-PID control for coordinate manipulation based on a hierarchical multitasking scheme. Simulation results on a dual-arm system prove that NI-PID adapts the controller weights online where trajectory errors are significantly reduced without, rather than using fixed weights. The use of NI-PID controller avoids the effort required for tuning control gains in classic approach. The use of NI-PID control can be extended for coordinate manipulation in dual mobile manipulator systems, where kinematics modeling and control are more challenging, and the gains tuning can be difficult and tedious.

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# Selfish Herd Optimizer for Solving Dynamic Economic Dispatch with Valve-Point Effects

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**Abstract:** Efficient operation of power generation systems has become a significant issue in the research community, driven by the increasing demand for sustainable energy solutions and mitigating the environmental impact. Dynamic Economic Dispatch (DED) is a well-known optimization problem in power system operation. To accurately model DED, it is crucial to account for valve-point loading effects and ramp-rate limits. These factors make DED a non-linear, non-convex, and non-smooth problem, which is challenging to solve using traditional optimization techniques. In contrast, the Selfish Herd Optimizer (SHO) is a novel algorithm capable of finding optimal solutions to complex problems. In this work the SHO algorithm is used to optimize the DED problem, to evaluate the effectiveness of the proposed approach, the SHO algorithm was applied to three distinct power generation systems. The results obtained demonstrate the competitive performance of the SHO algorithm.

## 1. Introduction.

The Economic Dispatch (ED) problem plays an essential role in power system operation. The principal objective of ED is to obtain the minimum operation cost needed to satisfy power balance, generating, and network operating limit constraints [1]. Economic dispatch is a process of efficiently sharing the total load on a power system among various generating plants to satisfy the load demand efficiently. The solution to the ED problem is not a trivial process that requires the use of novel optimization methods capable of solving problems with non-linear, non-convex, and non-smooth characteristics. The principal goal of these optimization techniques in ED is to optimize the energy generated by the system's generating units by minimizing fuel cost while meeting the load demand and power system constraints. An implicit benefit of optimizing power generation units is to assure higher reliability and security of the power system [2].

On the other hand, the dynamic version of the economic dispatch problem aims to manage the generated power output by using schedules within a period of time, considering physical constraints such as power and ramp-rate limits. This approach makes the DED a more complex problem due to the increased dimensionality compared to the ED [3]. Since the DED problem was introduced, several optimization techniques and procedures have emerged in the literature as an alternative to find optimal solutions. The most well-known traditional methods included linear programming [4] and non-linear programming [5], iterative lambda method [6], and Lagrangian relaxation [7], among others. Nevertheless, traditional methods commonly find suboptimal solutions for non-smooth or non-convex problems such as DED with valve-point effects.

The DED has been addressed from alternatives optimization perspectives to overcome these problems. Within metaheuristic techniques, the particle swarm optimization [8], ant colony optimization [9], genetic algorithm [10], differential evolution algorithm [11], and gravitational search algorithm [12] have been proposed. Although these methods achieve promising solutions, they still present certain shortcomings in balancing local exploitation and global exploration. More recent papers implement hybrid algorithms to improve global searching performance and accelerate the

<https://doi.org/10.61728/AE20255282>



convergence speed. These hybrid algorithms consist of a combination of existing algorithms such as PSO and TCO [3] or a combination of existing algorithms with chaotic searches such as an Improved-PSO [13], Differential bee colony [14], and Differential Evolution methods [15].

The Selfish Herd Optimizer is a novel swarm optimization algorithm that has attracted attention by its remarkable performance [16]. The SHO has been applied to solve diverse engineering problems [17-20]. At the same time, novel variants have emerged to improve its performance while maintaining the essence of the SHO. Among the most notable ones are the Refined Selfish Herd Optimizer (RSHO) [21], a Chaotic Selfish Herd Optimizer (CSHO) [22], and Selfish Herd Optimizer with Levy-Flight [23].

This paper is organized as follows, in section 2 the dynamic economic dispatch problem defined, with the constraints handled, section 3 describes the Selfish Herd Optimizer as well as three improved versions of the same, in section 4 is explained how these algorithms were implemented for DED problem, the results of this work are in section 5, and the conclusions are present in section 6.

## 2. Problem Formulation

The Dynamic Economic Dispatch is addressed as to simultaneously minimize the power production cost and meet the power system's load demand as well as several other systems constraints over the operating horizon and can be defined as:

$$F = \min \sum_{t=1}^T \sum_{i=1}^N f_i(p_i^t) \quad (1)$$

where  $F$  is the total fuel cost over all the dispatch periods.  $T$  is the number of intervals in the time horizon,  $N$  is the number of generating units,  $p_i^t$  is the power output of  $i$ th generating unit at time  $t$ ,  $f_i(p_i^t)$  is the fuel cost of  $i$ th generating unit at the output of  $p_i^t$ .

Usually, the fuel cost of each generating unit is represented as a quadratic convex polynomial function and is defined as:

$$f_i(p_i) = a_i + b_i p_i + c_i p_i^2 \quad (2)$$

where  $a_i$ ,  $b_i$ , and  $c_i$  are the coefficients of the generating unit  $i$ . Nevertheless, in real power systems with large steam turbines their steam valves produce a considerable increment in fuel cost due to the wire drawing effect each time that the valves are opened which makes the practical objective function (2) have no-differentiable points. Hence, in order to make the cost function of the generation units according to real systems a sinusoidal component is included, as defined on equation (3).

$$f_i(p_i) = a_i + b_i p_i + c_i p_i^2 + \left| d_i \sin(e_i(p_{i,\min} - p_i)) \right| \quad (3)$$

where  $d_i$ , and  $e_i$  are the coefficients of the generating unit  $i$ .



## 2.1. Constraints

### i. Power Balance

The sum of the power generated by each generating unit has to be equal to the power demanded by the load plus the total transmission loss of each time interval  $t$ .

$$\sum_{i=1}^N p_i^t = p_D^t + p_L^t \quad (4)$$

where  $p_D^t$  is the total load demand for time interval  $t$  and  $p_L^t$  is the transmission power loss on time interval  $t$ , and is calculated with Kron's loss formula known as B-matrix coefficients:

$$p_L^t = \sum_{i=1}^N \sum_{j=1}^N p_i^t B_{ij} p_j^t + \sum_{i=1}^N B_{0i} p_i^t + B_{00} \quad (5)$$

where  $B_{ij}$  is the  $ij$ th element of the loss coefficient square matrix.  $B_{0i}$  is the  $i$ th element of the loss coefficient vector and  $B_{00}$  is the loss coefficient constant.

### ii. Operating Limits

$$p_{i,min} \leq p_i^t \leq p_{i,max} \quad i = 1, 2, \dots, N; t = 1, 2, \dots, T \quad (6)$$

where the  $p_{i,min}$  and  $p_{i,max}$  are minimum and maximum power output for generation unit  $i$ .

### iii. Ramp rate limits

In order to prolong the life of generators, it is necessary to insure the thermal stress within the acceptable range of turbine [16].

This mechanical restriction is usually converted to a constraint on the rate of increase (ramp-up) or decrease (ramp-down) of the generator output which is called ramp rate limits.[14]. The ramp limits are included in DED problem to ensure the units works on a feasible zone and are defined as:

$$\begin{cases} p_i^t - p_i^{t-1} \leq UR_i \\ p_i^{t-1} - p_i^t \leq DR_i \end{cases} \quad i = 1, 2, \dots, N; t = 1, 2, \dots, T \quad (7)$$

where  $UR_i$  and  $DR_i$  are the up-rate and down-ramp limits of the  $i$ th generator.

## 3. Algorithm's overview.

The Selfish Herd Optimizer is a novel swarm optimization algorithm proposed by Fausto et. al (2017) for solving optimization problems [16]. The algorithm is inspired in the behaviors described on Hamilton's selfish herd theory (1971) [19]. The algorithm considers two different kinds of search agents: predators and prey. Each of these agents' movements are conducted by a set of unique rules and operators based on the observed natural behavior of individuals on a selfish herd while they are endangered by a pack of hungry predators. [17].

### 3.1. Original Selfish Herd Optimizer.

#### 3.1.1. Population Initialization.

The algorithms begins with a set  $X$  of individuals that includes two groups of animals, the preys  $H$  and the predators  $P$ , each individual position ( $X = \{x_1, x_2, \dots, x_N\}$ ) where  $N$  is the total number of individuals is represented by a  $n$ -dimensional vector  $x_i = [x_{i,1}, x_{i,2}, \dots, x_{i,n}]$  which will represent a feasible solution for a certain optimization problem. The positions are randomly initialized as follows:

$$an_{i,j} = \lim_j^{low} + rand(0,1) * (\lim_j^{high} - \lim_j^{low})$$

$$i = 1, 2, \dots, N \quad j = 1, 2, \dots, n$$
(8)

where  $\lim_j^{high}$  and  $\lim_j^{low}$  represent the upper and lower limits of the search space respectively as well as  $i$  and  $j$  correspond to the individual index and parameter index of each animal. The  $rand(0,1)$  denotes a random real number in the interval of  $[0,1]$ .

#### 3.1.2. Population split.

SHO employs two different types of search agents: the herd  $H = \{h_1, h_2, \dots, h_{N_h}\}$  and the predators  $P = \{p_1, p_2, \dots, p_{N_p}\}$ , where  $N_h$  corresponds to the total number of preys  $H$  and  $N_p$  corresponds to the total number of predators  $P$ , such that  $A = H \cup P$  and the number of individuals for each group is randomly selected as follows:

$$N_h = floor(N * rand(0.7, 0.9))$$
(9)

$$N_p = N - N_h$$
(10)

where  $rand(0.7, 0.9)$  denotes a random number between  $[0.7, 0.9]$  and  $floor(j)$  maps areal number to an integer number.

#### 3.1.3. Survival value.

In SHO the survival capability of each individual  $a_i$  (either the chance of survive a predator's attack or the chance to success killing a prey accordingly) is assigned with a survival value  $SF_{a_i}$ , and it represents its survival aptitude which is the quality of the solution and is relative to the current position within the solution space. The  $SF_{a_i}$  is defined as:

$$SV_{ai} = \frac{f(a_i) - f_{best}}{f_{best} - f_{worst}} \quad (11)$$

where  $f(a_i)$  denotes the fitness value corresponding to the evaluation of the objective function  $f()$  for individual  $ai$ .  $f_{best}$  and  $f_{worst}$  corresponds to the best and worst fitness values found so far by the evolutionary process of the algorithm. Considering a maximization problem these values are defined as:

$$f_{best} = \max \left( \left( \max(f(a_i)) \right)_j \right) \quad (12)$$

$$f_{worst} = \min \left( \left( \min(f(a_i)) \right)_j \right) \quad (13)$$

$$j \in \{0, 1, 2, \dots, k\}; i \in \{0, 1, 2, \dots, N\}$$

where  $k$  is the current iteration

#### 3.1.4. Selfish Herd movements.

SHO divides the herd population in three different roles in order to model the distinctive decision-making behaviors.

##### 3.1.4.1. Herd's leader.

The leader of the herd is the individual whose position inside the herd aggregation promotes it to have the highest chances of surviving a predator attack [Eshel et al. 2011]. Hence at each iteration  $k$ , the algorithm assigns a single individual  $h_k$  as the leader of the selfish herd. The individual  $h_k$  is chosen by considering the current survival value of each individual of the herd's aggregation as:

$$h_L^k = \left( h_i^k \in H^k \mid SV_{h_i^k} = \max_{j \in \{1, 2, \dots, N_h\}} (SV_{h_j^k}) \right) \quad (14)$$

The prey individual possessing the highest survival value among all other members of  $H$  is assigned as the leader, this will occur for each iteration.

Then two types of movements are performed based on the survival value of the leader, these movements are *seemingly cooperative leadership* and *openly selfish leadership*, and they are defined as:

$$h_L^{k+1} = \begin{cases} h_L^k + c^k & \text{if } SV_{h_L^k} = 1 \\ h_L^k + s^k & \text{if } SV_{h_L^k} < 1 \end{cases} \quad (15)$$

where  $c$  is a movement vector, which represents the decision taken by the leader to guide the herd to a better position and guarantee its safety, this decision will be taken only if the leader has the best position  $f_{best}$ . Movement vector  $c$  is calculated as:

$$c^k = 2 * \alpha * (-SV_{pM}) * e^{-\|p_M - h_L\|^2} * (p_M - h_L) \quad (16)$$

where  $(-SV_{pM})$  represents the survival value related to the predator's center mass as defined by (18).  $s$  is also a movement vector and represent the location that will increase the survival value of the leader only, and is defined as:

$$s^k = 2 * \alpha * e^{-\|x_{best} - h_L\|^2} * (x_{best} - h_L) \quad (17)$$

where  $x_{best}$  represents the best position so far and  $\alpha$  is a random number within  $[0,1]$ .  $\| \cdot \|$  is the Euclidean distance between the positions mentioned,  $SV_{pM}$  denotes the survival value related to the predator's center of mass which can be defined as:

$$p_M^k = \frac{\sum_{j=1}^{Np} SV_{p_j}^k * p_j^k}{\sum_{j=1}^{Np} SV_{p_j}^k} \quad (18)$$

where  $SV_{p_j}$  is the survival value of the individual  $p_j$ . The predator's center of mass is how SHO calculates a position with relatively higher risk for an individual of the herd. In same order of ideas SHO considers the existence of relatively safer central positions within the herd and is given by the herd's population center of mass defined as:

$$h_M^k = \frac{\sum_{j=1}^{Nh} SV_{h_j}^k * h_j^k}{\sum_{j=1}^{Nh} SV_{h_j}^k} \quad (19)$$

Since both  $h_M$  and  $p_M$  represents potential solutions within the solution space of a given optimization problem, a corresponding survival value can be computed for each position with (11).

#### 3.1.4.2. Nearest best neighbors.

The algorithm considers the nearest best neighbor for any individual  $h_i$  is whose possess two important traits: 1) It is the nearest herd member other than the leader  $h_L$ . 2) It has better aptitudes than the individual  $h_i$ . The nearest best neighbor is defined as:

$$h_{ci}^k = \left( h_j^k \in H^k, h_j^k \neq [h_j^k, h_L^k] \right) \left[ SV_{h_j^k} > SV_{h_i^k}, r_{ij} = \min_{j \in \{1,2,...,N_h\}} (\|h_i^k - h_j^k\|) \right] \quad (20)$$

where  $r_{ij}$  is the Euclidean distance between indexed herd members  $i$  and  $j$ .

#### 3.1.4.3. Herd's followers and deserters.



SHO classifies the members of the aggregation in two different groups, the herd followers  $H_F$  and herd's deserted  $H_D$  and the movement pattern performed by the herd depends on the role assumed by each individual. These two groups are defined as:

$$H_F^k = \{h_i^k \neq h_L^k | SV_i^k \geq rand(0,1)\} \quad (21)$$

$$H_D^k = \{h_i^k \neq h_L^k | SV_i^k < rand(0,1)\} \quad (22)$$

The position update of each individual is defined at each iteration by:

$$h_i^{k+1} = \begin{cases} h_i^k + f_i^k & \text{if } h_i^k \in H_F^k \\ h_i^k + f_i^k & \text{if } h_i^k \in H_D^k \end{cases} \quad (23)$$

where  $f_i^k$  is a movement vector computed with regard to the positions and survival aptitudes of other members of the herd. In addition, the members of the herd followers  $H_F$  are subdivided in two groups, the dominant  $H_d$  and the subordinates  $H_s$ , depending on their survival values in relation with the mean survival value of the herd population. Therefore, the movement vector  $f_i^k$  performed by each member of the group  $H_F^k$  is calculated depending on whether it is a dominant or subordinated member:

$$f_i^k = \begin{cases} Z * (\beta * \psi_{h_i, h_L}^k * (h_L^k - h_i^k) + \gamma * \psi_{h_i, h_{ci}}^k * (h_{ci}^k - h_i^k)) & \text{if } h_i^k \in H_d^k \\ 2 * \delta * \psi_{h_i, h_M}^k * (h_M^k - h_i^k) & \text{if } h_i^k \in H_s^k \end{cases} \quad (24)$$

where  $\beta$ ,  $\gamma$  and  $\delta$  are random numbers in the interval  $[0,1]$ . And the subgroups  $H_d$  and  $H_s$  are defined in equations (25) and (26). Same case for  $\psi_{h_i, h_L}^k$  and  $\psi_{h_i, h_{ci}}^k$  which are the selfish attraction experimented by herd member  $h_i$  toward the leader  $h_L$  and its best nearest neighbor  $h_{ci}$  as defined in equations (27) and (28). While  $\psi_{h_i, h_M}^k$  represent the attraction experimented by  $h_i$  towards the center of mass  $h_M$  as defined in equation (29)

$$H_d^k = \{h_i^k \in H_F^k | SV_{h_i}^k \geq SV_{H_\mu}^k\} \quad (25)$$

$$H_s^k = \{h_i^k \in H_F^k | SV_{h_i}^k < SV_{H_\mu}^k\} \quad (26)$$

where  $SV_{H_\mu}^k$  is the mean survival value of  $H$  at iteration  $k$  and is defined by:

$$SV_{H_\mu}^k = \frac{\sum_{i=1}^{N_h} SV_{h_i}^k}{N_h^k} \quad (27)$$

The attraction experimented by a herd member towards its leader and its nearest best member is defined as:

$$\psi_{h_i, h_L}^k = SV_{h_L} * e^{-\|h_i - h_L\|^2} \quad (28)$$

$$\psi_{h_i, h_{ci}}^k = SV_{h_{ci}} * e^{-\|h_i - h_{ci}\|^2} \quad (29)$$

$$\psi_{h_i, h_M}^k = SV_{h_M} * e^{-\|h_i - h_M\|^2} \quad (30)$$

In the case of the deserters  $H_d$  moves in a different way, based on desertion rule, independently of any other individual:

$$d_i^k = 2 * (\beta * \psi_{h_i, x_{best}}^k * (x_{best}^k - h_i^k) + \gamma * (1 - SV_{h_i}^k) \hat{r}) \quad (31)$$

where  $\psi_{h_i, x_{best}}^k$  denotes is the selfish attraction experienced by the individual  $h_i^k$  toward the current best position and is defined in (32),  $\beta$ , and  $\gamma$  represents random numbers from the interval  $[0,1]$ , also  $\hat{r}$  is a unit vector pointing to a random direction within the  $n$ -dimensional search space.

$$\psi_{h_i, x_{best}}^k = e^{-\|h_i - x_{best}\|^2} \quad (32)$$

### 3.1.5. Predators' movement.

The first step to model the movement of the predators is to assume that each herd member has a certain probability of being pursued by an attacking predator, this probability is computed in SHO as:

$$\mathcal{P}_{p_i, h_j} = \frac{\omega_{p_i, h_j}}{\sum_{m=1}^{N_h} \omega_{p_i, h_m}} \quad (33)$$

where  $\omega_{p_i, h_j}$  represents the prey attractiveness between  $p_i$  and  $h_j$ , this value considers consider the survival value of the herd member  $h_j$  as well as the distance between the prey and the attacking predator  $p_i$  as defined:

$$\omega_{p_i, h_j} = (1 - SV_{h_j}) * e^{-\|p_i - h_j\|^2} \quad (34)$$

The prey attractiveness  $\omega_{p_i, h_j}$  yield to higher values toward to herd members possessing lower survival values, whereas a higher survival value implies lower attractiveness value, this is analogous to the preference of a predator to attack weaker preys. Similarly, the value  $\omega_{p_i, h_j}$  will be increased as the distance between the predator and the prey  $\|p_i - h_j\|$  decreases, and vice versa. For the predators position update is considered the position of particular individual of the prey herd as defined below:

$$p_i^{k+1} = p_i^k + 2 * \rho * (h_r^k - p_i^k) \quad (35)$$

where  $\rho$  is a random number in the range of  $[0,1]$ . Furthermore  $h_r^k = h_j^k \in H^k$   $r \in \{1,2, \dots, N_h\}$  represent a herd member randomly chosen from the whole members of the herd  $H^k$  by applying the roulette selection method (Thomas,1996) [20] with regard to their individual pursuit probabilities  $\mathcal{P}_{p_i,h_j}$  defined in (33).

### 3.1.6. Recalculation of survival values.

After the herd's and predator's movements the survival value of the entire population could change, with this in mind, the survival value of all individuals is recalculated with equation (11).

### 3.1.7. Predation phase.

In SHO the predation phase is implemented to model the biological interaction between groups of prey and predators in which former individuals are hunted by the latter, and possible killed and later consumed. It is assumed that after both individuals, the prey and the predator have performed a movement, there is a chance for several herd members to be killed by attacking predators, which implies the exclusion of their respective solution from the search space. This process starts with the implementation of domain of danger which refers to the area where the prey is under a higher risk to be attacked, and it is a circular area around each predator member defined as:

$$R = \frac{\sum_{j=1}^n |lim^{low} - lim^{high}|}{2 * n} \quad (36)$$

Where  $lim^{low}$  and  $lim^{high}$  represent the lower and upper limits for the search space, and  $n$  is the number of dimensions, for simplicity SHO assumes that the radius of the domain of danger is the same for all preys.

Starting the predation phase, it is assumed that no prey has been killed, in order to keep a track on the number of preys killed, SHO initializes an empty set  $K$  that during the predation phase is used to group all prey members killed by a predator:

$$K = \{0\} \quad (37)$$

A predator will be able to success in its attack only if two specific condition are met: 1) the prey  $h_j$  has a lower survival value than  $p_i$  and 2) the distance between  $p_i$  and  $h_j$  is equal or lower than the domain of danger radius  $R$  as defined in equation (36) which implies that each predator is able to threat more than one prey individual, if and only if the two conditions are met. This can be defined as:

$$T_{p_i} = \{h_j \in H \mid SV_{h_j} < SV_{p_i}, \|p_i - h_j\| \leq R, h_j \notin K\} \quad (38)$$

where  $\|p_i - h_j\|$  is the Euclidian distance between  $p_i$  and  $h_j$ , and  $T_{p_i}$  is a set of preys threatened by predator  $p_i$ , is important to mention that the preys at this step are only threatened by one predator

only, if any of these prey members is killed, is randomly chosen by the roulette selection based on the probabilities to be hunted and it can be defend as:

$$\mathcal{H}_{p_i, h_j} = \frac{\omega_{p_i, h_j}}{\sum_{(h_m \in T_{p_i})} \omega_{p_i, h_m}}, h_j \in T_{p_i} \quad (39)$$

where  $\omega_{p_i, h_j}$  represents the prey attractiveness between the prey and predator as defined in equation (34).

### 3.1.8. Restoration phase.

In this step, the herd members that were killed during predation phase and stored in  $K$  are replaced implementing a special mating-like operator to generate new solutions based on the survival aptitudes of the remaining herd members. This operator considers positions and survival values of all survivors herd members, these survivors can be considered as a set of mating candidates  $M$  as defined below:

$$M = \{h_j \notin K\} \quad (40)$$

Each member  $h_j$  is considered to have a certain probability  $\mathcal{M}_{h_j}$  of being taking into account for the generation of new solution, and such probability is defined as:

$$\mathcal{M}_{h_j} = \frac{SV_{h_j}}{\sum_{(h_m \in M)} SV_{h_m}}, h_j \in M \quad (41)$$

As it can be seen, mating candidates possessing higher survival values will have a higher chance to influence the generation of new solutions whereas individuals with a lower survival value are less likely to be considered for such process.

In order to generate a new individual and candidate solution it is considered a set of  $n$  randomly chosen individuals selected by the roulette selection method [19] with regard the probabilities  $\mathcal{M}_{h_j}$  of each member within the set of mating candidates  $M$  as:

$$h_j = h_{new} = \text{mix}([h_{r_1,1}, h_{r_2,2}, \dots, h_{r_i,i}, \dots, h_{r_n,n}]), h_i \in K \quad (42)$$

where  $n$  is the dimensionality of the search space and  $\text{mix}()$  is a function that generates a new solution  $h_{new}$  by setting the  $i$ th element  $h_{r_i,i}$  of a candidate herd member  $h_{r_i}$  to the  $i$ th component of the  $h_{new}$ .

### 3.2. Refined Selfish Herd Optimizer.

Although the selfish herd optimizer can provide a good performance when finding an optimal solution, it has some oversights that cause problems in its exploitation ability. Additionally, it has shortcomings that influence the exploration and avoiding stagnation in local optima. In SHO the survival value is not only related to the survival aptitude of the individual but also to the decisions made by the predators to pursue specific prey and hence to the risk faced by the herd members. A higher survival value possessed denotes a better solution for solving the problem, the survival value is calculated from the current best and worst fitness values found on each iteration as defined in



equation (11), from this, it is easily observed that its value becomes smaller when its corresponding fitness value  $f(a_i)$  approaches the best fitness value, and it increases when  $f(a_i)$  gets close to the worst fitness value. This might be an oversight not corrected in the literature, an editing mistake [20] and the corrected value is defined as:

$$SV_{ai} = 1 - \frac{f_{best} - f(a_i)}{f_{best} - f_{worst}} \quad (43)$$

This definition avoids the implementation of any programming flags or change the position of the denominator variables according to the application of the algorithm, either for maximization or minimization.

The recalculation of the survival value by SHO is conducted after both, the prey and predator movements are completed. In consequence the survival values of the preys, used in the predator movement phase are not up to date as they should be due to the positions of the herd members change during the herd movement phase. The implementation of these values during the predator moving phase may lead to inappropriate exploitation and exploration of solutions conducted by the predators. This could influence the global convergence performance of SHO. From equation (34) the prey attractiveness is related to the survival value of the preys, using prey attractiveness computed from values that are not updated might result in a higher probability of being pursued for a herd member even when it has increased its survival value in a previous movement phase, this may mislead a predator to an incorrect position. A similar problem occurs in the herd movement in the second iteration when a survival value which has not been updated after a new solution generated in restoration phase is used. Hence the recalculation of the survival values should be done after every movement operator is implemented, either herd movement, predator movement or restoration phase if any new solution has been created.

The domain of danger is implemented as a pair condition, to avoid an imbalance between exploration and exploitation hence it can be considered a range of sub-search area in the entire solution space, in equation (36) after the values of  $lim^{low}$  and  $lim^{high}$  along with the number of dimensions  $n$  are determined, the radius of the domain of danger becomes a constant value during the entire process which means that using a large number of  $R$  during all iterations could lose its functionality during the last phase of the iteration, therefore the equation (41) is suggested to be implemented instead of (36),

$$R = \lambda * n * \|h_{max} - h_{min}\|_1 \quad (44)$$

where  $\lambda$  is a random number from the range  $[0, 1]$ ,  $n$  is the number of dimensions of the search space,  $\| \cdot \|$  represents the  $l_1$ -norm and  $h_{max}$  and  $h_{min}$  are vectors composed of the largest and smallest components in each dimension of  $H$ .

Different types of attractions are used to manifest the behaviors observed from the interaction between preys and predators, these attractions are modeled by using the common factor of the negative natural exponential function, where the square of the Euclidean distance between different vectors is used as input. When only the factor of the exponential is taking into consideration, the movement of the individuals will depend on how close or how apart are these individuals, if a predator is close to a



prey or center of herd, then the predator moves are close to the target, if the predator is far from the target then its movements will be small, in addition due to the squaring, the value computed by this factor is penalized heavily. Thus, even if the distance is not too far from the movement will become extremely small and the predator will remain in the area around its original position (this apply also for preys' movement) the below equations are proposed replace equations (16), (17), (28) to (30) and (32) respectively:

$$c^k = 2 * \alpha * (-SV_{PM}) + e^{-\|p_M - h_L\|} * (p_M - h_L) \quad (45)$$

$$s^k = 2 * \alpha * e^{-\|x_{best} - h_L\|} * (x_{best} - h_L) \quad (46)$$

$$\psi_{h_L, h_L}^k = SV_{h_L} * e^{-\frac{\|h_L - h_L\|}{n}} \quad (47)$$

$$\psi_{h_L, h_{ci}}^k = SV_{h_{ci}} * e^{-\frac{\|h_L - h_{ci}\|}{n}} \quad (48)$$

$$\psi_{h_L, h_M}^k = SV_{h_M} * e^{-\frac{\|h_L - h_M\|}{n}} \quad (49)$$

$$\psi_{h_L, x_{best}}^k = e^{-\frac{\|h_L - x_{best}\|}{n}} \quad (50)$$

From above equation,  $n$  represents the number of dimensions of the search space, and  $\| \cdot \|$  the Euclidean distance,  $x_{best}$  is the best fitness found so far.

### 3.3. Chaotic Selfish Herd Optimizer.

It has been proved that SHO can provide competitive results in comparison to other well-known metaheuristics algorithms, and its main problem as in many other algorithms, is that easily get trapped into local solutions with low precision and slow convergence speeds, in order to improve SHO's performance, chaotic search have been added to searching process of SHO [21].

In SHO, a random variable is used to decide whether the herd members are followers or deserters as defined in equation (24) and (31). This parameter plays an important role balancing the exploitation and the exploration of the algorithm because it directly influences the position update of every search agent on every phase.

In this version of SHO, a chaotic sequence generated from a chaotic map is implemented instead of a random variable to improve the performance of the algorithm as defined below:

- If  $SV_i \geq CV_k$ 
  - Apply herd following movement operator as in equation (24)
- Else:
  - Apply herd desertion movement operator as in equation (31)

#### 3.3.1. Chaotic maps

Chaos can be defined as deterministic and arbitrary strategy observed in a dynamic non-linear system which is bounded and non-converging, is the arbitrariness of a basic dynamic deterministic framework and the chaotic system might be considered as a source of randomness [22]. The implementation of these chaotic variables instead of random variables may perform downright

searches at higher speeds in comparison to randomized searches which depends on probabilities [23]. A large number of chaotic maps are available in the field of optimization [24-25]. In this particular application of the algorithm the Tent map was implemented because it improves the exploration of SHO and provides a higher variation in the possible solutions, the Tent map is defined as:

$$x_{k+1} = \begin{cases} 2x_k & x_k < 0.5 \\ 2(1-x_k) & x_k \geq 0.5 \end{cases} \quad (51)$$

Chaotic sequences are also generated in range [0,1]. For further analysis of all the chaotic maps implemented with SHO, please refer to [21]

### 3.4. Selfish Herd Optimizer with Levy-Flight

Selfish herd optimizer is a new optimization algorithm; however, its optimization performance is not satisfactory due to the weak global search ability, in order to increase it has been added the Levy flight distribution strategy. [26].

Some theories have proved that Levy-flight distribution strategy exist on the hunt process of the wild animals [27-33]. Based on this, the distribution is applied to the formula for update the position of the herd leader because it is the position of the prey leader the one that represents the global search process, hence with this improvement it will have a better opportunity to find global optimal solutions. The formula proposed is defined as:

$$h_L^{k+1} = h_L^k + \alpha \oplus Levy(\beta) \quad (52)$$

where  $\alpha$  is step-sized and is a random number of dimensions, which can be represent as  $random(size(n))$ ,  $\beta$  represents a random number between [0,1], the symbol  $\oplus$  represents entry-wise multiplication.

According to (30), the generation of step-sized is defined as follows:

$$g = random(size(n)) \oplus Levy(\beta) \sim 0.01 \frac{\mathcal{L}}{|v|^{1/\beta}} * (h_f^k - x_{best}) \quad (53)$$

where  $v$  and  $\mathcal{L}$  represents normal distributions and defined as:

$$v \sim N(0, \sigma_u^2), \mathcal{L} \sim N(0, \sigma_u^2) \quad (54)$$

having:

$$\sigma_u = \left( \frac{\Gamma * (1 + \beta) * \sin\left(\frac{\pi * \beta}{2}\right)}{\Gamma * \left(\frac{1 + \beta}{2}\right) * \beta * 2^{(\beta-1)/2}} \right)^{1/\beta} \quad (55)$$

where  $\Gamma$  is the standard gamma-function.

The condition for leader's position update is defined as:

$$h_L^{k+1} = \begin{cases} h_L^k + g & \text{if } SV_{h_L^k} = 1 \text{ and } \theta < 0.5 \\ h_L^k + c^k & \text{if } SV_{h_L^k} = 1 \text{ and } \theta \geq 0.5 \end{cases} \quad (56)$$

where  $\theta$  is a random number from the interval  $[0,1]$ .

#### 4. SHOs for DED Problem

As the reader can see, the differences between the original SHO and the new versions of SHO are related to the mathematics of the movement operators, or with the decision making of the leader of the herd and the aggregation for their movements. With that being said, the implementation of the algorithms to DED problem will remain essentially the same for all cases, with the few exceptions mentioned accordingly.

- **Step 1:** The initialization of the algorithms, remains the same for all of them, as is defined as in equation (8) with the limits of the space search defined by the maximum and minimum limits of power generation, and ensure that the individuals generated comply with the limits constraint as defined in equation (6)
- **Step 2:** Split the population of set  $A$  into herd and predators, as defined in equations (9) and (10).
- **Step 3:** Compute the survival values for the population with equation (11), for the case of the Refined SHO, the survival value is computed with equation (43) instead, the cost function defined in equation (3) remains the same for both cases, in addition the power losses for each individual, defined in equation (5).
- **Step 4:** Selfish herd movement operation in this step, for the Chaotic SHO, the herd movement will depend on the value of the chaotic variables, and they are defined as in equation (51). For the SHO with Levy-Flight is in this step when the operator is implemented as defined in equation (52)
- **Step 5a:** Predators movement operation, for the original SHO, the chaotic SHO and LFSHO
- **Step 5b:** The refined SHO will calculate the survival values of the herd with equation (43) after the movement of the herd.
- **Step 6a:** Recalculate the survival values for the entire population, or set  $A$  with equation (11) for the original SHO, the chaotic SHO and LFSHO after the completion of steps 4 and 5a
- **Step 6b:** After the completion of the step 5b, the refined SHO will then execute the predator's movements operator.
- **Step 7a:** Predation phase
- **Step 7b:** The refined SHO will perform a Re calculation of the survival values of the predators with equation (43)
- **Step 8a:** Restoration phase
- **Step 8b:** After computes the survival values for refined SHO, the next two steps are the same **Predation and Restoration** phase that for the other algorithms.
- **Step 9:** Start the next iteration,  $k = k + 1$  if applicable
- **Step 10:** Output the results, and start next dispatch

The definition of the best and worst positions ( $f_{best}$  and  $f_{worse}$ ) for this specific case, was implemented in a different way than the normal application to find the minimum or maximum value, this because the equality constraint of the DED problem, the best position will be the closest to the power load of the current dispatch.

## 5. Simulation and Results

In order to review the effectiveness and make a full comparison of the proposed SHO algorithms, these algorithms were implemented in three test cases where the time horizon is split in 24 dispatches for all three cases as defined below:

1. *Case 1:* 5-unit system with valve points effects, ramp-rate limits and considering power transmission losses.
2. *Case 2:* 10-unit system with valve points effects, ramp-rate limits and considering power transmission losses.
3. *Case 3:* 10-unit system with valve points effects and ramp-rate limits without considering power transmission losses.

These three cases are the most used test cases in the literature. The algorithms were implemented in Matlab® 9.9.0 (2020b) and executed on a processor AMD Ryzen™ 5 2500U at 2.00GHz with 8GB on RAM. The number of total individuals  $N$  was set to 30 accordingly to [21] for global optimization problems, and 750 iterations to reach the local optima but the Levy-Flight SHO which reaches the local optima with lesser iterations than the other algorithms.

The test was executed 30 times independently for each version of SHO to obtain the results.

### Test case 1: 5-unit system with power transmission loss.

For this test case, the valve point effects, the ramp-rate limits and the power transmission losses are considered. The input data for the 5-unit system is displayed on table 1, the loss coefficients matrix implemented to compute the power transmission losses in the 5-unit system is enlisted in table 2, the load demand for 24 hours is enlisted in table 3 and finally figure 1 displays the average total dispatch cost of each SHO version used.

| Dispatch        | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Power Load (MW) | 410 | 435 | 475 | 530 | 558 | 608 | 626 | 654 | 690 | 704 | 720 | 740 |
| Dispatch        | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  | 21  | 22  | 23  | 24  |
| Power Load (MW) | 704 | 690 | 654 | 580 | 558 | 608 | 654 | 704 | 680 | 605 | 527 | 463 |

Table 1.- Input data for test case 1.

|          |          |          |          |          |
|----------|----------|----------|----------|----------|
| 4.90E-05 | 1.40E-05 | 1.50E-05 | 1.50E-05 | 2.00E-05 |
| 1.40E-05 | 4.50E-05 | 1.60E-05 | 2.00E-05 | 1.80E-05 |
| 1.50E-05 | 1.60E-05 | 3.90E-05 | 1.00E-05 | 1.20E-05 |
| 1.50E-05 | 2.00E-05 | 1.00E-05 | 4.00E-05 | 1.40E-05 |
| 2.00E-05 | 1.80E-05 | 1.20E-05 | 1.40E-05 | 3.50E-05 |

Table 2.- B-matrix coefficients for test case 1.

| Generator         | 1      | 2      | 3      | 4      | 5      |
|-------------------|--------|--------|--------|--------|--------|
| $P_{i,max}(MW)$   | 75     | 125    | 175    | 250    | 300    |
| $P_{i,min}(MW)$   | 10     | 20     | 30     | 40     | 50     |
| $a_i (\$/h)$      | 25     | 60     | 100    | 120    | 40     |
| $b_i (\$/MW h)$   | 2      | 1.8    | 2.1    | 2      | 1.8    |
| $c_i (\$/MW^2 h)$ | 0.0080 | 0.0030 | 0.0012 | 0.0010 | 0.0015 |
| $d_i (\$/h)$      | 100    | 140    | 160    | 180    | 200    |
| $r_i (rad/MW)$    | 0.042  | 0.040  | 0.038  | 0.037  | 0.035  |
| $UR_i(MW)$        | 30     | 30     | 40     | 50     | 50     |
| $DR_i(MW)$        | 30     | 30     | 40     | 50     | 50     |

Table 3.- 24 hours Load demand for test case 1

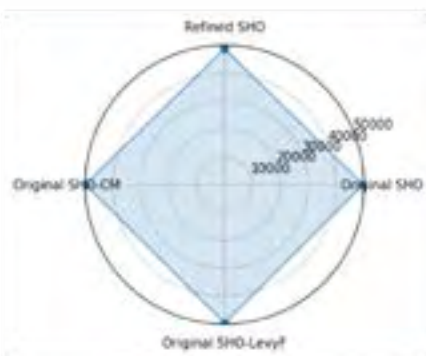


Fig. 1.- Average total cost (\$) for test case 1

Table 4 shows a comparison of fuel cost obtained by each version used of SHO against two other algorithms used for the same test case as reported in the literature.

| Method       | Minimum Cost (\$) | Average Cost (\$) | Maximum Cost (\$) | Transmission loss | Time in secs |
|--------------|-------------------|-------------------|-------------------|-------------------|--------------|
| CMAES        | \$43,526.00       | \$43,915.00       | \$44,191.00       | -                 | 16.36        |
| HPSTCO       | -                 | \$42,151.33       | -                 | 194.318           | 58.8         |
| Original SHO | \$48,745.52       | \$49,776.67       | \$50,987.37       | 191.833           | 17.87        |
| Refined SHO  | \$47,769.13       | \$48,867.63       | \$49,656.32       | 187.904           | 19.99        |
| CM SHO       | \$48,682.96       | \$50,097.77       | \$51,832.72       | 189.910           | 18.78        |
| LF SHO       | \$47,820.74       | \$49,767.64       | \$51,012.32       | 191.164           | 0.72         |

"-" means that the data is not available in the literature.

Table 4.- Algorithms comparison for test case 1

Figures 2 and 3 displays the convergence time of each SHO algorithm used, a detailed table enlisted the results obtained for each algorithm is present in the appendix section, where table A1 enlists the results of the Original SHO for 5 generation unit system, table A2 enlists the results of the Refined SHO, table A3 enlists the results of Chaotic SHO and table A4 enlists the results of Levy-Flight SHO, figures AF2 through AF5 displays a graphical representation of these tables.



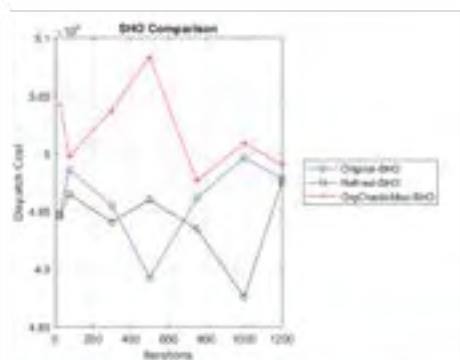


Fig. 2.- Average cost through iterations for test case 1

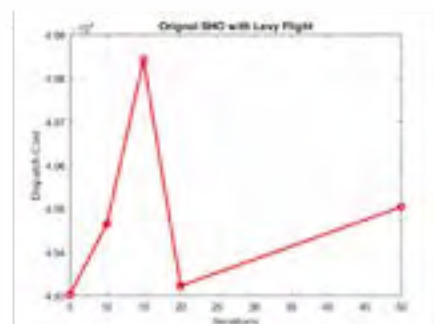


Fig. 3.- Average cost through iterations of the original SHO with Levy-Flight for test case 1

### Test case 2: 10-unit system with power transmission loss.

For this test case, the valve point effects, the ramp-rate limits and the power transmission losses are considered. The input data for the 10-unit system is displayed on table 5, the loss coefficients matrix implemented to compute the power transmission losses in the 10-unit system is enlisted in table 6, the load demand for 24 hours is enlisted in table 7 and finally figure 4 displays the average total dispatch cost of each SHO version used, from which the Refined SHO is lowest result obtained. The average total cost which is the sum of the total cost for each dispatch taking into consideration the same generators unit's constraints which are the valve-points effects, the ramp-rate limits, and the power loss, in the literature is in the neighborhood of \$1,050,000

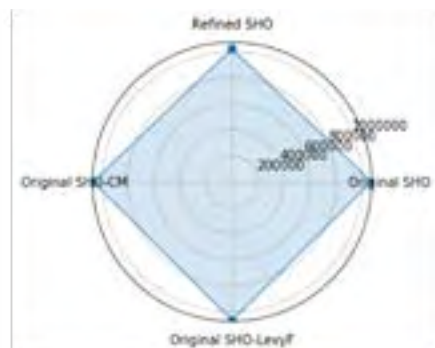


Fig. 4.- Average total cost (\$) of test case 2.

The results obtained of each version of SHO are directly compared to the results obtained of the aforementioned hybrid algorithms CDBCO[21] and HPSTCO[3] as well with other two well-known algorithms CMAES[34] and GSA[35]. From Table 8 it is observed that the minimum cost is \$953,726.19 computed with the Refined SHO while the fastest algorithm is the LFSHO with an average time of 1.2 sec. this because the number of iterations. In the Appendix section are the results of each algorithm, the table A5 displays the result of the test case for the original SHO, the table A6 displays the results of the refined SHO while table A7 displays the results of the chaotic SHO and table A8 displays SHO with Levy-Flight operator.

| Generator         | 1       | 2       | 3       | 4      | 5       | 6       | 7       | 8      | 9       | 10      |
|-------------------|---------|---------|---------|--------|---------|---------|---------|--------|---------|---------|
| $P_{Lmax}(MW)$    | 470     | 460     | 340     | 300    | 243     | 160     | 130     | 120    | 80      | 55      |
| $P_{Lmin}(MW)$    | 150     | 135     | 73      | 60     | 73      | 57      | 20      | 47     | 20      | 55      |
| $u_i (\$/h)$      | 958.2   | 1313.6  | 604.97  | 471.6  | 480.29  | 601.75  | 502.7   | 639.4  | 455.6   | 692.4   |
| $b_i (\$/MW.h)$   | 21.6    | 21.05   | 20.81   | 23.9   | 21.62   | 17.87   | 16.51   | 23.23  | 19.58   | 22.54   |
| $c_i (\$/MW^2.h)$ | 0.00043 | 0.00063 | 0.00039 | 0.0007 | 0.00079 | 0.00056 | 0.00211 | 0.0048 | 0.10908 | 0.00951 |
| $d_i (\$/h)$      | 450     | 600     | 320     | 260    | 280     | 310     | 300     | 340    | 270     | 380     |
| $e_i (rad/MW)$    | 0.041   | 0.036   | 0.028   | 0.052  | 0.063   | 0.048   | 0.086   | 0.082  | 0.098   | 0.094   |
| $UR_i(MW)$        | 80      | 80      | 80      | 50     | 50      | 50      | 30      | 30     | 30      | 30      |
| $DR_i(MW)$        | 80      | 80      | 80      | 50     | 50      | 50      | 30      | 30     | 30      | 30      |

Table 5.- Inputs for test case 2.

The random behavior of the algorithms through the iterations are represented with figure 5, which compares the total fuel cost obtained by all the algorithms that were executed with the same number of iterations, the Original SHO, Refined and with Chaotic maps varies in the same range, but they never reach stability and figure 6 displays the behavior of LFSHO which indeed reaches the stability.

|       |       |       |       |       |       |       |       |       |       |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 8.70  | 0.43  | -4.61 | 0.36  | 0.32  | -0.66 | 0.96  | -1.60 | 0.80  | -0.10 |
| 0.43  | 8.30  | -0.97 | 0.22  | 0.75  | -0.28 | 5.04  | 1.70  | 0.54  | 7.20  |
| -4.61 | -0.97 | 9.00  | -2.00 | 0.63  | 3.00  | 1.70  | -4.50 | 3.10  | 2.00  |
| 0.36  | 0.75  | 0.63  | 0.47  | 8.6   | -0.80 | 0.37  | 0.72  | -0.90 | -0.69 |
| -0.66 | -0.28 | 3.00  | 2.62  | -0.8  | 11.80 | -4.90 | 0.30  | 3.00  | -3.00 |
| 0.96  | 5.04  | 1.70  | -1.96 | 0.87  | -4.90 | 8.24  | -0.9  | 5.90  | -0.60 |
| -1.60 | 1.70  | -4.30 | 2.10  | 0.72  | 0.30  | -0.9  | 1.20  | -0.96 | 0.56  |
| 0.80  | 0.54  | 3.10  | 0.67  | -0.90 | 3.00  | 5.90  | -0.96 | 0.93  | -0.30 |
| -0.10 | 7.20  | -2.00 | 1.80  | 0.69  | -3.00 | -0.60 | 0.56  | -0.30 | 0.99  |

\* The coefficients are in the order of  $10_6$ .

Table 6.- H-matrix coefficients for test case 2.

| Dispatch        | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   |
|-----------------|------|------|------|------|------|------|------|------|------|------|------|------|
| Power Load (MW) | 1036 | 1110 | 1258 | 1406 | 1480 | 1628 | 1702 | 1776 | 1924 | 2072 | 2146 | 2220 |
| Dispatch        | 13   | 14   | 15   | 16   | 17   | 18   | 19   | 20   | 21   | 22   | 23   | 24   |
| Power Load (MW) | 2072 | 1924 | 1776 | 1554 | 1480 | 1628 | 1776 | 2072 | 1924 | 1628 | 1332 | 1184 |

Table 7.- Load demand for 24 hours.

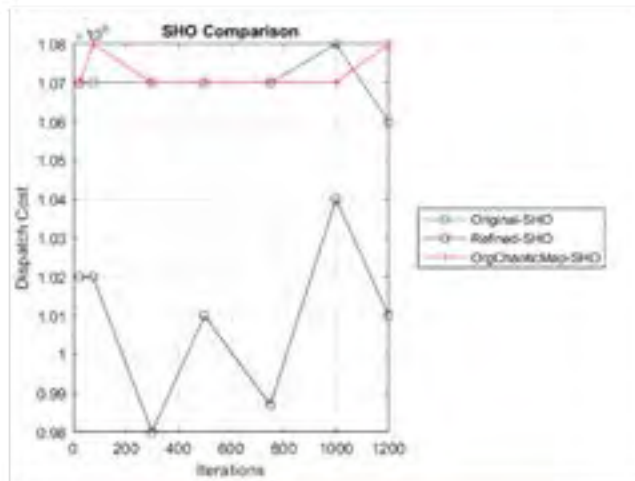


Fig. 5.- Average cost through iterations for test case 2.

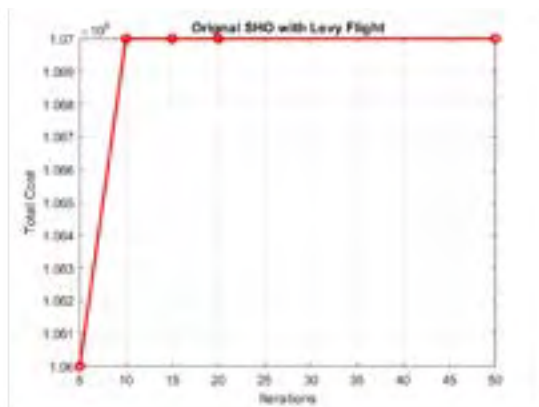


Fig. 6.- Average cost through iterations of the original SHO with Levy-Flight for test case 2.

| Method          | Minimum Cost (\$) | Average Cost (\$) | Maximum Cost (\$) | Time in secs. |
|-----------------|-------------------|-------------------|-------------------|---------------|
| GSA             | \$1,042,964.95    | \$1,046,216.74    | \$1,047,362.92    | 62.37         |
| CDECO           | \$1,042,900.00    | \$1,044,700.00    | -                 | 91.8          |
| HPSTCO          | \$1,035,750.20    | \$1,036,236.63    | \$1,036,987.34    | 111           |
| Original SHO    | \$1,061,714.19    | \$1,071,422.82    | \$1,084,631.13    | 25.155        |
| Refined SHO     | \$953,726.19      | \$1,024,264.48    | \$1,067,823.51    | 26.505        |
| CM SHO          | \$1,053,607.39    | \$1,070,217.58    | \$1,079,934.93    | 18.616        |
| Levy-Flight SHO | \$1,054,203.82    | \$1,068,160.76    | \$1,077,662.18    | 1.206         |

"-" means that is not available in the literature

Table 8.- Load demand for 24 hours test case 2.

The figures in appendix section AF5 through AF8 shows a graphical representation of the detailed results of the power generated by each generating unit, for each algorithm compared.

### Test case 3: 10-unit system neglecting power transmission loss.

For this test case, the valve points effects, the ramp-rate limits are considered, while neglecting the power transmission losses. The input data for the 10-unit system will be the same used in test case 2, enlisted in table 5, the load demand for 24 hours is the same for the test case 2, the figure 7 displays the average total dispatch cost of each SHO version used.

Figure 8 shows the fuel cost behavior over the iterations of the algorithms which used the same iterations, while figure 9 shows the fuel cost behavior of the LF-SHO.



Fig. 7.- Average total cost (\$) of test case 3.

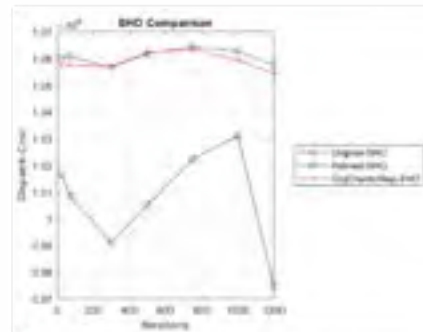


Fig. 8.- Average cost through iterations for test case 3.



Fig. 9.- Average cost through iterations of the original SHO with Levy-Flight for test case 3.

From Table 9 it is observed that the minimum cost is \$955,954.49 computed with the Refined SHO while the fastest algorithm is the LFSHO with an average time of 0.8 sec. this because the number of iterations. In the Appendix section are the results of each algorithm, the table A9 displays the result of the test case for the original SHO, the table A10 displays the results of the refined SHO while table A11 displays the results of the chaotic SHO and table A12 displays SHO with Levy-Flight operator, the figures AF9 through AF12 show a graphical representation of these results.



| Method       | Minimum Cost(\$) | Average Cost (\$) | Maximum Cost(\$) | Time in secs |
|--------------|------------------|-------------------|------------------|--------------|
| CMAES        | \$1,023,740.00   | \$1,026,307.00    | \$1,032,939.00   | 37.56        |
| GSA          | \$1,019,455.18   | \$1,020,172.36    | \$1,020,635.15   | 61.24        |
| CDHCO        | \$1,021,500.00   | \$1,024,300.00    | -                | 40.2         |
| ICPSO        | \$1,019,072.00   | \$1,020,027.00    | -                | 28.02        |
| Original SHO | \$1,043,033.74   | \$1,058,676.04    | \$1,068,186.75   | 21.330       |
| Refined SHO  | \$955,954.49     | \$1,007,706.10    | \$1,039,499.78   | 21.602       |
| CM SHO       | \$1,046,677.84   | \$1,059,576.63    | \$1,071,506.78   | 23.359       |
| LF SHO       | \$1,038,643.87   | \$1,055,167.21    | \$1,066,825.56   | 0.8013       |

Table 9.- Load demand for 24 hours test case 3.

## 6. Conclusions and future work

In this paper the Selfish Herd Optimizer as well as all the versions of the algorithm so far were implemented for the first time on a real engineering constrained optimization problem such as the dynamic economic dispatch.

All the versions proposed reach their goal and offers different improvements between them such as the minimum value, or the number of iterations needed to reach the local optima. In future, these algorithms could be implemented in some other versions of the economic dispatch problem like the multi-objective economic dispatch (MOED), or problems of another kind like image segmentation or combinatorial optimization.

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# Serious Videogame for Evaluating and Analyzing Behavior in Individuals with Potential ADHD

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**Abstract.** Attention Deficit Hyperactivity Disorder (ADHD) is a neurodevelopmental condition characterized by difficulties in maintaining attention, controlling impulses, and regulating behavior. Traditional diagnosis is based on a combination of questionnaires, clinical observation, and neuropsychological tests, such as the Test of Variables of Attention (TOVA), the MOXO Test, and the Conners' Scale. While these tools are useful, they are usually conducted in controlled environments and require the psychologist's subjective interpretation, which can make them somewhat boring, impractical, and sometimes inaccessible.

**Keywords:** ADHD, video game, neuroscience, behavioral analysis, physiological signals.

## 1 Introducción

Attention Deficit Hyperactivity Disorder (ADHD) is one of the most common neurodevelopmental disorders in childhood and can persist into adulthood, significantly affecting the quality of life of those who suffer from it. This disorder is characterized by difficulties in sustained attention, impulse control, and hyperactivity, which interfere with the academic, work, and social performance of individuals [1]. The main symptoms are grouped into three categories: inattention, hyperactivity, and impulsivity, with predominantly inattentive, hyperactive-impulsive, or combined presentations [2].

The diagnosis of ADHD is primarily based on clinical observation, structured interviews, and the application of objective tests, such as the Conners' Continuous Performance Test II and the MOXO d-Cpt test. These tools allow for the assessment of affected executive functions, such as sustained attention, impulse control, and response time. However, these methods are often static, repetitive, and unattractive to patients, especially in children and adolescent populations [3]. Furthermore, these tests lack dynamic stimuli that better represent the demands of the real environment.

In this context, the present research proposes an innovative alternative for the evaluation of ADHD, based on the dynamics of a video game conducted in Geometry Dash. This gamified approach not only maintains the user's interest during the evaluation but also allows for the analysis of cognitive and behavioral performance in an interactive

<https://doi.org/10.61728/AE20255299>





and progressive environment. Through five levels specifically designed, the game evaluates key aspects such as sustained attention, impulsivity, frustration, and cognitive flexibility, providing an experience closer to today's digital reality and fostering greater patient engagement.

The relevance of this project lies in its ability to improve diagnostic accuracy through an attractive and accessible approach, overcoming the limitations of traditional tests. By combining gamification with clinical assessment, it is expected to facilitate the early detection of ADHD and optimize the customization of therapeutic interventions, creatively enhancing the tools available for healthcare professionals to evaluate and treat this disorder. This innovative method aims to make the assessment process more engaging and reflective of everyday challenges faced by individuals with ADHD, thereby improving the overall effectiveness of interventions and support strategies offered to them.

## **2 Literature Review**

### **2.1 ADHD: Characteristics, Neurobiology, and Treatment Options**

Attention Deficit Hyperactivity Disorder (ADHD) is characterized by difficulty maintaining attention, increased distractibility, poor impulse control, hyperactivity, emotional instability, and disorganized behavior. This neurodevelopmental disorder is essentially characterized by deficits in executive functions, which can be defined as the actions an individual uses to self-regulate and achieve goals. The main executive domains affected in this population include time management, organization, problem-solving, motivation, and emotion management [1]. ADHD encompasses three main groups of symptoms: inattention, hyperactivity, and impulsivity [2]. Attention Deficit Hyperactivity Disorder (ADHD) is the most common neurodevelopmental disorder in childhood, of genetic and multifactorial origin with a neurological substrate mainly affecting the frontal lobe and its connections with the basal ganglia [3].

Attention Deficit Hyperactivity Disorder (ADHD) is associated with dysregulation of the catecholaminergic pathways, specifically the neurotransmitters dopamine and norepinephrine. This alteration affects executive functions such as attention, impulse control, and motor activity regulation [4]. Pharmacological treatments for ADHD include stimulant and non-stimulant medications. Stimulants, such as methylphenidate and amphetamines, work by increasing the availability of dopamine and norepinephrine in the brain [5]. Methylphenidate inhibits the reuptake of these neurotransmitters, while amphetamines, in addition to inhibiting reuptake, promote their release into the synaptic space. These mechanisms help to improve attention and reduce hyperactivity and impulsivity in patients with ADHD. On the other hand, non-stimulant medications, such as atomoxetine, work by selectively inhibiting the reuptake of norepinephrine, increasing its availability in the brain. Although their efficacy may be lower compared to stimulants, they represent a therapeutic alternative, especially in cases where stimulants are not well tolerated or are contraindicated [6]. It is essential that ADHD treatment be individualized and supervised by healthcare professionals, considering the specific



characteristics of each patient and regularly evaluating the efficacy and potential side effects of the medication.

Based on the types of symptoms, there are three types (presentations) of attention deficit hyperactivity disorder: predominantly inattentive presentation, predominantly hyperactive-impulsive presentation, and combined presentation (a combination of inattention and hyperactivity-impulsivity symptoms) [7]. Adults with ADHD may have difficulties with: managing their attention, completing long tasks unless they are interesting, staying organized, controlling their behavior, and/or symptoms of hyperactivity [8].

## **2.2 Assessing ADHD: Traditional Methods and a New Video Game-Based Approach**

In patients with ADHD, if the following behaviors are constantly present for more than 6 months, it is necessary to give importance due to the relationship it has in the behavior of a person with ADHD. In the realm of inattention, we have: often avoids, dislikes, or is reluctant to engage in tasks that require mental effort over a long period of time, loses things necessary for tasks and activities, has trouble organizing tasks and activities, does not pay close attention to details or makes careless mistakes, appears not to listen when spoken to directly, does not follow instructions and/or fails to finish tasks; in the realm of hyperactivity, we have the following behaviors: fidgets nervously or taps with hands or feet, leaves the seat in situations where remaining seated is expected, cannot play or engage in leisure activities quietly, acts as if "driven by a motor", talks excessively, blurts out an answer before a question has been completed, has trouble waiting their turn and/or interrupts or intrudes on others' activities [9].

From these behaviors and symptoms, a diagnosis is made, the diagnosis of ADHD is essentially clinical and is based on the confirmation of the presence of symptoms through clinical observations, structured, semi-structured interviews, and objective tests. Sometimes, it is also important to interview a family member or person living with the individual experiencing the symptoms [10]. Some of the tests used for detection include the Conners' Continuous Performance Test II, which assesses attention problems and treatment utility. It is a commonly used tool in ADHD research and clinical evaluations for participants aged 6 years and older. The test is performed on a computer. The participant presses the spacebar or clicks the mouse button when a letter other than X appears on the screen. Letters appear on the screen at varying time intervals [11]. The d-Cpt MOXO test is a tool that objectively measures executive functions using the evaluation of attention, response time, impulsivity, and hyperactivity; its system of distractors allows assessing the patient's performance in various environments using letters and/or beeps, which are less stimulating for evaluating ADHD [12].

Compared to traditional tests such as the Conners' Continuous Performance Test II and the d-Cpt MOXO test, the proposed project based on the dynamics of the video game Geometry Dash represents a more innovative and attractive approach to evaluating ADHD. While conventional tools are limited to controlled, repetitive environments with simple stimuli (letters and beeps), the proposal integrates an interactive and

gamified environment that evaluates the same metrics under more dynamic conditions closer to the reality of today's digital environment.

The design of the five levels of the video game allows a progressive and multifaceted evaluation of the executive functions affected by ADHD. Unlike traditional tests, where stimuli are static and monotonous, this approach introduces synchronized visual and auditory stimuli, increasing the level of complexity and variability at each stage. This evolution in difficulty not only allows for the assessment of sustained attention, impulsivity, and hyperactivity but also provides information on the patient's ability to adapt to changing situations and manage frustration.

### **3 Methodology**

To address this challenge, we developed MindRush, a system based on a video game designed to assess attention, impulsivity, stress tolerance, frustration, and boredom response through the analysis of interactional, behavioral, physiological, and emotional data. Unlike traditional tests, MindRush offers an interactive and dynamic environment that engages the subject with a naturally controlled stimulus environment, allowing for a more objective, fun, and accessible evaluation. The game consists of five progressive levels, each designed to provoke specific behaviors which will make it possible to differentiate between a person suffering from ADHD and one who does not. Level 1: Induction, Level 2: Attention, Level 3: Stress and Frustration, Level 4: Advanced Attention, Level 5: Boredom. As participants play, their physiological signals such as heart rate variability, brain activity (EEG), skin conductivity, and pinky finger temperature are recorded. Additionally, qualitative (behavioral) data such as anxious movements or expressions and how they interact and perform in the video game are collected, noting their reaction times, concentration, and progress. At the end of each level, participants complete the Self-Assessment Manikin (SAM) questionnaire, which measures how they felt during the activity in terms of valence, arousal, and dominance.

#### **3.1 Acquisition Protocol**

Data acquisition in the MindRush experiment followed a structured protocol that included signing informed consent, placing biosensors (heart rate, EEG, thermal conductivity, and temperature), playing the video game, and collecting behavioral and physiological metrics in real-time. During the game, correct, impulsive, hyperactive, and omitted jumps were evaluated, along with attempts and completion time. At the end of each level, the participant completed the Self-Assessment Manikin (SAM) questionnaire to assess their emotional experience. After the experiment concluded, the sensors were removed and disinfected, ensuring a proper closure. This approach allowed for a comprehensive evaluation of behavior, physiology, and emotions under different cognitive conditions (Fig 1).



**Fig. 1** Diagram of the Experimental Protocol for the MindRush Project, detailing the stages of the process with each participant. The sequence begins with an introduction to the experiment (1) and the delivery of the informed consent form (2). Then, the placement of biosensors (3) and the calibration of the physiological signal acquisition system (4) proceed. Once prepared, participants perform the video game tasks while behavioral and physiological metrics are recorded (5). Upon completion, the biosensors are disconnected (6), and participants are thanked for their participation, proceeding to clean the area and devices for the next evaluation (7).

### 3.2 Approaches to the Phases applied at each Level

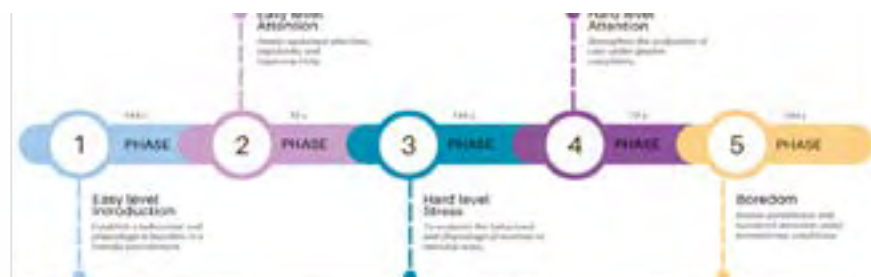
The purpose for which the protocol was designed was to induce the subject into psychological and physiological states that would allow us to identify the presence or absence of ADHD. To achieve this, it was necessary to create a significant gap/bias in the data we would take from participants to classify them.

The planning and development of the protocol consisted of analyzing symptoms and looking for potential triggering stimuli to be applied in a controlled manner to generate the characteristic bias of ADHD. An effective way to generate this was by creating a progression of phases/levels with different intentions seeking specific and planned effects, where, depending on the type of level, different data and metrics would be taken into account. The game is primarily divided into two types of levels, stimulative and metric.

Stimulative levels were created to trigger a specific type of emotion or behavior that, while affecting most participants in the same way, will not affect all of them to the same extent, and reactions will vary from one user to another depending on the psychological characteristics of the subject. By subjecting the subject to different levels of stress, pressure, frustration, boredom, etc., we can observe and measure various aspects considered, which are physiological data, performance data and interaction with the video game, and emotional states.

Metric levels are those based on the dynamics of other tests like MOXO, where different types of reaction to the same stimulus are measured. The intention of this level is to measure impulsivity, hyperactivity, attention, and the person's response time (Fig. 2).





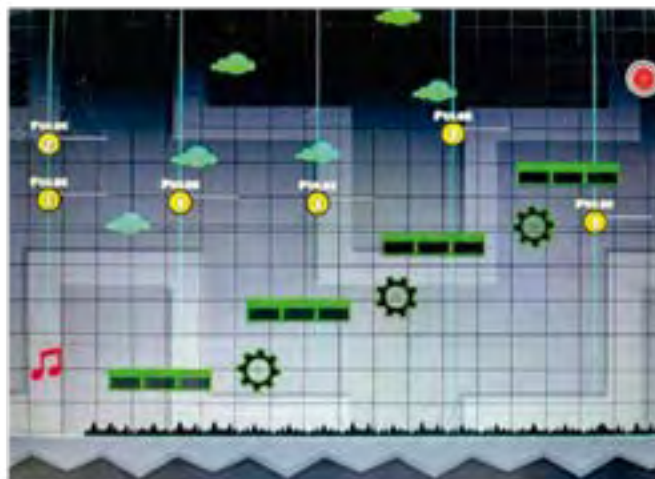
**Fig. 2** - Diagram of the five phases of the MindRush video game, designed for the assessment of ADHD. Each phase presents a specific level of complexity and objective: (1) Introduction: establishes a behavioral and physiological baseline in a friendly environment (144 s); (2) Attention: measures sustained attention, impulsivity and hyperactivity using specific visual stimuli (72 s); (3) Stress: assesses behavioral and physiological reaction to stressful and desynchronized tasks (144 s); (4) Advanced Attention: reinforces the assessment of attention under greater complexity and shorter response time (72 s); and (5) Boredom: analyzes persistence and sustained attention under monotonous conditions (144 s).

### 3.3 Description and Objectives of the Levels in MindRush

The progression of levels was created with a specific order to measure and compare basal states with states altered by stress, frustration, distraction, etc. Throughout all levels, physiological signals are monitored for analysis, and visual annotations by the applicator of anxious and hyperactive behaviors are made.

#### Level 1: Introduction Phase

The goal of this phase is to establish a baseline behavioral and physiological environment that allows for assessing the initial performance of the participant without generating much stress or frustration. The level design is based on precise synchronization between jumps, the rhythm of the music, and color changes, creating a fluid and intuitive experience for the player with the intention of being easy to pass. During this phase, the number of jumps made, the number of attempts required to complete the level, and the total completion time are recorded, providing a performance benchmark for later phases (Fig. 3).



*Fig. 3*

### **Level 2: Attention Phase**

The objective of this phase is to evaluate sustained attention, reaction time, impulsiveness, and hyperreactivity of the participant. The task involves jumping only at the appearance of a specific figure, ignoring the rest of the stimuli presented (Fig. 4). The level design aims to create a challenging but controlled environment, where correct responses require concentration and impulse control. During this phase, activation accuracy is recorded, differentiating whether the jump occurs on time or out of time, as well as impulsive jumps (jumping at an incorrect figure), hyperreactive jumps (repeated jumps after a correct stimulus), and omissions (not responding to the target stimulus). Work memory cues are also considered, assessing the participant's ability to remember and act according to instructions during the task. These data allow for identifying patterns of attentional behavior that will serve as a reference for later phases.



*Fig. 4*. Visual instructions in the attentional evaluation phase in MindRush. Participants are instructed to only jump at the appearance of the green figure, while any other stimulus requires inhibiting the motor response. This task allows measuring sustained attention, impulsivity and hyper-reactivity in real time.

### **Level 3: Stress Phase**



The goal of this phase is to evaluate the behavioral and physiological reaction of the participant to stressful tasks, challenging their ability to manage frustration and adapt to a challenging environment. The level design is based on the asynchrony between the music, color changes, and the location of obstacles, generating a misaligned environment that complicates anticipation of movements and increases task complexity. During this phase, the number of jumps made, the number of attempts required to complete the level, and the total completion time are recorded. This is to be compared with performance in other phases and to identify behavior patterns under stress, frustration, discomfort, and pressure (Fig. 5).



**Fig. 5** Capture of Level 3 (Stress Phase) of the MindRush video game. The yellow markers indicate the color change, but in this phase the synchronization between the music, the visual stimuli and the timing of the jump is misaligned, the obstacles are irregularly designed to complement the purpose of the phase.

#### Level 4: Advanced Attention Phase

The objective of this phase is to reinforce the evaluation of attention in a more complex environment, considering the impact of cognitive fatigue after stressful tasks. The level design is similar to the initial attention phase but with more complex stimuli and shorter response times, demanding greater concentration and inhibitory control. During this phase, activation accuracy is recorded, including correct jumps (timely or delayed), impulsive activations (response to incorrect stimuli), hyperreactive jumps (repeated jumps after a correct stimulus), and omissions (lack of response to the target stimulus). These data help identify how difficulty and previous exposure to stress affect attentional performance and behavioral self-regulation of the participant (Fig. 6).



**Fig. 6** Jump metrics in phases 2 and 4 of the MindRush video game, designed to assess sustained attention, impulsivity and hyper-reactivity. Green stripes represent correct stimuli, red stripes represent distractors and blue stripes represent rest intervals. The initial yellow stripe marks the instruction period. Stimuli and rests are presented at equal intervals, varying between 0.5, 0.75 and 1 second, assessing the participant's adaptation to different processing speeds. In

Phase 2, 13 correct stimuli are presented in 72 seconds, while in Phase 4, with greater complexity and shorter response time, 18 stimuli are presented in the same period. A jump is considered correct if it occurs during the green box, while if it is not jumped at that time but in the consecutive blue box, it is classified as a correct jump with delay. If the participant jumps in both the green and subsequent blue boxes, it is considered a hyper-reactive jump. A jump during a red box is classified as impulsive, and if after that impulsive jump the player jumps again in the subsequent blue box, the second jump is also considered hyper-reactive. Finally, omission is recorded if the participant does not jump in either the green or the following blue box. This classification allows the assessment of sustained attention, impulsivity and hyperactivity, providing a detailed view of the participant's cognitive and behavioral control.

### Level 5: Boredom Phase

The goal of this phase is to evaluate the persistence and sustained attention of the participant under monotonous conditions, analyzing their ability to maintain focus and motivation in the absence of attractive stimuli. The level design includes an initial minute with relaxing music and a neutral background, followed by an empty environment without visual or auditory stimuli. During this stage, false and true obstacles are presented to assess the player's perseverance and cognitive flexibility in the absence of clear feedback. Metrics recorded include the number of attempts made, jumps performed, and strategy changes, providing key information on boredom tolerance and the participant's ability to regulate their behavior.

### 3.4 Instruments and Equipment for Data Acquisition

For the acquisition of the selected biosignals, four biosensors were used, selected for their previous use and the quality of results obtained; these can be seen in Table 1 and (Fig. 7), which describes the type of sensor, model, application in the study, and an image of them.

**Table 1. Sensors**

| Sensor             | Model                          | Application                                                         | Image    |
|--------------------|--------------------------------|---------------------------------------------------------------------|----------|
| Sensor GSR         | Grove GSR                      | Acquisition of skin conductance                                     | Fig. #.3 |
| Temperature Sensor | LM335                          | Acquisition of body temperature                                     | Fig. #.4 |
| Photoplethysm      | Phototransistor and Photodiode | Acquisition of cardiac pulses                                       | Fig. #.2 |
| Single Channel EEG | INA-129                        | Acquisition of electroencephalographic activity of the Fp1 channel. | Fig. #.5 |

#### *GSR Sensor*

A galvanic skin resistance sensor from Seed Studio®, model Grove GSR, was used. This sensor measures the body's resistance using two electrodes into which a small current (on the order of microamperes) is injected, and the resistance value varies

depending on skin perspiration. The higher the perspiration, the lower the resistance. The electrodes are positioned on the ring and middle fingers of the right hand [13].

#### *Temperature Sensor*

A high-precision temperature sensor, model LM335 from ST Microelectronics®, was used. This sensor has a resolution of 10mV/1°K for body temperature measurements [13].

#### *Photoplethysmography*

The circuit detects heartbeats using an infrared LED and a photodetector, whose signal is filtered to eliminate noise, amplified to increase its intensity, and compared to an adjustable threshold using a TL084. When the signal exceeds the threshold, an LED is activated that blinks in rhythm with the pulse [13].

#### *Single Channel EEG*

A circuit developed by us was used for the capture of a single EEG channel, this circuit consists of four stages, which included a pre-amplification phase that converts microvolts to millivolts, using the instrumental amplifier INA-129. The second phase consists of a third-order High-Pass filter of 1Hz to eliminate noises that are common in our work area; followed by a Low-Pass filter of 100Hz, to limit the frequencies obtained in electroencephalographic activity. Finally, an amplification phase that converts millivolts to volts, using the instrumental amplifier INA-129, and thus able to read the signal [13].

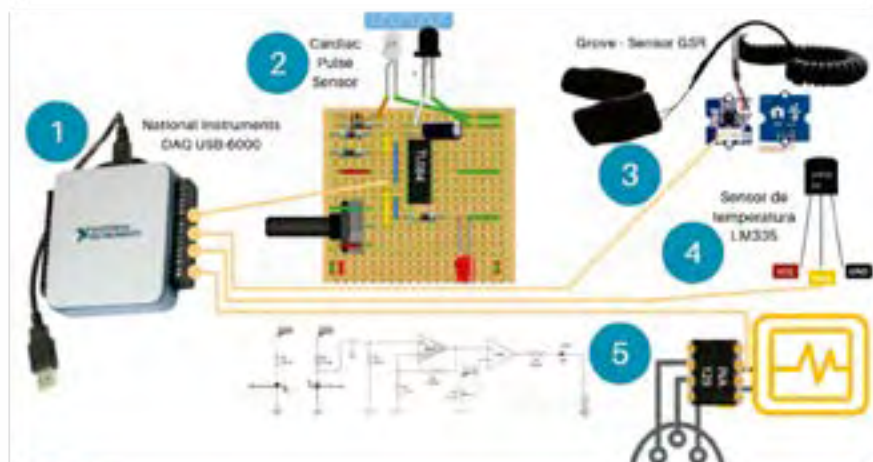


Fig. 7

The acquisition of these biosignals was carried out using a DAQ card, model USB-6000 from National Instruments®. This card provides both digital and analog inputs and outputs with a 32-bit counter. The biosignals for heart rate, skin conductance, body temperature, and EEG have approximate sampling frequencies of 100 Hz, 4 Hz, 2 Hz, and 80 Hz, respectively. Since the data acquisition card cannot acquire signals at



different sampling frequencies, the highest necessary frequency from those sources was chosen for acquisition ( $f_s = 250$  Hz).

### 3.5 Using Forms for Subject Evaluation

Each time the participant completed a level, they rated their state using the Self-Assessment Manikin (SAM) system, which involves assigning a value (between 1 and 9) to each affective image based on three emotional dimensions: valence, arousal, and dominance (see Fig. 8).

This evaluation consists of three rows of drawings, each representing one of the previously mentioned emotional dimensions. Each participant can provide values for each emotional dimension according to the emotion they experience, with a score of 9 indicating the highest intensity for any given dimension.

**Autoevaluación del Maniquí**  
Self-Assessment Manikin (SAM)

**Valencia**  
Valence

**Activación**  
Arousal

**Dominancia**  
Dominance

Fig. 8 SAM (Self-Assessment Manikin)

## 4 Results

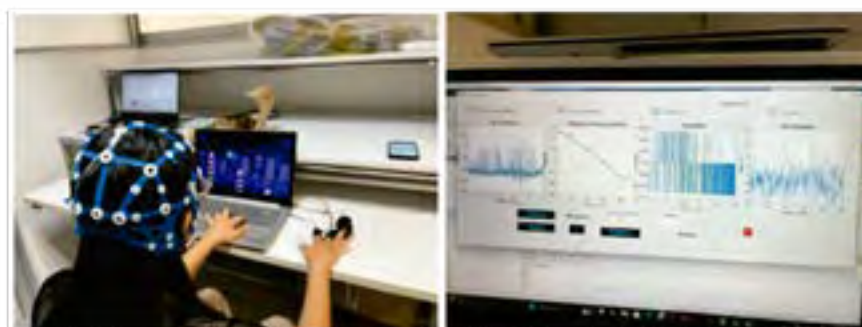
A database was obtained consisting of 16 subjects (Fig. 9), with high-quality signals from the four previously mentioned sensors, ensuring the reliability of the data for processing. Currently, the data is in the analysis stage using a developing network designed to optimally classify participants based on their performance and physiological responses.



The protocol was practiced and refined through multiple trials, achieving an average duration of 30 minutes per subject. The participants' response was positive, showing interest and commitment during the activity, which facilitated data collection without interruptions or apathetic behaviors. Additionally, observing the performance in the game allowed for the identification of distinctive patterns in individuals with ADHD, highlighting differences in jump accuracy, reaction times, and behavior under stress and monotony conditions. These preliminary findings suggest that the dynamics of the video game are not only engaging but may also serve as an effective tool for detecting and evaluating characteristics associated with ADHD.

| SUBJECT | Date            | Age   | Gender   | Have you previously been diagnosed with ADHD or ASD by a specialist? | Do you consider yourself a Video Gamer? | Have you played Geometry Dash? | GROUP   |
|---------|-----------------|-------|----------|----------------------------------------------------------------------|-----------------------------------------|--------------------------------|---------|
| 1       | Monday 10/02/23 | 21-30 | 18 years | Male                                                                 | No                                      | No                             | Control |
| 2       | Monday 10/02/23 | 21-30 | 17 years | Female                                                               | No                                      | No                             | Control |
| 3       | Monday 10/02/23 | 21-30 | 22 years | Female                                                               | No                                      | No                             | Control |
| 4       | Monday 10/02/23 | 21-30 | 27 years | Male                                                                 | No                                      | No                             | Control |
| 5       | Monday 10/02/23 | 21-30 | 27 years | Male                                                                 | No                                      | No                             | Control |
| 6       | Monday 10/02/23 | 21-30 | 27 years | Male                                                                 | No                                      | No                             | Control |
| 7       | Monday 10/02/23 | 21-30 | 22 years | Female                                                               | No                                      | No                             | Control |
| 8       | Monday 10/02/23 | 21-30 | 28 years | Female                                                               | No                                      | No                             | Control |
| 9       | Monday 10/02/23 | 21-30 | 19 years | Male                                                                 | No                                      | No                             | Control |
| 10      | Monday 10/02/23 | 21-30 | 14 years | Male                                                                 | No                                      | No                             | Control |
| 11      | Monday 10/02/23 | 21-30 | 18 years | Female                                                               | No                                      | No                             | Control |
| 12      | Monday 10/02/23 | 21-30 | 25 years | Female                                                               | No                                      | No                             | Control |
| 13      | Monday 10/02/23 | 21-30 | 19 years | Female                                                               | No                                      | No                             | Control |
| 14      | Monday 10/02/23 | 21-30 | 27 years | Male                                                                 | No                                      | No                             | Control |
| 15      | Monday 10/02/23 | 21-30 | 19 years | Female                                                               | No                                      | No                             | Control |
| 16      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 17      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 18      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 19      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 20      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 21      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 22      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 23      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 24      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 25      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 26      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 27      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 28      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 29      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 30      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 31      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 32      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 33      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 34      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 35      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 36      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 37      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 38      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 39      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 40      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 41      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 42      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 43      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 44      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 45      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 46      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 47      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 48      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 49      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 50      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 51      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 52      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 53      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 54      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 55      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 56      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 57      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 58      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 59      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 60      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 61      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 62      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 63      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 64      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 65      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 66      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 67      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 68      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 69      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 70      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 71      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 72      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 73      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 74      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 75      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 76      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 77      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 78      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 79      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 80      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 81      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 82      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 83      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 84      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 85      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 86      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 87      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 88      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 89      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 90      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 91      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 92      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 93      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 94      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 95      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 96      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 97      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 98      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 99      | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |
| 100     | Monday 10/02/23 | 21-30 | 22 years | Male                                                                 | No                                      | No                             | Control |

**Fig. 9.** Distribution of participants according to age, gender, previous ADHD diagnosis, affinity for video games and experience with Geometry Dash. The table shows the classification of subjects into control and ADHD groups, allowing a comparative analysis of the metrics obtained during the experiment.



**Fig. 10** Data acquisition process during the MindRush experiment. On the left, participant equipped with an electroencephalography (EEG) cap and galvanic skin response sensors while interacting with the video game. Right, real-time display of physiological signals recorded, including heart rate, galvanic skin response, body temperature, and encephalographic activity.

## 5 Conclusion

MindRush is a project with a promising outlook, ready to be optimized and applied in real-world settings. Although the final results are still under development, the methodological foundation, data collection, and technological integration achieved demonstrate its viability as an advanced assessment tool, paving the way for a more accurate, accessible, and personalized diagnosis and treatment.

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# Automatic Emotion Detection through Biosignals and Standardized Emotional Stimuli

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**Abstract.** Monitoring physiological signals using biomedical devices has experienced significant growth due to its wide range of applications in various fields, such as Health and Education. This work reports on implementation of a physiological data acquisition system based on the Mehrabian and Russell model, associating emotional dimensions with specific parameters: valence (heart rate), activation (skin conductance), and dominance (temperature). System allows interpretation of human emotional states, including happiness, anger, fear, and sadness, using standardized stimulations from International Affective Picture System (IAPS) and Digital Affective Sounds (IADS).

**Keywords:** Emotion Detection, Conductance, Temperature, Heart Rate, IAPS, IADS.

## 1 Introduction

Biosignal monitoring has traditionally been focused on diagnosis and follow-up of physical diseases, overlooking its potential in evaluating and understanding mental health. Relative lack of technologies that effectively integrate these parameters, allowing assessment of relationship between specific physiological responses and emotional states, limits practical application of scientific advances in this field. Different emotional states manifest themselves in different physiological ways. By studying biosignals of subjects in whom a research protocol has been used to induce a specific emotional state, it is possible to analyze these signals in a general way better to understand physiological responses to a subjective situation. By better understanding how a person thinks, feels, and acts, it is possible to improve educational, work, and business systems, among many others.

<https://doi.org/10.61728/AE20255305>





### 1.1 Study of Emotions

Traditionally, study of emotions has been restricted to subjective methods, such as questionnaires and self-assessments, which have limitations regarding accuracy and reproducibility. Therefore, development of innovative biomedical devices that allow accurate interpretation of emotional states improves monitoring in this field and contributes to closing gap between scientific research and its application in everyday life. For this purpose, present work deals with design and implementation of an automatic emotion detection system using biosignals and standardized emotional stimulations based on acquisition of physiological data such as skin conductance, body temperature, and heart rate, capable of identifying human emotional states (happiness, anger, fear, sadness).

### 1.2 Justification

This automatic detection system is designed for use in various sectors., including mental health professionals, who can benefit from continuous monitoring of their patient's emotional states; educators, who could adapt their teaching methods according to students' emotional responses; and researchers interested in exploring relationship between physiological responses and emotions, in developing more effective approaches to treatments of emotional disorders or gain more precise insights into the relationship between emotional system and people's physiological state. System processes and classifies these signals using machine learning techniques, allowing identification of four basic emotional states. This technology aims to reduce reliance on subjective methods, facilitate integration of scientific advances into everyday life, and promote a more accurate approach to understanding and managing emotions.

### 1.3 Hypothesis

- Biosignals such as skin conductance, body temperature and heart rate can be used to objectively and accurately identify different emotional states.
- Machine learning techniques like neuronal networks are most effective in classifying emotional states from biomedical data.
- Accuracy and reproducibility of automatic detection system is more reliable compared with traditional methods of emotional assessment based on self-reports and questionnaires.

### 1.4 Literature overview

Several studies have addressed identifying and analyzing emotions from biosignals, exploring methodologies and technologies that integrate machine learning, biomedical

sensors, and advanced computational models. Among them, García Manzo's thesis [1] analyses the possibility of detecting emotions using biosignals such as skin conductance, body temperature, and heart rate in combination with virtual reality environments. His methodology involves recording, processing, and classifying physiological signals through machine learning models, using standardized emotional stimuli such as International Affective Picture System (IAPS) and the International Affective Digitized Sound System (IADS) to induce and evaluate emotional responses.

In affective neuroscience, Dalglish [2] examines involvement of brain structures such as amygdala, hippocampus, and prefrontal cortex in emotional processing. In addition, he analyses their interaction with autonomic nervous system, providing a fundamental framework for understanding physiological mechanisms underlying changes in parameters such as skin conductance, temperature, and heart rate, which are essential in biosignal-based emotion detection.

On the other hand, Aqajari et al. [3] have developed an open-source tool for analyzing galvanic skin response (GSR) as an indicator of stress. Their model employs deep learning algorithms and statistical methods to extract meaningful features from GSR, achieving 92% accuracy in detecting stress levels. Since emotional arousal is reflected in skin conductance, this study is highly relevant for automatic biosignal emotion detection.

Similarly, Gao [4] has developed an electronic skin capable of continuously monitoring nine physiological biomarkers associated with stress response. This device, which incorporates advanced sensors to measure skin conductance and temperature, represents a significant advance in real-time physiological monitoring, with direct applications in detecting and analyzing emotional states.

Another relevant work is Spanish adaptation of International Affective Picture System (IAPS) [5], which provides a standardized set of visual stimuli used in emotion research. Validating this system in different populations is crucial to ensuring its effectiveness in inducing emotional states in experimental studies.

Finally, Ean-Gyu et al. [6] propose a real-time emotion recognition method based on photoplethysmographic (PPG) and electromyographic (EMG) signals using convolutional neural networks (CVCNN). Their approach, which achieved an accuracy of over 80%, demonstrates potential of integrating cardiac signal processing with machine learning models to identify emotional states accurately.

Several authors have explored quantification of emotional states from physiological signals. Works such as Koelstra et al. [7] and Chanel et al. [8] have demonstrated feasibility of these methods for assessing emotional responses using biomedical signals. In this work, we have proposed a protocol that is as controlled as possible, with homogeneous stimulations as much as possible, to avoid introducing biases in interpretation of results and, based on references we have, to improve this type of analysis.

Unlike other approaches, experimental protocol incorporated in this work is highly standardized. It is based on IAPS and IADS systems, ensuring all participants are exposed to same audiovisual input with a homogeneous design. In addition, a three-dimensional model of emotions, according to Mehrabian and Russell, is employed, allowing for a more complete quantification of affective states regarding valence, activation, and dominance. This approach, coupled with simultaneous integration of multiple biomedical sensors and rigorous control of experimental conditions, *represents a significant advance over previous studies in the field.*

## 2 Metodology

### 2.1 How to quantify an emotion?

An emotion is a multi-component response to an emotionally potent antecedent event, causing changes in subjective quality of feeling, expressive behavior, and physiological activation [9]. In analysis of emotions, the function of the autonomic nervous system is known, which, from interactions with neurotransmitters (chemicals that transmit information to neurons from a synapse), produces involuntary reactions [10]. Under influence of emotions, autonomic nervous system produces quantifiable physiological and behavioral manifestations [1].

Based on the above, selection of four base emotions considered in this project is based on identifying quantifiable manifestations, specifically on activation, valence, and Dominance levels. **Valence** refers to how pleasant or unpleasant an experience is and is directly related to Heart Rate; Arousal reflects state of agitation or calmness as measured by galvanic skin response (GSR), while **Dominance** indicates how much control one has over emotion as represented by peripheral temperature.

García Manzo [1] uses Mehrabian and Russell's three-dimensional model to represent emotions through these three fundamental parameters as it is based on discrete emotions. In this approach, each emotion is situated within a three-dimensional space defined by these levels, allowing for a more accurate characterization of emotional responses.

This model is incredibly convenient when implementing Machine Learning Techniques because it allows for better accuracy in emotion classification compared to label-based models. As shown in **Table 1**, spatial coordinates of emotions are represented on valence, activation, and dominance axes.

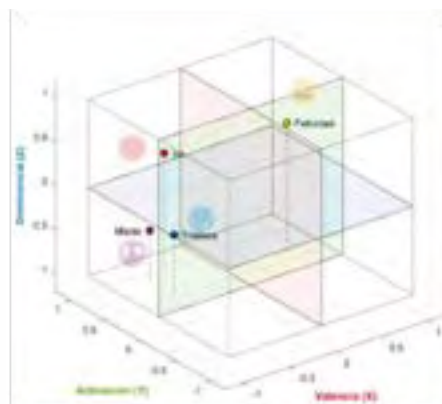


Fig. 1. Representation of Mehrabian and Russell's three-dimensional model [1].

Table 1. Spatial coordinates of emotions

| Emotion   | Valence (X) | Arousal (Y) | Dominance(Z) |
|-----------|-------------|-------------|--------------|
| Happiness | 0.76        | 0.48        | 0.35         |
| Anger     | -0.43       | 0.67        | 0.34         |
| Fear      | -0.64       | 0.6         | -0.43        |
| Sadness   | -0.63       | 0.27        | -0.33        |

## 2.2 Stimulus

Experimental study of emotion requires stimulation that reliably evokes psychological and physiological reactions. Over the last few years, stimulus batteries have been developed that cover different sensory modalities and can generate different emotional states, such as International Affective Picture System (IAPS) and International Affective Digitized Sound (IADS) [10].

IAPS was developed to provide a set of normative emotional stimuli for experimental emotion research. It includes various images in (*.jpg*) format that can be classified within three dimensions (valence, activation, and dominance). It includes stimuli of humans, animals, landscapes, and objects that vary in complexity, color, and composition. IADS was developed for same purpose, using auditory rather than visual stimuli, including audio files in *.wav* format.

For stimulation of emotions, videos were produced by selecting images and audio that presented valence, dominance, and activation levels most consistent with each emotion, according to values shown in Table 1.



### 2.3 Circuit and sensors for biosignal acquisition

For data acquisition during emotional stimulus session, evoked by IAPS and IADS databanks, three primary sensors were used: a galvanic skin response sensor (GSR from Seed Studio), a temperature sensor (LM335), and a heart rate sensor based on photoplethysmography, which incorporates amplification by a TL084 integrated circuit and an optical pair. Each sensor is operated in a specific way according to its characteristics and efficiency in relation to project's objectives.

- **Galvanic skin resistance sensor (GSR Grove - Seed Studio).** Galvanic skin response (GSR) sensor measures electrodermal activity or skin resistivity, directly related to sympathetic nervous system activation and, thus, emotional responses [11]. Variations in skin resistivity are detected as a function of sweat gland activity. Among main characteristics of sensor provided by the manufacturer, we can find that it has a measurement range of 10 k $\Omega$  to 4.5 M $\Omega$ ; its supply voltage is 3.3-5 V; it has a high sensitivity, with immediate response to changes in sweating and communication with acquisition cards is through an analog output, which allows easy integration with microcontrollers [12]. GSR is widely used in psychophysiological studies to measure emotional arousal, especially in response to affective stimuli such as IAPS images and IADS sounds. Previous research has shown that GSR is a reliable biomarker differentiating between high and low emotional arousal states [3] [4].
- **Temperature sensor (LM335).** LM335 is a high-precision semiconductor-based temperature sensor that provides a linear output proportional to absolute temperature in degrees Kelvin. This sensor has been integrated into project's emotion detection system because of close relationship between skin temperature and emotional states. It has been observed that emotions such as stress or excitement can cause detectable thermal changes in peripheral areas of body, such as skin of fingers, making it possible to use this variable as an indicator for emotional assessment. For main characteristics of sensor, a measurement range of -40 $^{\circ}$  C to 100 $^{\circ}$  C, an accuracy of  $\pm 1^{\circ}$  C, an operating voltage of 2 - 20 V, and a linearity of 10 mV/ $^{\circ}$ K are recorded in its datasheet [13]. When discussing its efficiency in detecting emotions, it has been shown that peripheral temperature decreases in states such as anxiety or stress and increases in relaxation conditions [2]. Its integration with other sensors improves classification of emotional states.
- **Heart Rate Sensor - Photoplethysmography with TL084.** Circuit shown in Fig. 2 uses an optical pair consisting of an infrared LED and a receiver photodiode (optical pair), which allows changes in light absorption caused by blood flow in capillaries to be captured. Signal obtained is amplified by a TL084 operational amplifier, which includes two stages to improve signal quality.

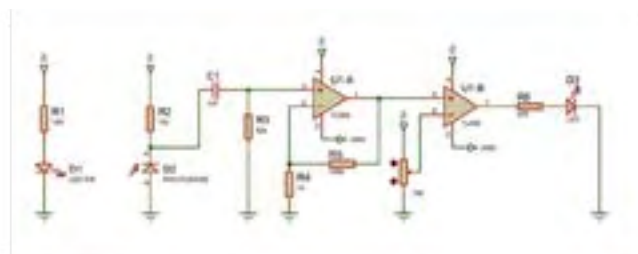


Fig. 2. Diagram of the proposed circuit for heart rate detection (photoplethysmography).

Heart rate is a key indicator of emotional response. Accelerations of pulse may be associated with emotions such as fear or excitement, while a decrease may indicate relaxation or sadness [14].

This photoplethysmography method has an analog signal output picked up by acquisition board. The proposed circuit consists of 4 stages: an acquisition stage with optical pair, then filtering with a cut-off frequency of 2 Hz using a passive filter; signal is then passed to an amplification stage with a TL084 operational amplifier configured in a non-inverting way; gain of proposed circuit is about a factor of 100, so signal coming out of this stage is easier to handle and depending on 5 V supply. Last stage is not vital for data acquisition of the project as it is only a display stage that uses a variable resistor to visualize heartbeat with an LED to ensure that circuit works correctly without need to connect it to a computer to visualize data on display.

Power supply for the whole circuit was covered by using an Arduino UNO board (5V). A USB-6000 DAQ acquisition board was used for data acquisition; the choice of this acquisition board was based on its ability to provide a stable and sufficient sampling frequency ( $f_s$ ) for capturing biomedical signals. Sampling frequency is critical to ensure proper signal processing, especially when working with physiological signals of low amplitude and high temporal variability. An  $f_s$  of 100 Hz was selected to accurately capture dynamic variations of signals without risk of aliasing, ensuring that information contained in time domain is reliably represented. USB interface and compatibility with programming environments such as Matlab facilitated the integration of hardware with acquisition software to perform process efficiently and synchronized, ensuring that database construction stage was robust, accurate, and reproducible.

## 2.4 Data acquisition protocol.

In order to guarantee the best possible quality in acquisition of signals required to create database and, above all, to guarantee safety of test subjects at all times, an acquisition protocol was designed to ensure that information worked with follows same standard, homogeneity, and quality necessary to achieve best possible accuracy in results, minimizing external factors that may influence physiological measurements.

Before participation, a form was provided to assess subjects' eligibility. Main inclusion criteria were:

- To be over 18 years of age.
- No history of epilepsy or heart disease.
- No photosensitivity or severe discomfort when viewing or listening to audiovisual content.
- Not to be under effect of substances or medications that can modify mood (anxiolytics, antidepressants, among others).
- If you have nail polish or false nails, remove them before procedure to avoid interference in acquiring photoplethysmographic signal.

In addition, complementary data such as regular sugar consumption, menstrual cycle phase, and recent emotionally significant events were recorded. Although these were not exclusion criteria, they were considered for future analysis of results.

Efforts have been made to maintain a gender balance, with an equal distribution of 50% men and 50% women (9 men and nine women in total, as shown in **Table 2**). This helps to minimize possible biases arising from physiological differences in emotional expression. In addition, average age of subjects is 21 years, which allows for greater homogeneity in sample.

**Table 2.** Test subjects

| Sub-<br>ject | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|--------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Age          | 22 | 22 | 23 | 23 | 21 | 24 | 22 | 28 | 21 | 22 | 21 | 22 | 21 | 21 | 19 | 19 | 22 | 21 |
| Gender       | F  | M  | M  | M  | M  | M  | M  | F  | F  | F  | F  | F  | M  | M  | M  | F  | F  | F  |

Upon arrival at the study area, the research team welcomed each test subject and gave a brief presentation of study, explaining its objectives and experimental procedure. Subsequently, they were asked to sign an informed consent form detailing the experiment's conditions, guaranteeing the methodology's non-invasive nature, confidentiality of data, and freedom to discontinue participation at any time.

Once consent form has been signed, test subjects are asked to remove metallic objects such as bracelets, rings, watches, mobile phones, and other accessories that may interfere with data acquisition. They then proceed with placement of sensors according to an established standard:

- Photoplethysmography (PPG): Sensor placed on left hand's ring finger.
- Skin conductance (GSR): Sensor electrodes placed on middle and ring fingers of right hand.
- Skin temperature: Sensor placed on index finger of right hand.

Headband headphones were also placed to isolate external noise and improve immersion in auditory stimuli. It was indicated to maintain a comfortable posture to fix eyes on monitor and thus reduce involuntary hand movements, minimizing noise in physiological signal.

Before starting formal data acquisition, brief training sessions of 10 seconds each were carried out to familiarize participant with task and verify correct functioning of sensors. These sessions allowed for detection of possible artifacts in signal and for making necessary adjustments before proceeding with leading acquisition.

Each experimental session consisted of presentation of 4 videos each one associated with a specific emotion: fear, happiness, sadness, and anger; order in which each of videos was presented was determined taking into account quantification of parameters of activation, valence, and dominance of each of four emotions concerning values shown in **Table 1**, thus separating as much as possible emotions with very similar values in one or more parameters in order to achieve a better distinction in results. Each video contains seven IAPS images displayed for 30 seconds, interspersed with 10-second intervals of blank screen. In addition, three IADS sounds synchronized with images 2, 4, and 6 and having coherence with displayed image have been presented; sounds used in each case respected activation, valence, and dominance values for each emotion, shown in **Table 1**.

Each subject generated four text files, one per-video, with a total recording time of 4:40 minutes per file, sampled at an fs of 100 Hz. During acquisition, research team monitored process in real-time and noted any relevant occurrences.





Fig. 3. Test subject during the biosignal acquisition protocol.

At the end of each video, each participant was given a short break for comfort and to interrupt immersion in previous emission. This allowed participant to evaluate quality of acquisition and to make annotations on possible noise or artifacts. If significant noise was detected in data, corrective strategies were implemented before continuing with next video.

Finally, after five videos are acquired, each participant is provided with a general explanation of subsequent use of collected data, thanked for his or her collaboration, and session is cordially concluded.

### 3 Neural Network

#### 3.1 Data Pre-processing

All physiological signals were processed to remove noise and any potential artifacts that could affect the information they contain.

For galvanic skin resistance and temperature signals, a degree twenty polynomial filter was applied to preserve the overall trend of these biosignals.

Additionally, the heartbeats were transformed into a tachogram signal. This involved calculating the interval between beats and then deriving the inverse of this period to capture variations in heart rate over time (tachogram). This signal was also conditioned using a degree twenty polynomial filter to create a version that reflects general variations in heart rate.

#### 3.2 Neural Network Setup

In this study, “raw” acquired data are used as inputs for an artificial neural network implemented in Matlab, which has been designed to classify emotional states into four distinct categories. Architecture of network comprises an input layer with four neurons, responsible for receiving physiological signals processed, a hidden layer of 10 neurons that allows extraction of complex patterns in data, and an output layer con-

sisting of 2 neurons, whose combination enables prediction of emotional state experienced by subject. Choice of this structure responds to need to find a balance between model's ability to capture nonlinear relationships in data and prevention of overfitting, ensuring that network can generalize adequately when processing samples.

Activation's function used in this study was sigmoid for both hide and output layer. Sigmoid activation function was chosen for hidden layer due to its ability to introduce non-linearity and constrain outputs between 0 and 1, which aligns with normalized input data. Network's output layer consists of two neurons, with each neuron using a sigmoid activation function to produce outputs between 0 and 1. This configuration requires a binary encoding scheme to represent four emotions, such as:

- Happiness: (1,0)
- Anger: (0,1)
- Fear: (1,1)
- Sadness: (0,0)

This encoding approach allows network to differentiate between emotions based on combination of activations from two output neurons.

Richness of database is a key aspect of efficiency of neural network since an extensive and balanced training set improves model's ability to identify patterns in physiological activity associated with different emotional states. By integrating multiple recordings per subject and emotion, model's generalization is favored, reducing risk of overfitting and improving its performance in classifying new samples. Furthermore, acquisition of data in individual sessions using an appropriate sampling frequency and calibrated measurement devices strengthens consistency of dataset, ensuring that neural network can extract meaningful features from obtained signals. In this sense, standardization of acquisition protocol and th efficiency of recorded data play a determining role in accuracy of predictive model, not remaining a simple technical requirement but being an essential element for correct implementation of machine learning models in study of physiological activity linked to human emotions.

## 4 Results

The intra-subject multi-class classification results indicate that a simple neural network model can accurately classify four emotional states: happiness, anger, fear, and sadness. Table 3 presents the accuracy rates for each emotion and the overall accuracy for all 18 subjects, with an average accuracy of 92% within subjects. The model's accuracy varied between 0.78 and 0.99 depending on the participant.

The results indicate that the neural network achieved high classification performance, with most subjects reaching accuracy values above 0.90. The best-performing subject was Participant 16, attaining an accuracy of 0.99, indicating that the model correctly classified nearly all evaluated instances. In contrast, the lowest accuracy was observed for Participant 3, with a value of 0.78, suggesting more incredible difficulty in identifying consistent patterns in this

individual's physiological data. This outcome may be attributed to inter-individual variations in physiological responses to emotional stimuli, signal noise, or preprocessing quality.

It is important to note that the selection of input features is crucial for a neural network to perform classification effectively. In this study, galvanic skin resistance, temperature, and photoplethysmography sensors provided the network with sufficient relevant information for the multi-class classification task. Additionally, the choice of emotional stimuli plays a crucial role in eliciting distinct physiological responses. While subjective factors can influence emotions, standardized materials such as the International Affective Picture System (IAPS) and International Affective Digital Series (IADS) have been shown to reliably induce targeted emotional states.

Regarding the network's ability to differentiate between emotions, anger and fear exhibited the highest average accuracy, ranging from 0.89 to 1.00 depending on the subject, suggesting that the physiological patterns associated with these emotions are more distinct. On the other hand, happiness and sadness, while still achieving high accuracy, showed slightly lower values for some subjects, possibly due to reduced variability in their physiological parameters or more significant overlap in their physiological characteristics.

From a methodological perspective, the Levenberg-Marquardt algorithm facilitated rapid convergence and minimized training error, contributing to model stability. However, inter-subject variability in accuracy highlights the need for additional optimization strategies, such as implementing more robust data normalization techniques or dynamically adjusting hyperparameters based on signal quality.

**Table 3.** Results of intra subject multiclass classification.

| Subject        | 1           | 2           | 3           | 4           | 5           | 6           | 7           | 8           | 9           |
|----------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Accuracy model | <b>0.95</b> | <b>0.89</b> | <b>0.78</b> | <b>0.92</b> | <b>0.97</b> | <b>0.98</b> | <b>0.89</b> | <b>0.97</b> | <b>0.94</b> |
| Happiness      | 0.99        | 0.96        | 0.89        | 0.95        | 0.98        | 1.00        | 0.93        | 0.98        | 0.96        |
| Anger          | 0.97        | 0.92        | 0.86        | 0.97        | 0.98        | 0.99        | 0.96        | 0.98        | 0.99        |
| Fear           | 0.97        | 0.96        | 0.92        | 0.96        | 0.98        | 0.99        | 0.92        | 0.98        | 0.97        |
| Sadness        | 0.96        | 0.93        | 0.88        | 0.97        | 0.99        | 0.98        | 0.96        | 0.98        | 0.95        |
| Subject        | 10          | 11          | 12          | 13          | 14          | 15          | 16          | 17          | 18          |
| Accuracy model | <b>0.87</b> | <b>0.93</b> | <b>0.96</b> | <b>0.96</b> | <b>0.94</b> | <b>0.84</b> | <b>0.99</b> | <b>0.93</b> | <b>0.84</b> |
| Happiness      | 0.95        | 0.97        | 0.98        | 0.99        | 0.96        | 0.92        | 0.99        | 0.96        | 0.91        |
| Anger          | 0.90        | 0.99        | 0.98        | 0.99        | 0.99        | 0.89        | 1.00        | 0.96        | 0.93        |
| Fear           | 0.97        | 0.94        | 0.98        | 0.97        | 0.95        | 0.94        | 1.00        | 0.97        | 0.94        |
| Sadness        | 0.91        | 0.95        | 0.97        | 0.97        | 0.98        | 0.94        | 0.99        | 0.97        | 0.89        |

## 5 Conclusions

Results obtained in this study confirm that biosignals such as skin conductance, body temperature, and heart rate can be used to objectively and accurately identify different emotional states, thus validating the first hypothesis. Implemented neural network achieved a mean accuracy of 92% (intra-subject), supporting the second hypothesis that machine learning techniques, specifically neural networks, are effective for classifying emotional states from biomedical data.

Furthermore, system demonstrated superior accuracy and reproducibility when compared to traditional methods based on self-reports and questionnaires, affirming the third hypothesis. This outcome reinforces project's justification, as automatic detection system effectively reduces reliance on subjective evaluations, promoting a more accurate and objective approach to understanding and managing emotions.

Standardizing experimental protocol, using validated emotional stimuli (IAPS and IADS), and structured acquisition of physiological signals ensured robustness and consistency of results. These findings highlight potential of this system to be applied in mental health, education, and research, enabling continuous monitoring of emotional states and facilitating more personalized approaches in these fields.

In conclusion, successful implementation of this project demonstrates how biosignal-based emotion detection systems can bridge gap between scientific advancements and their practical application in everyday life.

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# Failure Detection in Continuous Glucose Monitors Using Transformers

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**Abstract.** In this paper, we propose a method for detecting failures in Continuous Glucose Monitors (CGMs) using Transformer-based neural networks. CGMs are critical for diabetes management, providing continuous glucose level readings. However, failures such as spikes, and loss of sensitivity can compromise the accuracy of these devices, posing risks to users' health. The Transformer architecture, known for its ability to process sequential data efficiently, to classify CGM signal segments and identify faults. The proposed approach is compared against classical methods such as Long Short-Term Memory, Multi-Layer Perceptron, and Support Vector Machines. The Transformer model achieved the highest F1-score, outperforming the other approaches. Our results demonstrate the potential of Transformers in improving fault detection in CGMs, ensuring more reliable diabetes management.

**Keywords:** Transformers · Glucose continuous monitor · Fault detection.

## 1 Introduction

Continuous glucose monitors (CGM) are at the forefront of the transformation of diabetes management, offering a revolutionary approach to monitoring blood glucose levels. Diabetes, a chronic condition affecting over 463 million adults worldwide (diagnosed) [17], is characterized by the body's inability to produce or effectively use insulin, leading to elevated blood glucose levels [14] [3]. Without proper management, diabetes can result in severe complications, including cardiovascular disease, kidney failure, and neuropathy [13]. Traditional methods of glucose monitoring, such as periodic finger-prick tests, are invasive, inconvenient, and provide only snapshots of glucose levels. In contrast, CGMs provide continuous, real-time readings of glucose levels throughout the day, enabling patients and healthcare providers to make more informed decisions about insulin dosing, diet, lifestyle adjustments, and providing continuous readings of glucose levels in blood throughout the day without relying on periodic finger prick tests [23].

CGMs work by using a small sensor inserted under the skin to measure glucose levels in the interstitial fluid. These sensors transmit data wirelessly to a

<https://doi.org/10.61728/AE20255312>



receiver or smartphone app, allowing users to track their glucose trends and receive alerts when levels fall outside predefined thresholds [1]. This continuous stream of data not only improves glycemic control but also reduces the risk of hypoglycemic and hyperglycemic episodes, which can be life-threatening. However, like any electronic device, glucose monitors can experience failures that affect the accuracy of measurements and put users' health at risk[11]. Failures such as spikes, loss of sensitivity, false detections can lead to unreliable data and potentially harmful treatment decisions [23]. These failures can arise from various factors, such as sensor degradation, electromagnetic interference, or improper insertion. For example, a sensor spike might result in an erroneously high glucose reading, prompting unnecessary insulin administration and increasing the risk of hypoglycemia. Conversely, a loss of sensitivity might lead to undetected hyperglycemia, leaving the patient vulnerable to long-term complications.

Early detection of glucose monitor failures is crucial to ensure the safety and efficacy of diabetes treatment. Traditional methods of fault detection, such as laboratory testing and visual inspections, can be costly, time-consuming and are not always reliable. In recent years, the use of techniques, such as transformers [18], Kalman filter [10], some nonlinear filters [12], k-medoids clustering algorithm [22], has been explored to improve fault detection in glucose monitors[25, 9].

A Transformer (attention-based encoder-decoder model) is a deep learning neural network architecture designed to process data streams, such as text, efficiently and in parallel [19]. It was introduced in 2017 in the article "Attention is All You Need." [20] and has revolutionized the field of Natural Language Processing (NLP) [8]. Unlike previous models, such as Recurrent Neural Networks (RNN) or Long-Term Memory Networks (LSTM), Transformers do not process sequences sequentially, but analyze all parts of the sequence simultaneously, which allows capturing long-term dependencies and complex relationships between elements [19]. Unlike convolutional networks, Transformers require minimal inductive biases in their design and are naturally suited as ensemble functions [6]. Transformers can be seen from three perspectives: architectural modification, pre-training, and applications [7]. Transformers are widely used in various areas, such as medical image synthesis/reconstruction, registration, segmentation, detection and diagnosis, as well as medical image analysis [4]. They are also used in the field of automatic language processing (ALP) and computer vision, for modeling time series data [21], among others. This article proposes a method for fault detection in continuous glucose monitors (CGMs) using Transformers due to its performance shown. The article is structured as follows: Section 2 is the methodology, Section 3 presents the experimental results obtained through confusion matrices. Finally, Section 4 concludes the paper and discusses possible future applications.

## 2 Methodology

Failure detection will be performed over a delayed vector of size  $d = 16$  containing the measurements of glucose sensor then input of the approaches is  $X = \{x_1, x_2, \dots, x_{16}\}$  and a binary output where one means without failure and zero means with failure. The transformer is compared against three classical approaches to classify, Long short-Term Memory neural network (LSTM) [5], Multi-Layer Perceptron (MLP)[16, 15], and Support Vector Machine (SVM)[2].

The dataset used is Shanghai\_T2DM presented in [24] which contains measurements of 100 patients for a period of 3 to 14 days with a sensing frequency of 15 minutes, measurements of a patient are shown in Fig.1.

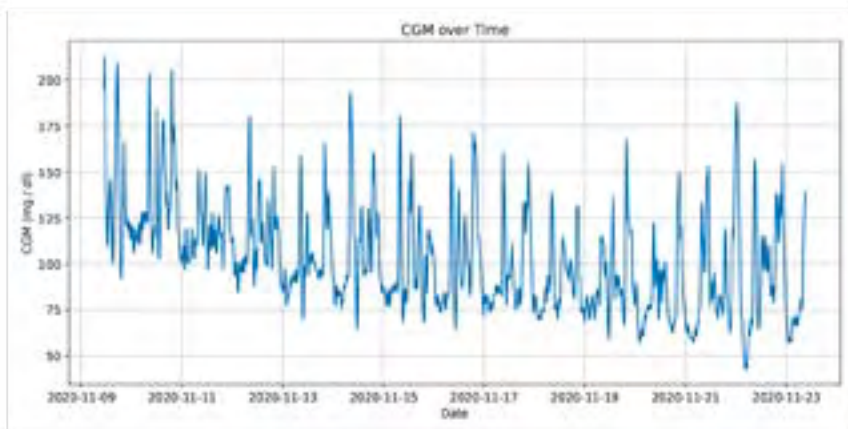


Fig. 1: signal of the CGM

Among the time series of some patients there are some instants that were omitted, to fill the measurements absent, the previous value was preserved. With the times series consistent three types of failures were generated artificially, noise, when it goes to zero and holding the previous value as is shown in Fig.2. Then a new dataset is produced forming vectors of size  $d$  taking all the measurements with their previous  $d - 1$  values. The previous dataset ends with 82,671 samples for training and 28,687 samples for testing. For the transformer the input embedding block was excluded as is presented in Fig. 3. Each one of the techniques were trained for 100 epochs with a binary cross entropy as loss function except for de SVM which uses a Kernel of radial base.

As the test dataset is unbalanced having 21487 without failure and 7200 with failure being an unbalanced dataset leading to problems such as the accuracy is not a reliable metric, the models tend to class with more samples more often since it may not learn the characteristics of the minority class properly. After fitting



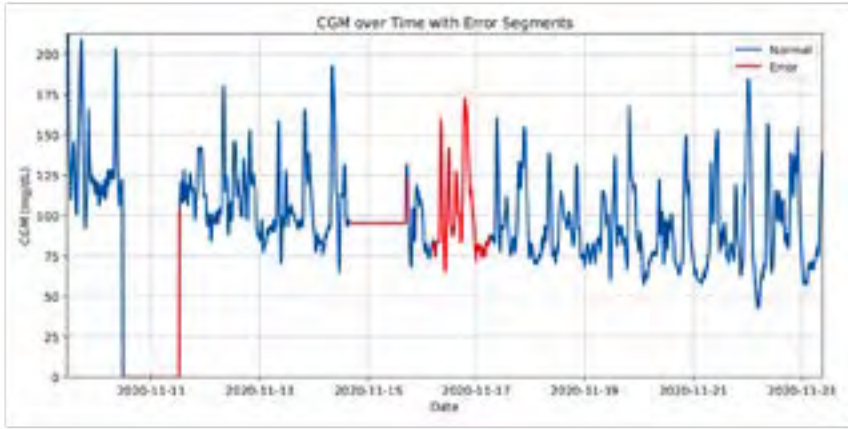


Fig. 2: Time series with artificial errors generated



Fig. 3: Blocks of the transformer

the model, the metrics of accuracy, precision also called positive predictive rate, recall named as true positive rate and F1 score were calculated according to

$$accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (1)$$

$$precision = \frac{TP}{TP + FP} \quad (2)$$

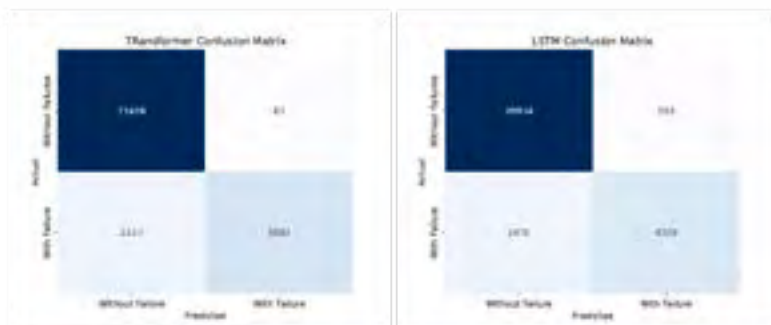
$$recall = \frac{TP}{TP + FN} \quad (3)$$

$$F1 - score = 2 \cdot \frac{precision \cdot recall}{precision + recall} \quad (4)$$

where TP is the number of correct samples classified as the class of interest in this case are the samples correctly identified as faults, FP are the samples of the other class incorrectly identified as the class of interest, FN is the number of samples incorrectly classified as which are of the class of interest but were classified as other class TN are the correct classification of no interest class.

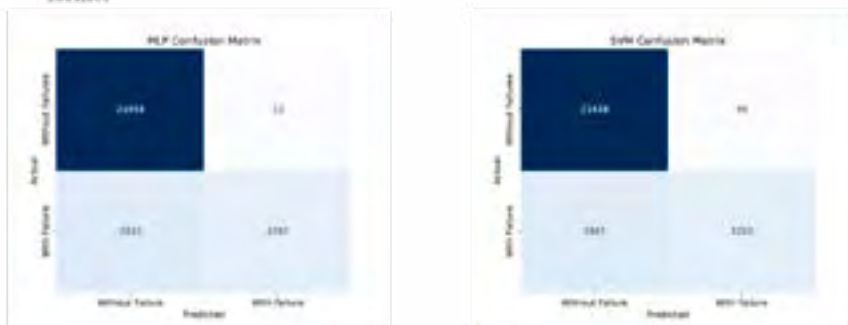
### 3 Results

To measure the performance of the classifiers, a test dataset consisting of 28,687 samples was used. The results were evaluated using confusion matrices, which provide a detailed breakdown of the model's predictions compared to the actual labels. These confusion matrices, shown in Fig. 4, summarize the performance of the algorithm and allow for further inspection of its effectiveness. To quan-



(a) Confusion matrix of the transformer

(b) Confusion matrix of the LSTM



(c) Confusion matrix of the MLP

(d) Confusion matrix of the SVM

Fig. 4: Confusion matrix of all approaches to identify failure

tify the performance of the classifiers, several key metrics were calculated from the confusion matrices: Accuracy measures the proportion of correctly classified samples out of the total number of samples. It is a general indicator of the model's overall performance. Precision indicates the proportion of true positive predictions out of all positive predictions made by the model. It reflects the model's ability to avoid false positives. Recall represents the proportion of true positives correctly identified out of all actual positives. It measures the model's ability to detect all relevant instances. F1 Score the harmonic mean of precision

and recall, providing a balanced measure of the model's performance, especially useful when dealing with imbalanced datasets.

The metrics calculated from the confusion matrices are presented in Table 1. The results highlight the following key findings: The transformer-based classifier achieved the best overall performance, with an F1 score of 0.8236. This score integrates both precision and recall, showing the model's ability to balance accurate predictions with comprehensive detection of positive cases. The transformer outperformed the other models in most metrics, showing an 8% improvement in F1 score compared to the second-best model. While the Multilayer Perceptron (MLP) achieved the highest precision among the classifiers, its overall performance was lower than the transformer. This suggests that the MLP is effective at minimizing false positives but may struggle with false negatives, as reflected in its lower recall and F1 scores. The remaining classifiers (e.g., LSTM, SVM) showed competitive results but were consistently outperformed by the transformer.

The superior performance of the transformer model can be attributed to its ability to capture complex patterns and dependencies in the data, particularly in sequential or time-series datasets like those generated by continuous glucose monitors (CGMs). Unlike traditional models, transformers take advantage self-attention mechanisms to analyze the entire sequence of data simultaneously, enabling them to detect subtle anomalies and long-term trends that other models might miss.

The MLP's higher precision indicates that it is more conservative in making positive predictions, which can be advantageous in scenarios where false positives are costly. However, its lower recall and F1 score suggest that it may miss some true positive cases, which could be critical in applications like fault detection in CGMs, where missing a failure could have serious health implications.

Table 1: Classification Metrics

| Approach    | Accuracy      | Precision     | Recall        | F1 Score      |
|-------------|---------------|---------------|---------------|---------------|
| Transformer | <b>0.9241</b> | 0.9881        | <b>0.7060</b> | <b>0.8236</b> |
| LSTM        | 0.8946        | 0.8953        | 0.6568        | 0.7577        |
| MLP         | 0.8617        | <b>0.9900</b> | 0.4537        | 0.6223        |
| SVM         | 0.8607        | 0.9852        | 0.4518        | 0.6195        |

## 4 Conclusions

The proposed method uses Transformer neural network architecture to effectively detect faults in CGMs. By analyzing segments of CGM time series, the Transformer model showed superior performance compared to traditional methods such as LSTM, MLP, and SVM, achieving an F1-score of 82.36%. This highlights the ability of transformers to capture complex patterns in sequential

data, making it a promising tool for improving the reliability of sensors. The results suggest that Transformers can play a significant role in enhancing fault detection systems, ultimately contributing to safer and more accurate diabetes management. Future work could explore the application of this approach to other medical devices and real-time monitoring systems.

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# Autoencoder with Differential Evolution Approach for Sensor Fault Detection in Robotic Manipulators

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**Abstract.** Fault detection is a topic of great relevance due to its importance in the control of various types of systems. In particular, the most common faults usually occur in actuators or sensors. This paper proposes the use of autoencoders for the detection of faults in the joint sensors of a robotic manipulator during trajectory tracking tasks. The proposed methodology addresses the identification of faults caused by disconnections, noise and blockage in the sensors of all the joints of the manipulator. In addition, a differential evolution optimization algorithm was implemented to select the optimal threshold that determines whether or not a fault occurs, which increases the accuracy of the system. The applicability of this approach is demonstrated by detecting faults in the sensors of a 5-degree-of-freedom (DOF) manipulator. The results obtained show that autoencoders are a powerful and versatile tool for fault detection in robotic manipulators, at least in most of their joints.

**Keywords:** Autoencoder · Robot manipulators · Fault detections. · Differential Evolution

## 1 Introduction

Robotics has transformed manufacturing, medicine and space exploration, driving the automation of complex, dangerous [19], [9] or repetitive tasks (such as pick and place, painting or welding) [21]. The production lines or tasks where they work often run for long periods of time, which means that both actuators and sensors are prone to failures. Sensor failures often result in noise, loss of information, skew, shunting, etc. [10]. The detection and diagnosis of these faults is crucial to avoid and prevent accidents, guaranteeing the safety of the processes being carried out, as well as of the people around them[18].

Traditional fault detection methods, based on threshold analysis and pre-defined rules, are often insufficient to detect subtle anomalies, incipient faults or intermittent faults [22], [16]. These methods can generate false positives or negatives, which can lead to unnecessary shutdowns or failure to detect critical faults.

<https://doi.org/10.61728/AE20255329>



Autoencoders are unsupervised artificial neural networks that learn representations of data by dimensionality reduction, encode and decode input data, capturing latent representations of the information [2], they are also capable of reconstructing missing signals using the remaining signals [8]. Their ability to model the normal distribution of data allows them to detect deviations and anomalies that may indicate the presence of sensor faults, in some cases they can eliminate noise [13], [1]. Some of the applications of autoencoders range from application in heavy mechanical equipment [22] or escalator bearing [12] [5], wind turbines [11], [23], hydraulic machinery [17] and maritime [7], improved Printed Circuit Board (PCB) designs [15] They are even used in nuclear and thermal power plants to detect single failures in multiple subsystems [14, 3] and in same way industrial robots [4].

This work proposes a sensor fault detection method for robotic manipulators using autoencoders. Unlike approaches based on Recurrent Neural Networks (RNN) or Convolutional Neural Networks (CNN), autoencoders do not require labeled data sets with and without faults, thus avoiding data imbalance problems that hinder training. In addition, the differential evolution algorithm is employed to optimize the threshold that determines the presence of faults, improving the F1-score, a particularly useful metric for unbalanced data sets. The effectiveness of the method is validated by detecting faults in position sensors on a 5-degree-of-freedom robotic manipulator during trajectory tracking tasks.

The article is structured as follows: Section 2 describes the differential evolution algorithm; Section 3 details the autoencoder architecture and threshold selection for fault detection; Section 4 presents the experimental results and Section 5 concludes the work.

## 2 Differential Evolution

Differential Evolution (DE) is a stochastic, population-based algorithm designed for global optimization. Each individual  $x_i$  in the population represents a candidate solution, where  $i = 1, 2, \dots, N$  and  $N$  is the population size. The algorithm improves solutions across generations through three key operations: **mutation**, **crossover**, and **selection**.

Mutation for each individual  $i$ , a mutant vector  $v_i$  is generated using:

$$v_i = x_{r1} + F(x_{r2} - x_{r3}), \quad (1)$$

where  $x_{r1}, x_{r2}, x_{r3}$  are randomly selected individuals ( $r1, r2, r3 \in [1, N]$ ) distinct from each other and from  $i$ . The parameter  $F \in [0, 2]$ , known as the *amplification factor*, scales the difference between  $x_{r2}$  and  $x_{r3}$ .

Crossover a trial vector  $u_i$  is created by combining components of the mutant vector  $v_i$  and the original individual  $x_i$ :

$$u_{ij} = \begin{cases} v_{ij} & \text{if } r_j \leq CR \text{ or } j = r_i, \\ x_{ij} & \text{if } r_j > CR \text{ and } j \neq r_i, \end{cases} \quad (2)$$

where  $CR \in [0, 1]$  is the *crossover constant*,  $j = 1, 2, \dots, D$  (with  $D$  as the problem dimension), and  $r_j, r_i$  are random numbers.

Selection the trial vector  $u_i$  is compared to the original vector  $x_i$  using an objective function  $f$ . If  $f(u_i)$  performs better than  $f(x_i)$ ,  $u_i$  replaces  $x_i$ ; otherwise,  $x_i$  is retained for the next generation.

For further details on DE and its variants, refer to [6], [20].

### 3 Methodology

Autoencoders are trained similarly to traditional Neural Networks, where the input and output are identical. The network learns to reconstruct the input as accurately as possible. The input is defined as  $X = \{x_1, x_2, x_3, \dots, x_d\}$ , where  $d$  is the vector size, and the output is  $\hat{X} = \{\hat{x}_1, \hat{x}_2, \hat{x}_3, \dots, \hat{x}_d\}$ .

The proposed autoencoder architecture, illustrated in Fig. 1, consists of an encoder and a decoder. The encoder comprises four layers, starting with 128 neurons and halving the number in each subsequent layer. The decoder also has four layers, beginning with 16 neurons and doubling the number in each layer, followed by the output layer. All neurons use hyperbolic tangent activation functions, except for the output layer.

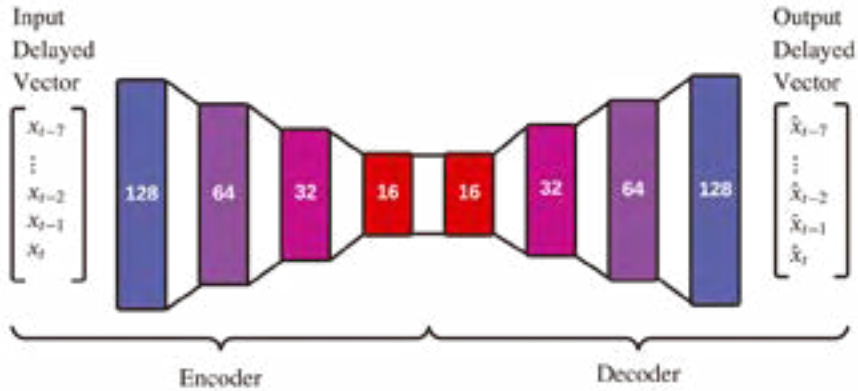


Fig. 1: Architecture of the autoencoder with size  $d = 8$  for the delayed vector.

For sensor fault detection in a 5-degree-of-freedom (DOF) robotic manipulator, the input vector for the autoencoder is constructed using the current joint measurement at time  $t$  and the  $(d - 1)$  previous joint measurements. The input vector for the  $i$ -th joint is defined as:

$$X_i = \{q_i^t, q_i^{t-1}, q_i^{t-2}, \dots, q_i^{t-(d-1)}\}, \quad (3)$$

where  $i = 1, 2, 3, 4, 5$  represents each joint. A separate autoencoder is used for



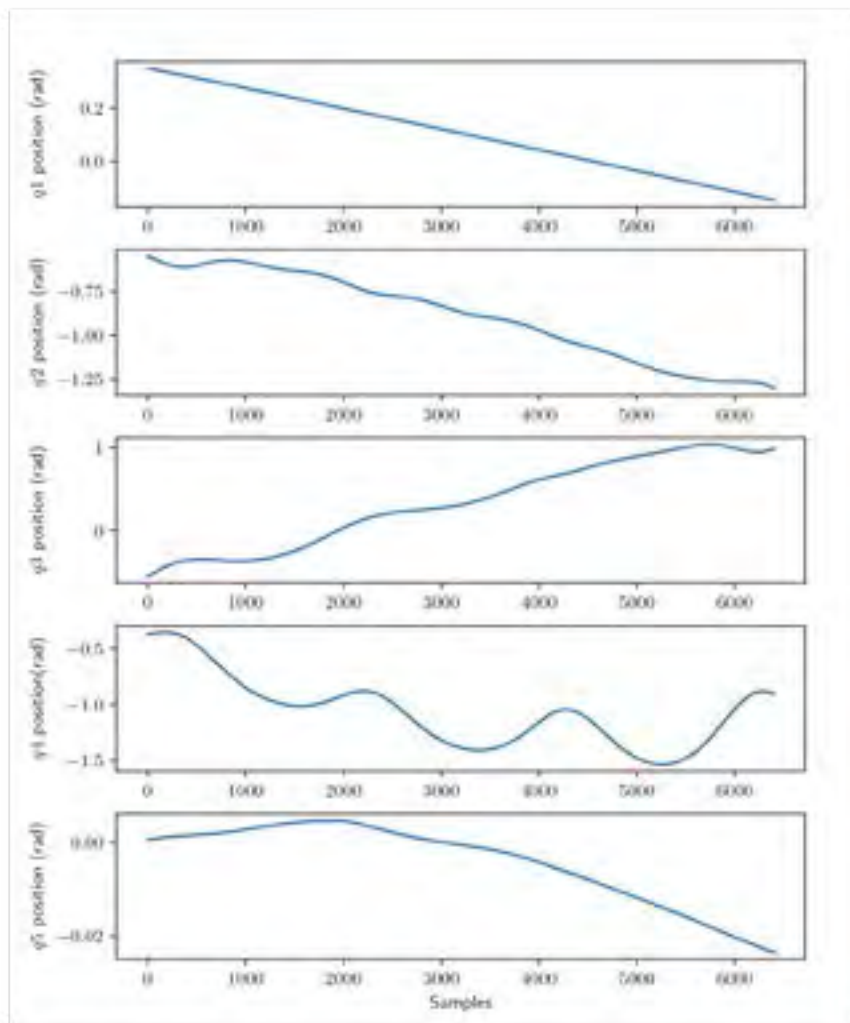


Fig. 2: The sensor measurements for each joint in the 5-degree-of-freedom (DOF) manipulator are represented as  $q_i$ , where  $q_i$  denotes the position measurement of the  $i$ -th joint ( $i = 1, 2, 3, 4, 5$ ).

each joint, all sharing the same architecture as shown in Fig. 1. During a successful trajectory tracking task, a dataset was created containing measurements from all 5 joint position sensors are illustrated in Fig. 2.

The autoencoders were trained using 6276 samples collected over sixty seconds of trajectory tracking, as shown in Fig. 2. The Mean Absolute Error (MAE) was used as the loss function, and the Adam optimizer was employed for training over 50 epochs. Several versions of the autoencoder were trained with varying input sizes ( $d = 4, 8, 16, 32$ ) to determine the optimal configuration. The loss function values during training for each epoch are presented in Fig. 3.

To identify the best input size  $d$ , four configurations ( $d = 4, 8, 16, 32$ ) were tested, aiming to determine which size yields the best performance.

Fault detection is performed by calculating the reconstruction error  $e$  between the input  $X$  and the output  $\hat{X}$ :

$$e = \sum_{j=1}^d |x_j - \hat{x}_j|. \quad (4)$$

A fault is detected when  $e > \alpha$ , where  $\alpha$  is a predefined threshold. This threshold determines whether the reconstruction error  $e$  is classified as a fault or not.

To select the optimal threshold value  $\alpha$ , the Differential Evolution (DE) algorithm is employed. The objective function  $f$  for this optimization is the F1-score, which is defined as:

$$\text{F1-score} = 2 \cdot \frac{\text{precision} \cdot \text{recall}}{\text{precision} + \text{recall}}, \quad (5)$$

where *precision* (positive predictive value) and *recall* (true positive rate) are calculated as:

$$\text{precision} = \frac{\text{TP}}{\text{TP} + \text{FP}}, \quad \text{recall} = \frac{\text{TP}}{\text{TP} + \text{FN}}. \quad (6)$$

Here, TP represents the number of correctly identified fault samples, FP denotes the number of non-fault samples incorrectly classified as faults, and FN corresponds to the number of fault samples incorrectly classified as non-faults.

The F1-score ranges from 0 to 1, where 1 indicates perfect precision and recall, and 0 indicates a complete failure in either precision or recall. The optimization problem is formulated as:

$$\arg \max_{\alpha} f(\alpha) = \text{F1-score}. \quad (7)$$

To solve this optimization problem, the DE algorithm is applied with the following parameters: 100 iterations, a population size of  $N = 30$ , an amplification factor  $F = 0.5$ , and a crossover constant  $CR = 0.3$ .

## 4 Results

To test the autoencoders three different types of faults are introduced via software (disconnection, loss of accuracy, and freeze). For q1 a freeze fault from the

instant 1000 to 1500, in  $q_2$  the data goes to zero from instant 1500 to 2000,  $q_3$  has a freeze from instant 4000 to 4500,  $q_4$  and  $q_5$  have noise (loss of accuracy) from instant 5500 to 6000 as is shown in Fig. 3.

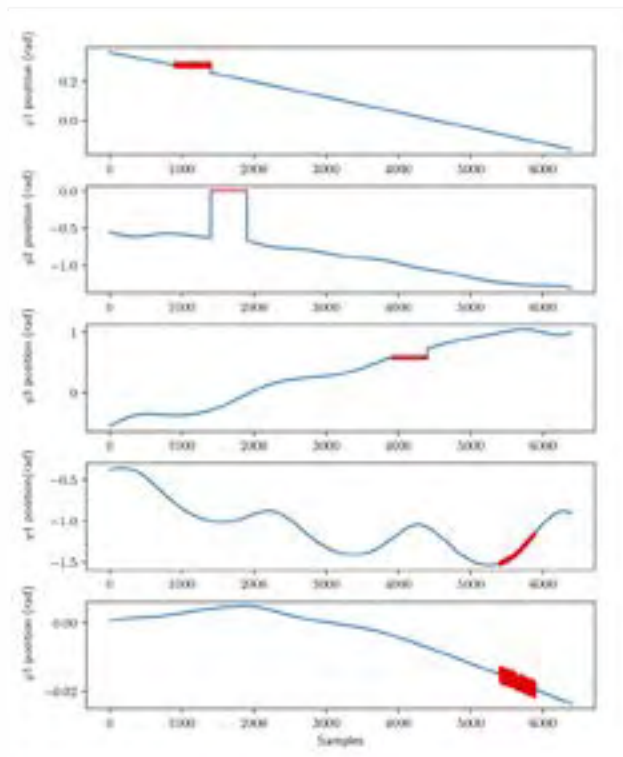


Fig.3: Signals with fault

The results of applying DE and varying the size of the delayed vector to select the optimal threshold and size of the input are shown in Table 1 getting that for  $q_1$  the size selected is eight and the best threshold  $\alpha$  is 0.0136 to get a precision, recall and F1-score of 0.9861, 1 and 0.993 respectively for the classification of the fault which can be confirmed with the confusion matrix presented in Fig. 4a. For the joint  $q_2$  the threshold  $\alpha$  value is 0.2229 and the input size is equal to 4, obtaining metrics of precision = 0.994, recall = 1, and F1-score of 0.997 according to Fig. 4b. For these two joints as the recall shows all the faults were correctly detected.

Table 1: Results of the threshold  $\alpha$  obtained with DE and their F1-score. Bold letters indicate the best results.

|      |          | Delayed Vector Size $d$ |               |               |        |
|------|----------|-------------------------|---------------|---------------|--------|
|      |          | 4                       | 8             | 16            | 32     |
| $q1$ | $\alpha$ | 0.0234                  | <b>0.0136</b> | 0.0918        | 0.1751 |
|      | F1-score | 0.570                   | <b>0.9930</b> | 0.7725        | 0.7751 |
| $q2$ | $\alpha$ | <b>0.2229</b>           | 0.2229        | 0.2229        | 0.2409 |
|      | F1-score | <b>0.9970</b>           | 0.9930        | 0.9852        | 0.9354 |
| $q3$ | $\alpha$ | 0.0367                  | 0.0830        | <b>0.1446</b> | 0.3692 |
|      | F1-score | 0.7339                  | 0.3153        | <b>0.9183</b> | 0.3133 |
| $q4$ | $\alpha$ | 0.0440                  | 0.0622        | <b>0.1307</b> | 0.2377 |
|      | F1-score | 0.5601                  | 0.9630        | <b>0.9810</b> | 0.9701 |
| $q5$ | $\alpha$ | 0.0014                  | <b>0.0037</b> | 0.0109        | 0.0279 |
|      | F1-score | 0.9744                  | <b>0.9929</b> | 0.9890        | 0.9777 |

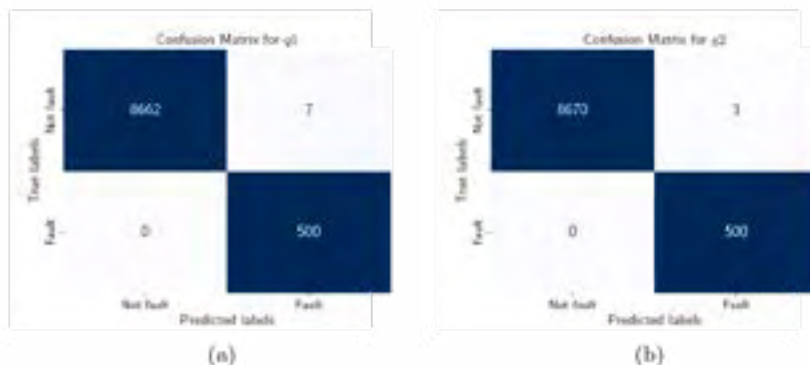
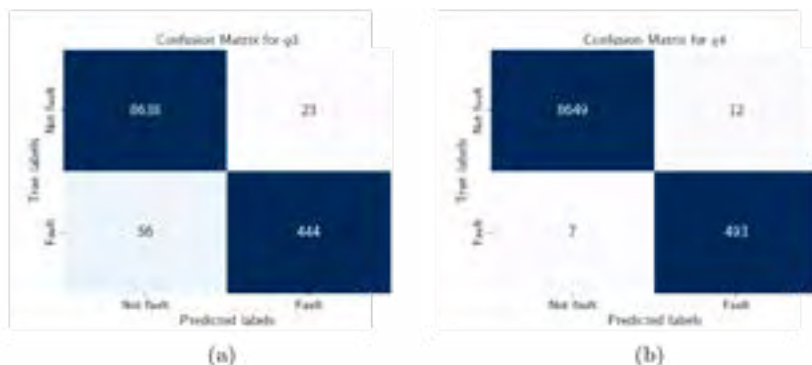
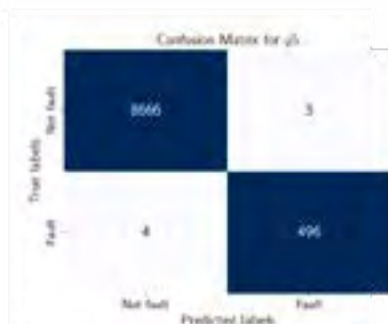


Fig. 4: Confusion Matrix for  $q1$  and  $q2$

For the signals of  $q3$  and  $q4$  the size of the input chosen is 16 having an F1-score of 0.918 and 0.981 with a threshold of 0.1446 and 0.1307 respectively. As is shown in Table 1  $q3$  got the lowest scores among all the joints, even when the F1-score is up to 0.9 the recall is 0.888 according to results shown in the Fig. 5a which could be due to the fact that it is the signal that does not have a noticeable trend or periodicity, and the size of the input could lead to a larger error without actually having a failure. In the case of  $q4$  there is no such a problem as with  $q3$  just that not all the faults were detected as can be seen in Fig. 5b.

For  $q5$  the selected threshold value is 0.0037 being the lowest of all the joints. This threshold gets the metrics of recall and precision of 0.992 and 0.993 respectively according to the confusion matrix in Fig. 6, which represents that less than 1% of the samples with failures were not detected, at the same time less than 1% of the samples without failure were considered failures,



Fig. 5: Confusion matrix for  $q_3$  and  $q_4$ Fig. 6: Confusion matrix for  $q_5$ 

## 5 Conclusion

The fault detection is a significant topic of interest in broad real-world applications. Neural networks prove to be a powerful tool able to obtain characteristics of the observed data to recognize healthy samples and samples with fault. The proposed approach implements a neural network architecture called autoencoder to get a model that can get the characteristics of the signal and with the part of the decoder reconstruct it with minimal error. In this case to reconstruct the signal of five joints rotation of a robot manipulator. It is noticeable all the autoencoders have the same quantity of inner layers with different input and output layers, since some sizes could not have enough values to be representative of the signal. With the addition of the optimal threshold selection made by the Differential Evolution algorithm for all the joints and sizes of the delayed vector lead to achieving the distinction of faults with F1-scores of at least 90% for all the joints of the robot.

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# Drivers Attention Detection Based on Quantized Convolutional Neural Network

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**Abstract.** There are a lot of reasons why a road accident happens, including road conditions, weather, car failures and human errors among others, that aren't easy to avoid or prevent, that's why in the last decade the technology has gained a main role when it comes to avoid these accidents as the Advance Drivers Assistance System or ADAS, where some of these technologies try to minimize road accidents due to lack of attention of the drivers on the road by detecting whether the driver is drowsy or distracted and notify him. However, not all vehicles are equipped with such systems. This paper presents a cost-effective and straightforward solution by implementing a quantized Convolutional Neural Network (CNN) on a low-cost module, achieving an accuracy of 86.7% of accuracy.

**Keywords:** CNN · Drivers Attention · Low-cost

## 1 Introduction

Whenever a traffic accident occurs, it not only puts the driver in danger, but it also puts those around them at risk, including other drivers, passengers, pedestrians, and cyclists. According to the 2017 Annual Road Safety Report, traffic accidents claim approximately 1.3 million lives worldwide each year, and an estimated 50 million people suffer serious injuries. Among the most vulnerable victims are the elderly, pedestrians, cyclists and motorcyclists [5].

Over the last decade, technology has taken a main role in preventing road accidents, a clear example of this is the Advance Driver Assistance System, or ADAS for short, which consists of the integration of sensors, mechanisms, algorithms, and even machine learning to give feedback to the driver about possible dangers or even take the control of the car to prevent these dangers [6][8].

In the field of machine learning, convolutional neural networks (CNN) are powerful algorithms for extracting features from structured data, particularly images. They are very effective in detecting and classifying objects, making them applicable to a wide range of fields, including automation, facial recognition, home security, and mores [7]. Since the introduction of classical CNNs, newer and more advanced architectures such as LeNet-5, AlexNet, VGGNet, and ResNet

<https://doi.org/10.61728/AE20255336>





have significantly improved the efficiency, performance, and accuracy in image recognition [1]. These advances have contributed to the increasing importance of object recognition in various real-world applications over the years.

The performance of CNNs depends not only on the training process but also on the hardware specifications they run on. CNNs can be deployed on various types of hardware, including high-performance GPUs, desktop or high-end CPUs, edge/mobile GPUs, FPGAs, and microcontroller units (MCUs), each with its own advantages and limitations [2]. While many hardware alternatives, such as high-end GPUs, desktop computers, and even less powerful microprocessors like the Raspberry Pi, are capable of handling large and complex CNN models, they can be unnecessarily expensive and impractical for certain applications. Running CNN models on microcontrollers presents a challenge due to their hardware limitations; however, it is still feasible. Despite this, microcontrollers are often regarded as a non-viable alternative for running high-performance AI models like CNNs due to their constrained processing power and different intended use cases.

Thanks to open-source machine learning frameworks like TensorFlow Lite Micro, it is now possible to run AI models on microcontrollers, even though their capacity and processing power are significantly lower compared to other types of hardware [3]. The ESP32 is one of the most suitable options for this purpose, primarily due to its hardware capabilities and the use of quantization techniques to optimize AI models for low-power execution. However, despite its potential, the integration of AI into microcontrollers has yet to be widely applied to critical real-world scenarios, such as driver drowsiness and attention detection. This is why deploying a CNN on a low-cost microcontroller equipped with a camera sensor, such as the ESP32-CAM, could provide a practical solution to alert drivers when they become distracted or fatigued. Additionally, it could demonstrate the feasibility of integrating AI with microcontrollers, expanding their application in safety and real-time monitoring systems.

This paper aims to review existing AI-based alternatives and projects designed to address real-world problems, particularly car accidents caused by human errors such as distraction or drowsiness while driving. It will compare the setup requirements and effectiveness of these solutions and explore how the ESP32-CAM, combined with a CNN model, could serve as a viable alternative. Additionally, the paper will detail the development process for locally running a pre-trained CNN model on an ESP32-CAM, covering the tools and techniques used. Finally, it will present the overall testing results, evaluate the performance of the system, and discuss potential improvements for future iterations of the project.

## 2 Related Work

One of the most versatile sensors used in ADAS is the camera, which can monitor both the vehicle's surroundings and its interior. In some cases, cameras are also used to detect driver behavior, such as eye blinking or head movements, to

determine whether the driver is distracted and needs to stop [6]. These and other technologies are primarily integrated by car manufacturers. While some external installations are relatively easy and affordable, others require significant modifications and come at a much higher cost.

When it comes to detecting driver drowsiness, there are three general approaches: vehicle-based, behavioral-based, and physiological-based. Among the proposed detection techniques are steering wheel movement monitoring using sensors, head tilt angle and blink rate analysis through cameras, and electroencephalogram (EEG) or heart rate monitoring [10]. Drowsiness detection should not only be non-intrusive but also ensure that the driver is effectively alerted without increasing the risk of an abrupt reaction—such as one caused by a sudden loud alarm—which could compromise safety.

There are ongoing studies and research efforts focused on developing new technologies and techniques to enhance Advanced Driver Assistance Systems (ADAS), particularly in estimating driver attention. These approaches analyze various factors, such as gaze direction and eye tracking, using eye shape detection and head pose estimation. To achieve this, multiple cameras and sensors are combined with machine learning algorithms, including fuzzy logic, neural networks, Bayesian networks, and supervised, semi-supervised, and unsupervised learning techniques, among others, to assess the driver's awareness of their surroundings [8]. While these technologies demonstrate significant potential, some face technical and practical limitations. For example, the use of sunglasses can interfere with eye tracking and shape detection, making it more challenging to accurately monitor driver attention.

There is a clear gap between a simple CNN running on a device like the ESP32 and the combination of advanced algorithms and AI techniques running on high-performance hardware. However, in terms of cost and accessibility, the ESP32-CAM presents a viable alternative for vehicles without built-in ADAS technology, providing an additional layer of safety while driving. With its easy setup and affordability, it offers a practical solution for enhancing driver awareness and road security.

### 3 Methodology

This section will outline the key steps and processes involved in the development of the project. It will include a brief review of the hardware and software components used, along with the tools selected. Additionally, it will cover the training process of the CNN model, the quantization of the model, and its deployment on an ESP32-CAM.

#### 3.1 Hardware and Software Overview

The main component of this project is the ESP32-CAM module, which features a 2MP OmniVision OV2640 camera, as shown in Fig. 1. This module includes a built-in ESP32 microcontroller unit (MCU), which is powered by a

dual-core 32-bit processor running at 240 MHz. It has 448 KB of ROM, 520 KB of SRAM, and supports Wi-Fi (802.11n, 2.4 GHz, up to 150 Mbps) and Bluetooth (v4.2 BR/EDR and Bluetooth LE), among other features [4]. The ESP32-CAM was selected over other alternatives due to its hardware capabilities and ease of programming. For programming the module, the ESP32-CAM-MB board can be used, which includes a built-in CH340G USB-UART chip for serial communication via micro-USB/type-C. Alternatively, a general USB serial FTDI programmer, as shown in Fig. 2 can also be used. The data pre-processing, model architecture, training, validation, and quantization were conducted on a TensorFlow/Keras GPU-enabled workstation. The binary quantized model was generated by converting a TFLite file into a .h file using a Git-Bash command. Finally, the model deployment on the ESP32 was carried out using the MicroTFLite library within the Arduino<sup>1</sup> IDE.



Fig. 1. ESP32-CAM Front and back.

**3.2 Data Pre-Processing And Model Architecture** A CNN model requires a dataset for training, so the first step was to collect representative data using the same hardware intended for testing. With the help of Arduino libraries, a dataset of 2,986 images was gathered. Leveraging the Wi-Fi capability of the ESP32-CAM, the microcontroller was connected to a home network, where the router assigned an IP address, allowing easy access from a PC. This setup enabled local image storage, with the images automatically categorized into three separate folders, each containing approximately 1,000 representative samples. The categories were labeled as focused driver, distracted driver, and drowsy driver, as illustrated in Fig. 3.

<sup>1</sup> Arduino is a registered trademark of Arduino AG. Hardware and software are available under open-source licenses. All rights reserved.





**Fig. 2.** Communication modules.

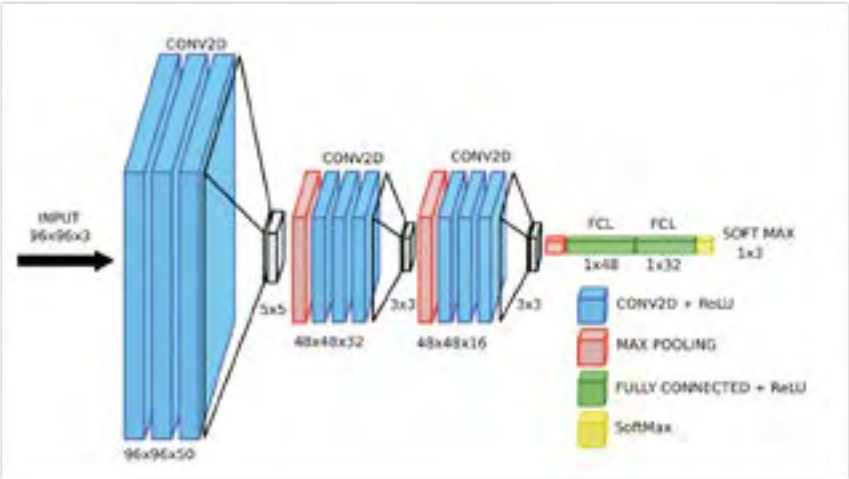


**Fig. 3.** Set of labeled images taken from the train dataset.

With the collected representative data, a CNN model can be built and trained. To achieve this, a model architecture is required, either based on an existing design or a custom-made one developed using empirical criteria. The custom approach was chosen over pre-existing models to allow optimization for the limited memory space available on the MCU. The selected architecture is shown in Fig. 4. Before training, the dataset must be divided into three subsets to ensure proper training and validation: The largest portion of the dataset is allocated



for training, providing the model with sufficient examples to learn from. Half of the remaining dataset is used as a validation set during training. This subset is essential for evaluating the model's performance at the end of each epoch, helping to detect overfitting and guiding necessary hyperparameter adjustments. The other half is reserved for final validation, used to assess the overall performance of the model once training is complete.



**Fig. 4.** Model Architecture (241,131 total parameters).

An additional technique to prevent overfitting is data augmentation, which involves generating new data from the existing dataset by applying reasonable modifications based on the study case. This process includes mirroring images along different axes, adjusting brightness, applying edge-enhancing filters, rotating images, and other transformations to increase the diversity of the training dataset. In Table 1 presents all the transformations applied to the training dataset, which initially comprised 2,090 images (70% of the original dataset). After applying data augmentation, the dataset size increased by 60%, resulting in a final training set of 3,344 images.

**Table 1.** Augmentation Transformations.

| Transformation Type            | Range      | Probability |
|--------------------------------|------------|-------------|
| Horizontal Flip                | Y mirror   | 60%         |
| Random brightness and contrast | $\pm 20\%$ | 60%         |
| Sharpen                        | 50% - 100% | 60%         |

3.3 Model Training And quantization

The model was trained using 3,344 samples for training and 448 for validation, with a custom-scheduled learning rate for each epoch. Initially, a constant learning rate of 0.0001 was maintained for the first 38 epochs. In subsequent iterations, the learning rate was configured to decrease exponentially, scaled by a factor of 0.05, as an additional measure to prevent overfitting. To monitor model performance throughout training, a metric list was set up to track categorical cross-entropy loss and validation loss, alongside categorical accuracy, validation accuracy, recall, and precision. The loss function and accuracy trends over the epochs are presented in Fig. 5 and Fig. 6 respectively.

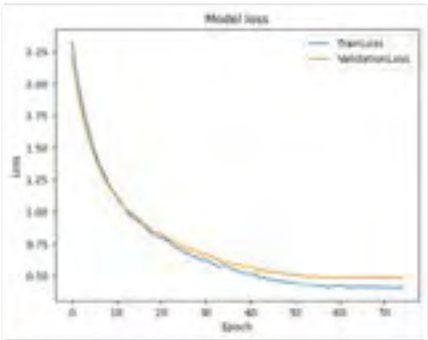


Fig. 5. Model loss and validation loss evolution per epoch.

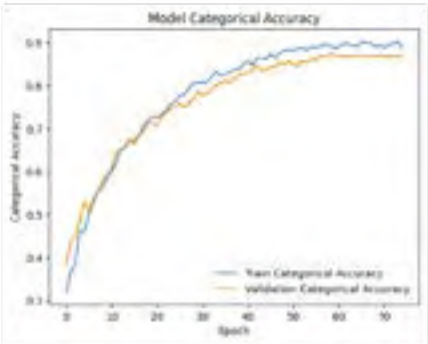


Fig. 6. Model categorical accuracy and validation categorical accuracy evolution per epoch.

The quantization process must be properly configured to generate a model compatible with the target device, in this case, the ESP32. Due to the ESP32's data management and processing limitations, it is necessary to define the input and output types of the quantized model, as well as the format in which operations are performed. In this case, all operations are set to int8 to optimize performance. Additionally, the custom quantization process for the ESP32 architecture requires a set of representative data from the test dataset to improve the model's efficiency. This step follows a procedure similar to validation in the original model training, ensuring the quantized model retains its accuracy while being optimized for deployment on the ESP32.

### 3.4 Quantized Model Deployment

Once the model is converted into a .tflite file, it must be transformed into a binary array to be loaded into the ESP32-CAM's memory. This can be accomplished using Git Bash with the following command: `xxd -i model.tflite > model.h`. This command generates a binary equivalent of the model, which can then be copied and pasted into a designated memory space on the ESP32. The model is then passed to the interpreter provided by the MicroTFLite library in the Arduino IDE for execution. The MicroTFLite library includes a basic example demonstrating its use with a simpler model that predicts the sine function directly on the ESP32. The implementation for this project was based on that example, adapting it for the CNN model.

## 4 Results

This section will evaluate the overall performance of both the original trained model and its quantized version. It will present the confusion matrix, along with an analysis to determine recall, precision, and F1-score for each category, as well as the overall accuracy of the quantized model based on validation dataset testing.

As a first approach to assess model performance, a small sample set from the test dataset was used to compare the model's predictions with their true labels. As shown in , 7 the model successfully predicted the correct labels for most of the sample set. Additionally, it demonstrated the ability to recognize diverse facial patterns, including different perspectives, hairstyles, the presence of glasses or hoods, and varying distances from the camera. This indicates good generalization capability. However, the model exhibited some confusion between the "drowsy" and "distracted" categories, highlighting the need for a confusion matrix analysis to further assess its classification accuracy and potential areas for improvement.

A confusion matrix is a graphical representation that illustrates the final performance of a model by comparing its predicted labels against the true labels from an unseen dataset that was not used during training. From this matrix, key performance metrics such as precision and recall can be derived. Precision represents the percentage of correct predictions relative to all instances recognized



Fig. 7. True and prediction comparing on a small set of samples from the test dataset.

by the model. Recall represents the percentage of correct predictions relative to all actual instances of that class in the dataset. Using precision and recall, a general performance metric, the F1-score, can be calculated. This metric provides a balanced evaluation of the model's accuracy, with a higher value (closer to 1) indicating better performance [9]. Since the model classifies samples into one of three categories, these metrics must be computed for each class separately to assess how well the model distinguishes between them. The performance metrics for the model are presented in Table 2 based on the data from the confusion matrix in Fig. 8.

Table 2. Classification metrics.

| Category   | Precision | Recall | F1-score |
|------------|-----------|--------|----------|
| Attention  | 0.888     | 0.931  | 0.909    |
| Drowsy     | 0.882     | 0.789  | 0.833    |
| Distracted | 0.874     | 0.926  | 0.899    |



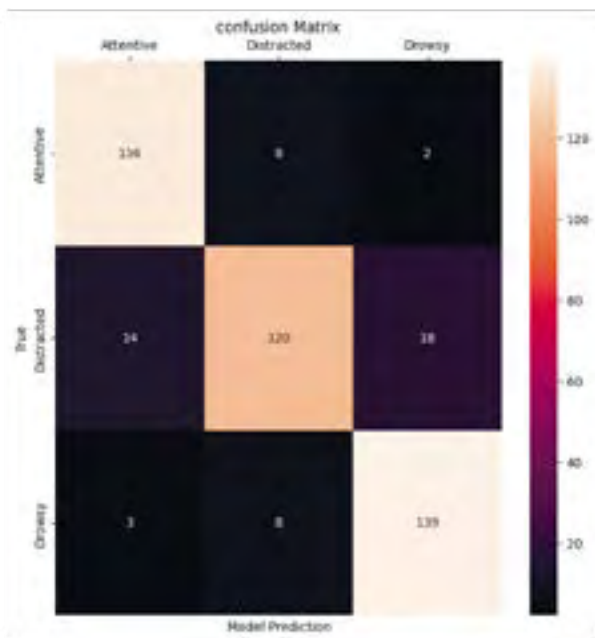


Fig. 8. Confusion matrix from test validation.

The performance evaluation of the quantized model was conducted by calculating its accuracy on the same test dataset used to assess the original model. The quantized model achieved an accuracy of 0.867. Based on this result, the model was deployed on the ESP32-CAM for real-world testing. Under similar conditions to those in the test dataset, the model's performance remained consistent, closely matching the calculated accuracy.

## 5 Conclusion

This study tested the implementation of quantized models on microcontrollers to evaluate their potential as a cost-effective and versatile alternative to certain ADAS technologies for inferring driver attention status. The proposed model achieved an 86.7% accuracy on unseen data, and the deployed version running locally on the ESP32-CAM demonstrated performance close to the estimated accuracy. For future improvements, considerations will include expanding the dataset to increase diversity and size, as well as exploring alternative model architectures to further enhance robustness and improve the reliability of the system.

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# Laparoscopy Smart Tracking Camera (TrakingScope)

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**Abstract.** Laparoscopic surgery is a minimally invasive technique that improves patient recovery, reduces post-surgical complications, and enhances precision. However, these procedures require an additional assistant to control the laparoscopic camera, which can be inefficient and increase fatigue for medical personnel. This paper presents an autonomous robotic arm that enhances control in laparoscopic surgeries by eliminating the need for a human camera assistant. The proposed system employs an advanced computer vision-based tool tracking method, ensuring continuous and precise tool centering in real time. Unlike existing solutions such as the da Vinci Xi system, this approach leverages a low-cost, efficient, and adaptable mechanism for various laparoscopic procedures. The system integrates real-time object detection using YOLO and OpenCV, coupled with a robotic arm programmed to follow surgical tool movements. Our experimental results demonstrate improved camera stability, reduced procedural time, and enhanced surgeon comfort. This innovation represents a step towards intelligent surgical assistance systems, bridging the gap between autonomous robotics and minimally invasive procedures.

**Keywords:** Laparoscopic Surgery, Robotic Arm, Autonomous System, AI in Surgery, Medical Image Processing, Tool Tracking

## 1. Introduction

The area of Laparoscopy is a complex area that presents several challenges, but in turn also brings with us quite advantages such as for example that the surgeries that are minimally invasive which leads to a better recovery since the surgeons employ methods which cause less damage therefore this quick recovery is given and effective. As a result, the patient also gets a shorter hospitalization, it also has the flexibility of patient treatment, since the patient can be external or internal (depending on the doctor's instructions).

<https://doi.org/10.61728/AE20255343>





For this examination, you will be given drugs through an IV in order to induce general anesthesia. During the procedure, you will have a tube in your throat that connects to a respirator. A small incision is made in the abdominal wall near the navel, where the laparoscope is placed. A small volume of gas is injected into the abdomen to expand it and facilitate observation of organs. We also have the option of making smaller incisions in the lower belly to insert various cutting instruments for removal or biopsies in abnormal areas, which are then examined in the laboratory.

The performance of the individual assisting the physician with the camera must be extremely precise, serene and anticipate the doctor's movements, since it is he who provides vision to the physician during the operation. Therefore, you must maintain effective but not overly noisy communication so that the doctor can focus and have all these attributes, while also taking time to understand how each specialist physician and each physician operates.

There are currently different types of image formats that help to have a wider vision, higher contrast attenuation to be able to see the colors more vivid and can differentiate organs and tissue in a better way, but there is no mechanism or device to keep an eye on the clamps in the surgical area

Which brings us to work on this smart image capture device, it is planned to carry out thanks to an endoscope of training which are similar to the professional cameras used in the operations of minimal invasion that adapts to a program in python, thanks to its libraries of image capture, in this way the camera captures the colors and the shape of the tongs and in that way sends the signal to the motors of the robotic arm which will know thanks to the image where they have to move so that the camera does not lose sight of the tongs, in turn we realize that no such sudden movements are required since being an operation of minimal invasion the space is reduced by it the camera is of zero vision degrees so that the movements are subdued therefore one has the desired vision without the need for have a very large chamber or attachments that make it possible to comply with the regulations established by NOM-006.the robotic arm is so large that it can hinder the doctor's movements

## **2. Related with the project**

The work carried out in the area of laparoscopy is extremely important so care must be taken all details to have many precautions when creating any device that has to do with this area so any device that fits this area brings improvements to make the performance of surgeries as for example the most famous device that has today is the da Vinci Xi. The da Vinci Xi is widely recognized for its high-definition 3D vision, which provides surgeons with a detailed view of internal organs and anatomical structures during interventions. This system, illustrated in Figure 1, allows for greater precision in

laparoscopic procedures while minimizing the surgeon's hand tremor through robotic-assisted movements. This high definition and 3D image allows for greater precision and control during operation, among its other great contributions is the precision of the da Vinci Xi system device that allows surgeons to manipulate surgical tools with a precision that is not possible with the human hand alone despite the great pulse control that can reach to obtain specialists in this area; is a robotic platform with robot arms which are very flexible and allow precise movements in angles and directions that would normally be difficult to achieve with conventional techniques [1].

It is equipped with four robotic arms mounted on a mobile trolley that is positioned over the patient (although not all of them are used simultaneously in each surgery). These arms have multidirectional joints, allowing them to mimic and improve the movements of the human hand. Specialized surgical instruments such as tweezers, scissors, scalpels or cameras are placed at the ends of the arms. These instruments are interchangeable depending on what the surgery will require or what the doctor in charge of this, The surgeon controls the robotic arms from an ergonomic console remotely, observes the surgical field in high-definition 3D and uses special controls to move the arms, the surgeon's movements are translated in real time to robotic arms, but with filters that eliminate tremors and allow smoother and more precise movements



Figure 1. The da Vinci Xi robotic surgical system, known for its high-precision control and 3D visualization capabilities. *Source: Adapted from Abex Systems.*

Speaking more specifically of mink, a camera is placed in one of the 4 available arms and this arm is the one that serves as the role of "guide arm" which is extremely important because without the vision of the camera they only have 3D vision and lose a very important part of the whole system that makes up the da Vinci Xi [2].

#### **High-definition resolution with contrast**

Endoscopic camera system with intelligent vision which defines with color contrast uses the latest system developed by Mindray that is the UX5 series 4K/NIR, Integrates the next generation hardware platform with novel software algorithms greatly increases image performance. Autofocus, automatic scene recognition and intelligent image algorithm work together to present high-quality images. The Mindray UX5 system

provides a 4K imaging experience with Near-Infrared capabilities, making it an essential tool for laparoscopic procedures (Figure 2). Advances in fluorescence imaging technology make hidden lesions and stained boundaries truly visible, allowing for more precise surgical navigation.

#### **Ultra-high fluorescence sensitivity**

The dual excitation and image optimization reduces the sensitivity of the fluorescence signal capture at the level of the nanomoles, which favors the clinical detection of small metastatic lesions at low doses and offers a higher penetration capacity at the same dose.

These improvements in vision are very useful when we can do the suture which provides us with a better performance thanks to the different contrasts that can be applied depending on the required need [3].



Figure 2. The 4K/NIR Mindray Series UX5 laparoscopic imaging system, featuring intelligent vision, autofocus, and fluorescence imaging technology for enhanced surgical navigation. Source: Adapted from [Mindray](<https://www.mindray.com/mx/products/laparoscopic-products/hypixel-ux5>).

### **3. Description of project development**

Our project takes care of the area that is not yet explored much which is to focus more on the help of the surgeon's concentration by reading vision and signals sent from the image captured by the camera that has the program designed in python that we allows by image capture recognize the tweezers we want to follow at all times of surgery and for that we take into account all the equipment that can be required in the space of minimal invasion and do not alter the processes just like the rules already established.

We have enough and varied equipment in Laparoscopic, but for this the patient should already be prepared for surgery therefore had to follow the instructions already indicated as not to eat food before the surgery as well as avoid drugs marked as analgesics.



The surgeon makes a small incision below the navel, which involves the insertion of a needle or hollow probe known as a trocar. Carbon dioxide is supplied to the abdomen through the probe or needle. The gas helps to enlarge the area, giving the surgeon more space for his work and allowing him to visualize the organs more clearly.

A small video camera (laparoscope) is inserted through the trocar and used to examine the inside of the pelvis and abdomen. Smaller incisions are possible if other instruments are required to improve vision in some organs [4].

### **Optical and display equipment**

**Laparoscope:** A laparoscope is a surgical instrument used to observe the inside of the abdominal and pelvic cavity during surgery.

**Cold light source:** Cold light lamps use a halogen or xenon light source and are designed to provide cooler light that reduces heat emission and prevents tissue dehydration

**High definition monitor:** is display equipment whose main function is to show clear texts and images for any health professional.

### **System of inflating**

**CO2 Insufflator:** It is a general purpose insufflator unit for use in laparoscopic examinations and operations. Controlled insufflation of the peritoneal cavity is used to achieve the required working space for laparoscopic surgery by stretching the antero-lateral abdominal wall and depressing the hollow organs and soft tissues.

**Inflator tube:** A device that connects the inflator with the inflator trocar to administer CO<sub>2</sub>.

### **Access and surgical ports**

**Trocars:** Is a pen-shaped instrument with a pointed triangular tip at one end, typically used inside a hollow tube, known as a cannula or sleeve, to create an opening in the body through which the sleeve can be inserted, to provide an access port during surgery.

**Sealing valves:** Prevent CO leakage through the trocars.

### **Laparoscopic instrumental**

**Laparoscopic Forceps:** The intestinal laparoscopic forceps, also known as intestinal forceps, are a form of gripping instrument designed to safely manipulate delicate abdominal tissue during laparoscopic procedures. One of its main functions is to facilitate



proper access to the surgical site by keeping the intestinal tissue free from the operating field.

**Laparoscopic scissors:** A disposable laparoscopic instrument with ratchet function when opening and closing for greater control and comfort of the surgeon.

**Electrocautery:** A device that cuts and coagulates tissues using electrical current or ultrasound.

**Hemostatic clips or sutures:** Materials used to close blood vessels or tissues without the need for traditional sutures.

**Dissectors and separators:** Instruments that allow separate anatomical structures without damaging them.

**Vacuum/irrigator:** A device that sucks liquids and allows the abdominal cavity to be washed during surgery.

**Surgical table and hinged arms:** Adjustable surface where the patient is positioned to optimize surgical access [5].

Laparoscopes are essential tools in minimally invasive surgeries, providing high-definition visualization of the surgical field (Figure 3). These devices allow surgeons to navigate through narrow spaces with precision, reducing patient trauma and improving recovery time.



Figure 3. High-definition laparoscope used in minimally invasive surgeries. These devices provide enhanced visualization and precision. Source: Adapted from [St-Endoscopia](<https://st-endoscopia.es/productos/endoscopia-rigida/familia-opticas-rigidas/laparoscopios/laparoscopio-hd/>).

The impact of our project can help people to reduce the concerns they may have when having to resort to an operation of this type, because people feel more relaxed if they know that the process is more automated and does not depend on the synchrony of two people, we also have the advantage of small clinics that do not have the inputs, can acquire the device we also have the advantage that the equipment train together with the device what can provide them safety and preparation for a surgical operation medical they can get used to in a simpler way to this type of operation they can also

The project also proposes and has the possibility of being able to adapt to the market since it has a support for technologies already existing on the market in turn the project may seem attractive to companies that have devices for laparoscopy and look for the form of adapt it to your teams to make them more attractive and adapt it to different markets to expand your repertoire of options to offer.

## Hardware

The movement of the robotic arm is based on the use of servomotors which are highly specialized motors designed for precise control of rotary or linear movements. It is a rotation or translation motor which employs a feedback mechanism to ensure accurate positioning, usually by means of a control signal that dictates the movement of the motor to a desired position. This mechanism allows for precise control of several components, making servo motors crucial in applications that require precise positioning and smooth movement.

For the above points of the servo motor is that we adapted this component to be able to develop effectively the project

At the heart of every servo motor lies its ability to precisely control the position of its output axis. This is achieved through sophisticated interaction between several key components of the servo motor:

**Control signal:** It is the starting point of the operation of the servo motor. This is an electrical signal sent by the controller, which specifies the desired position or movement. The signal is usually a variable width pulse, known as pulse width modulation (PWM), which encodes the target position,

**Motor and gear mechanism:** Once the control signal is received, the internal circuit of the servomotor drives the motor to move it to the desired position. The motor is usually connected to a gearbox to increase torque and control the precise movement and speed of the output shaft [6].

## Software

The main programming language to be used is python for its use of computer vision which refers to the process by a machine or an automated system that interprets visual information from the environment, like how it would be done by the human eye. This field includes a wide range of applications, from object recognition to autonomous vehicle navigation. The implementation of these systems requires the use of advanced algorithms to process and analyze digital images [7].

Together with the OpenCV library, Python, created by Guido van Rossum in the late 1980s, stands out as an interpreted, high-level, and multi-paradigm programming language [8]. It was developed at the Centrum Wiskunde & Informatica (CWI) in the

Netherlands as a successor to the ABC programming language, aiming to offer clear syntax, exception handling capabilities, and interaction with multiple operating systems.

We also utilize the YOLO system, the latest version of the "You Only Look Once" object detection algorithm, which has been applied in various domains, showcasing its applications, improvements, and performance in different scenarios [9].

### **YOLO Applications**

#### **Intrusion Detection Systems**

YOLO segmentation has demonstrated high precision in various domains, including intrusion detection systems and UAV-based object tracking (Figure 4). This model's capability to detect and classify objects in real-time makes it a valuable tool in numerous AI-driven applications. By leveraging datasets, YOLO can accurately recognize and categorize intrusions, achieving high precision and recall rates. Integration with Python and OpenCV allows seamless incorporation into existing security frameworks, enhancing surveillance technology across various environments [10].

#### **UAV Aerial Photography**

In unmanned aerial vehicle (UAV) aerial photography, YOLO has been optimized to address the challenges of detecting small objects. The UAV-YOLO model incorporates Wise-IoU for better localization and an attention mechanism to enhance the processing of critical information. This results in improved detection performance and reduces missed detection rates, making it suitable for civilian, commercial, and military applications [11].



Figure 4. YOLO segmentation applied to real-time object detection in AI-driven systems: The model enhances object classification through convolutional neural networks. Source: Adapted from [VisionPlatform](<https://visionplatform.ai/es/yolov8-deteccion-de-objetos-de-ultima-generacion-en-recomocimiento-de-imagenes-computer-vision/>).

## Code

This project implements a computer vision system to detect and track blue objects in real time using the OpenCV library. In addition, it uses serial communication to send commands to a microcontroller based on the position of the object in the image.

The process starts with live video capture using OpenCV. Then, the image is converted to HSV color space, and a filter is applied to detect blue tones within a specific range (Figure 5). This technique allows real-time object detection and tracking, which is fundamental in applications such as robotic-assisted surgery and medical imaging. From this filtered image, the contours of the blue objects are identified, and their centroid is calculated to determine their position in the image.

Based on the X-coordinate of the detected object, decisions are made to send commands through the serial port, indicating movements in different directions. Subsequently, the system displays on screen the processed image with the contours and position of the detected object, allowing the user to visualize the tracking in real time. In addition, the program has a termination option using the 's' key, which closes the serial connection and frees the camera resources.

The developed system can accurately detect blue objects and calculate their position in the image, enabling its use in applications such as the control of robots or automated devices. As future enhancements, multiple color detection, dynamic threshold adjustment and optimization of data delivery can be added to improve the efficiency and accuracy of the system.



Figure 5. Real-time video capture and processing using OpenCV in Python. This system detects and tracks objects dynamically through HSV filtering and contour recognition



*Emerging Trajectories. Advances in Cyber-Physical Systems, Biorobotics  
and Cyber-Human Integration.*

Edited in october 2025  
at Astra Ediciones' workshops

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Zapopan, Jalisco, Mexico.

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