Humanizing Fault Management: Implementing AI-Generated Avatars for Industrial Process Monitoring

Victor H. Benitez[1], Jesus Pacheco[1], Alberto Fuentes-Trasviña[1], Jesús H. Ramírez-Romero[1], José R. Reyes-Zárate[1] and Guillermo Cuame-Cruz[1]

[1] Universidad de Sonora, Hermosillo, Son, Luis Encinas y Rosales S/N, C.P. 8300 México
victor.benitez@unison.mx

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

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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

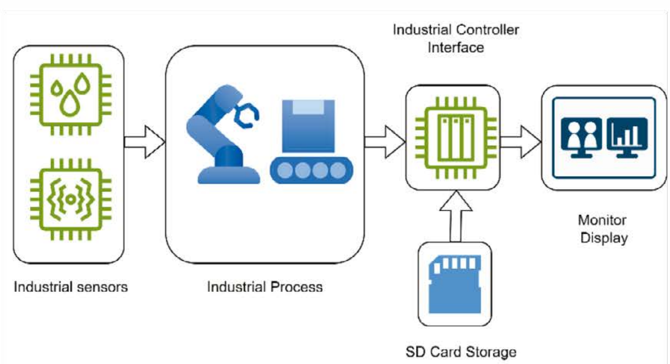

Fig. 1. System Components architecture.

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).

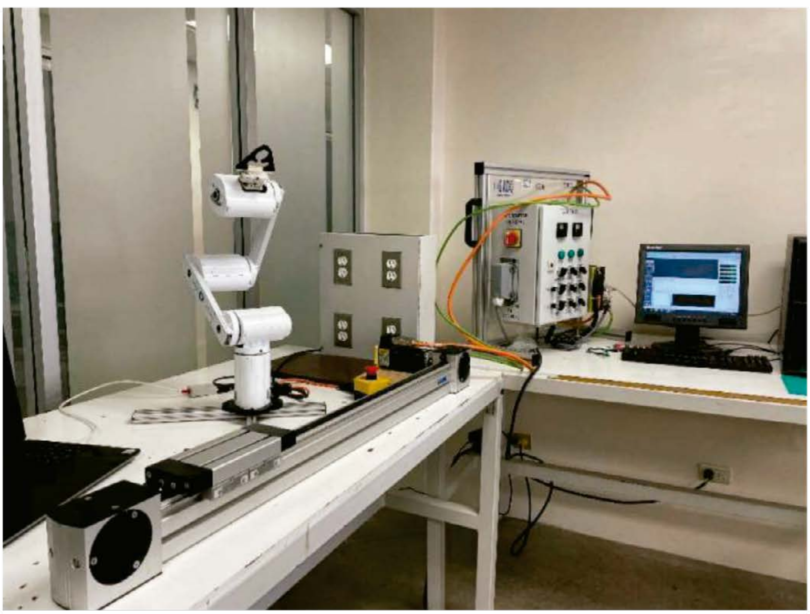

Fig. 2. System testbed used.

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.

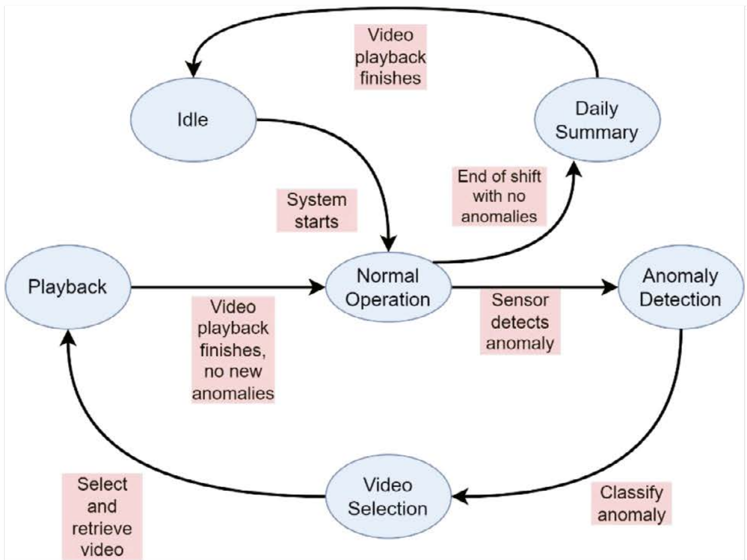

Fig. 3. State Machine for the Avatar-Based Fault Management System.

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 - Accuracy of anomaly classification - System stability and real-time performance	- The time delay between anomaly detection and alert - Correct classification vs. predefined conditions - Latency analysis under varying load conditions
User Experience	* Clarity of avatar communication * Perceived trustworthiness and engagement * Cognitive load reduction	* Operator surveys and comprehension tests * User feedback on avatar realism and tone * Comparison of operator response effort
Operational Impact	- Reaction time to alerts - Decision-making efficiency - Integration potential with existing IoT systems	- Time taken by operators to acknowledge alerts - Improvement in problem diagnosis and resolution - 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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