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Article

Digital Twins in Industrial Maintenance: Integrating Virtual and Augmented Reality for Innovation

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Abstract: The optimization of processes, cost reduction, and increased efficiency stand as primary objectives within the textile industry. With the advancement of technologies, the digital twin concept – a digital representation model of the processes and physical objects within the manufacturing environment – has been extensively employed. This article aims to examine and investigate how it is possible to integrate the use of augmented and virtual reality technologies with a digital twin model, in order to enhance equipment maintenance within this industry. In addition to a review of the current state of the art in this field, several articles related to the topic were studied, complemented by the results of a small-scale experiment. These findings indicate that the utilization of these technologies is indeed advantageous in supporting equipment maintenance and managing the flow of data generated by real physical objects and processes.

Keywords: Digital Twin, Augmented Reality, Virtual Reality, Textile Industry.

1. Introduction

Nowadays, due to the significant development and advancement of technologies, there is a strong initiative for industry updates, particularly in the realm of information technologies. These innovations play a crucial role in transforming the industry, driving efficiency, and fostering innovation. The new technologies optimize processes, reduce costs, and facilitate logistics. The intelligent adoption of these innovations is essential to boost competitiveness. With the goal of monitoring, analyzing, understanding, and predicting the performance/results achieved by a manufacturing system, the digital twin concept emerges. This concept represents a dynamic model allowing the digital representation of an entire manufacturing system. However, at times, managing the vast amount of data generated by the model can be challenging for a significant number of users. Thus, virtual and augmented reality come into play, aiming to be the link between both technologies, providing a more

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intuitive experience for the user, according to [1]. Indeed, the use of these technologies has increasingly become a significant ally in this sector.

According to opinions in [2], augmented and virtual reality together play crucial roles in enhancing user experiences and efficiency in the ever-evolving landscape of digitized industries. The purpose of this article is to examine the useful uses of augmented and virtual reality technologies, particularly as they relate to equipment maintenance in an actual manufacturing environment. These devices are a component of a larger system that a digital twin model represents digitally. In order to accomplish this, a selection of IEEE approved publications will be made first, and then a cutting-edge analysis of the key themes and ideas covered will be conducted. Finally, this article will conclude with a small-scale experiment aimed at evaluating the effectiveness of an augmented reality application for digital twin model equipment maintenance. The goal of this, is to not only highlight the potential of these technologies but also to offer insightful information about how they actually affect industrial operations and maintenance procedures in the real world.

2. Systematic Review

To obtain a list of related works, a systematic review was conducted. Initially, the review included all papers published on IEEE within the last 5 years, emphasizing the keywords ”Digital Twin”, “Augmented Reality” and “Virtual Reality” as the central theme. However, this resulted in an enormous quantity of papers. To narrow down the results it was decided to include only the ones published in the last five years and with the keyword “Manufacturing”, resulting in 31 different papers. In the end, this systematic review was used to select 14 papers as an initial research base (Figure 1). Additionally, brief summaries were provided for some of these papers.

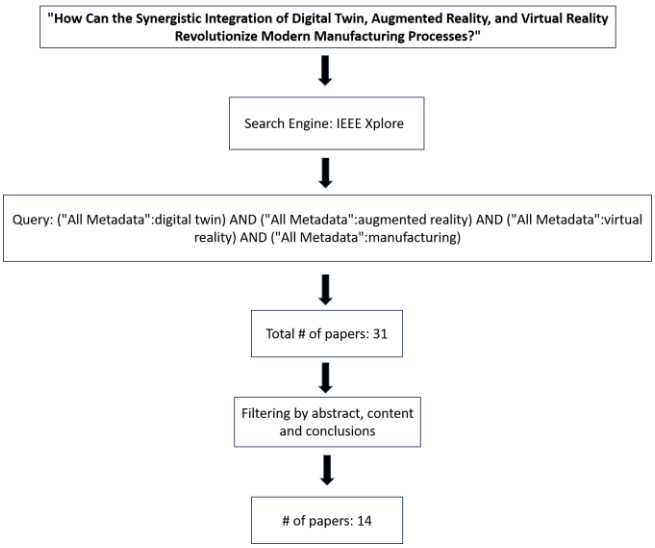

Figure 1. Stages, options and numbers of systematic review performed.

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In [3] is emphasized that, digital twin technology not only lowers sustainment costs and enhances product improvement but also provides vendors with early insights into system design. By facilitating real-time collaboration between vendors and end users, it reduces the need for costly in-person events, fostering continuous feedback loops in system design. Integrating high-fidelity digital twins into immersive training applications allows realistic training before system deployment, potentially saving costs on New Equipment Training (NET) and live fire events. While virtual reality can't fully replace real-time interaction, immersive experiences with digital systems models offer substantial benefits in terms of cost reduction, increased reliability, and improved operator proficiency.

A cost-effective Digital Twin platform is introduced [1], using augmented reality and free software. Tested in a modular classification station, the platform, controlled by a Raspberry Pi board, achieves real-time monitoring through the Firebase cloud. The board provides additional benefits, including ample storage, libraries, and efficient data processing, enhancing connectivity. The Digital Twin facilitates industrial process automation, remote monitoring, data collection, and analysis, enabling increased digitalization. Implementing solutions derived from Digital Twin-generated data enhances process efficiency and reliability.

In this study, a digital-twin-assisted bearing fault diagnosis method is presented to address challenges in acquiring fault data and training fault diagnosis models under dynamic working conditions [4]. The digital twin virtual workshop is utilized to provide extensive fault data for training purposes, with the trained model then transferred to the actual workshop to save time and knowledge. The proposed method is experimentally validated in an actual machining workshop. Digital twin-assisted deep transfer learning, combined with PVS (Process Visibility System), visualizes, and abstracts the fault diagnosis process in real-time, enhancing efficiency and sustainability in intelligent manufacturing.

In [5] the authors conduct a systematic literature review on the application potential of augmented reality for digital twins. Examining 42 research articles and book chapters, the researchers selectively synthesize findings from 25 of them. The initial step involves creating a standardized definition by extracting defining characteristics from the various terms – mixed reality, augmented reality, digital twin, and virtual twin – provided across the 42 sources. The categorized contributions encompass diverse research topics, predominantly focused on information visualization, task guidance, and AR interaction with digital twins in manufacturing and educational contexts. Despite a lack of user involvement, the study identifies evaluation methodologies, challenges, and open research questions for further exploration in the field.

A guideline for XR (eXtended Reality) system development in manufacturing is established by [6], emphasizing usability and user acceptance to promote widespread adoption of XR technologies (which encompass virtual, augmented and mixed reality) for enhanced manufacturing activities. Conducting six cases using a user-centered design approach, the framework comprises five phases: requirements analysis, solution selection,

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data preparation, system implementation, and system evaluation. Validated through empirical and identified previous studies, the guideline aids industrial practitioners in integrating XR technologies for Industry 4.0, fostering usability, user acceptance, and a user-centered development approach.

3. Essential Concepts

This section introduces some key concepts regarding the topics of this article.

3.1. Internet of Things

The Internet of Things (IoT) refers to a network of inter-connected physical devices that collect and share data over the internet. These devices can range from simple sensors to complex machine systems, all working together to optimize processes and improve efficiency. It is essential for monitoring and enhancing manufacturing processes, providing valuable real-time data that can be used for more informed and proactive decision-making on the production line. In terms of applications in textile manufacturing, IoT involves the use of connected sensors and smart devices to monitor and control production processes in real time. This technology has the potential to transform how the industry operates, from inventory management to machine maintenance. However, the use of IoT in these contexts requires that the manufacturing process be built upon a comprehensive data infrastructure that enables the acquisition, routing, merging, and storage of accumulated data. This means that production machines need to be equipped with appropriate interfaces to make their data accessible comprehensively during the manufacturing process. The implementation of Industrial Internet of Things (IIoT) in companies, therefore, demands a fundamental adaptation of their technical and digital infrastructures [7].

3.2. Digital Twin

The Digital Twin can be referred to as a virtual replica of an object, process, or physical system. It uses data from sensors to fuel computational simulations and is primarily used to monitor, analyze, and optimize the performance of the object, process, or physical system existing in the real world. However, considering the definition of Digital Twin in the textile sector, it pertains to the creation of a precise and detailed digital model of a textile product or process. This virtual model is an exact replica of the physical process and is employed for simulating, analyzing, and optimizing the performance and production of textiles. Through the use of advanced data and algorithms, it enables the testing of different scenarios and predicting outcomes without the need for physical prototypes, thereby saving time and resources. Furthermore, it contributes to enhance the quality and innovation in the design and production of fabrics and garments.

According to [8], the primary reason for implementing the Digital Twin was its ability to receive real-time feedback about the production line. This allowed for the early prediction

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of downtime issues. The current development aligns with the fourth industrial revolution, which leverages device connectivity to make the concept of Digital Twin a reality for production operations.

3.3. Process Representation

Before developing the digital twin system, it is essential to appropriately represent the processes it will encompass. One possibility for representing processes is the BPMN (Business Process Model and Notation) model. The BPMN model allows a visual and precise representation, using intuitive graphical symbols, of the various elements and activities composing a process [9]. Through the use of this model, a clear and consistent understanding of business processes can be achieved. This model is employed in the intelligent maintenance architecture [10], characterized as part of the "Industry 4.0", i.e., the integration of advanced technologies in industrial production to create smarter, more efficient, and connected manufacturing environments [11].

3.4. Artificial intelligence for predictive maintenance

Sensors, embedded in various objects within the system, are employed to provide and capture real-time data, with the aim of obtaining a digital representation. Consequently, the maintenance of equipment in a Digital Twin model is heavily influenced by the action and utilization of these sensors. Thus, maintenance is triggered when a malfunction is detected. However, it is possible to identify errors in the physical system before a malfunction occurs. To achieve this, the capabilities of Artificial Intelligence (AI) are utilized in a mode referred to as predictive maintenance. This involves the implementation of one or more AI algorithms to foresee future malfunctions [12].

Nevertheless, a predictive maintenance algorithm requires a comprehensive set of data from various environmental operating conditions, and sometimes the actual volume of system data may not be sufficiently large. Therefore, according to [13], mathematical models can be employed to generate synthetic data as an alternative. On the other hand, model incompatibility can also introduce errors into the predictive maintenance framework, especially in complex systems and environments. At this juncture, the concept of synthetic data can be extended to Digital Twins because, with the assistance of crucial resources such as simulation of various domains and behavioral matching, Digital Twins can generate high-fidelity synthetic data [14]. This synthetic data can be employed in scenarios where real, large-volume data is unavailable.

3.5. Augmented and Virtual Reality

In order to facilitate the processing of data generated by the digital twin model, particularly in understanding them for the purpose of directing potential maintenance actions,

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Augmented Reality (AR) and Virtual Reality (VR) come into play. These technologies will enable a more intuitive user experience.

Virtual Reality is a technology that immerses users in a completely simulated and computer-generated environment. In VR, users are isolated from the real world and placed in a digital environment where they can interact with a computer-generated reality. VR typically involves the use of specialized headsets and controllers, providing users with a highly immersive and often interactive experience. Unlike AR, VR creates a wholly synthetic environment, transporting users to a virtual world distinct from their physical surroundings.

Augmented Reality refers to a technology that overlays digital information, such as images, text, or 3D models, onto the real-world environment. Unlike virtual reality, AR does not replace the real world; instead, it enhances the user's perception by blending computer-generated elements with the surroundings. AR is commonly experienced through devices like smartphones, tablets, or AR glasses, allowing users to interact simultaneously with the physical and digital worlds [15].

According to [2], AR and VR jointly assume pivotal roles in augmenting user experiences and improving efficiency within the constantly evolving landscape of digitized industries. [3] supports this viewpoint, emphasizing that virtual reality offers the capability to engage with high-fidelity 3D system visualizations that evolve seamlessly throughout the product lifecycle. The convergence of both technologies is recognized as integral to shaping enhanced user interactions and operational efficiency in the dynamic realm of digitized industries.

4. AR and Digital Twin Experiment

In order to explore the use of augmented reality in the maintenance of industrial equipment within a digital twin model, a small experiment was conducted.

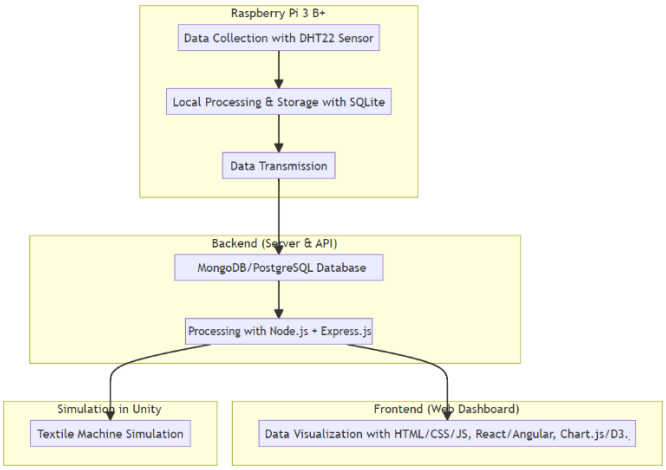

Figure 2. Application structure diagram.

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The objective was to investigate the application of Internet of Things technologies for environmental monitoring. Using the Raspberry Pi 3 B+, a compact and efficient platform, the project focuses on real-time temperature data collection through sensors. The significance of the project lies in the practical demonstration of how IoT technology can be integrated into everyday solutions, providing insight into the collection and analysis of environmental data. The system structure, as depicted in Figure 2, includes data reading by the Raspberry Pi, local processing and storage, and the transmission of this data to a web server, which will later communicate with the Vuforia application. The Raspberry Pi is a compact and economical computer widely used in IoT projects. It is ideal for storing and processing data, controlling devices, and communicating with other networks. Its flexibility and ease of use make it suitable for a variety of IoT applications, from home automation to industrial projects.

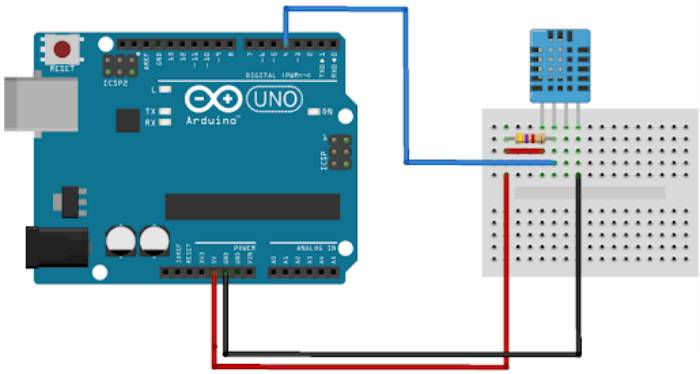

Figure 3. DTH11 Raspberry Pi configuration.

Connected to this computer was a humidity and temperature sensor named DTH11 (Figure 3), providing the percentage of humidity in the location as well as the temperature in degrees Celsius. This sensor was placed in the laboratory for a week, where continuous data harvesting occurred at 30-second intervals. The configuration of this sensor is represented in the following figure. Subsequently, the data is sent to a MongoDB [16] database. MongoDB is a NoSQL (Not Only SQL) database management system known for its flexible and document-oriented approach. Unlike traditional relational databases, MongoDB stores data in BSON (Binary JSON) documents, structured similarly to JSON. This feature provides MongoDB with great versatility, allowing efficient manipulation of complex and unstructured data.

Next, an Application Programming Interface (API) was developed using the Node.js Express tool [17]. Node.js, in con- junction with the Express framework, is a powerful combination for the rapid and efficient development of web applications. Node.js allows the execution of server-side code asynchronously, while Express simplifies the creation of routes to handle HTTP requests, facilitating the construction of clear and concise RESTful APIs. This serves as the connecting link between the database and the final Vuforia [18] application.

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The final application was developed using the Vuforia Software Development Kit (SDK) and the Unity game engine [19]. The Vuforia SDK is a powerful tool for the development of augmented reality applications. Integrable with Unity, a popular game engine, Vuforia offers an accessible approach to create interactive and engaging experiences. The SDK provides advanced features such as object tracking, markers, and image recognition, enabling developers to incorporate virtual elements into the real world.

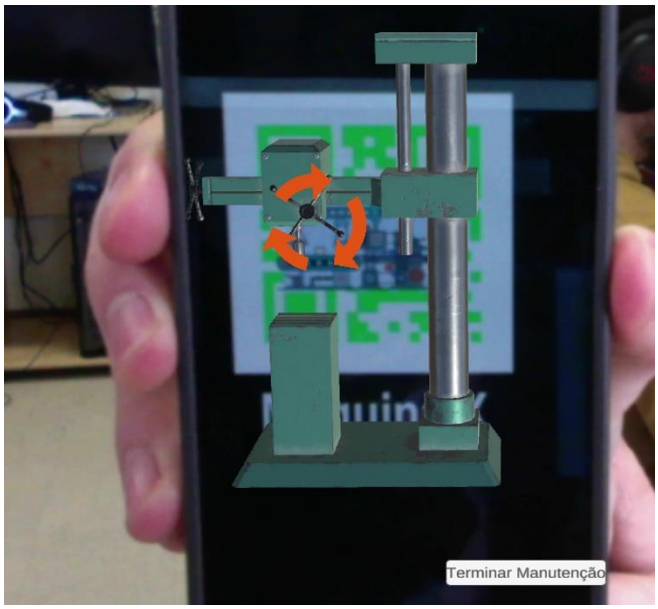

Figure 4. Final Prototype Application.

Therefore, an application was developed that functions as a small simulation of a potential maintenance scenario for a real industrial machine. To achieve this, a script in C# was developed. Whenever the sensor detects a temperature exceeding a specific value (in this example, 24 degrees Celsius as a temperature harmful to the machine's operation), a message will be sent to the User Interface (UI) of the application requesting maintenance of the machine. To carry out the maintenance, the user must point the camera of their mobile device at the marker created to represent the machine in this example. After that, a fictitious model of the machine and a button on the interface will be displayed (Figure 4). Pressing the button will show a visual indication of the maintenance action to be performed, facilitating the execution of the machine maintenance. Considering that this application is merely an experimentation, only one maintenance step is contemplated in solving this problem. After the maintenance is completed, as indicated by the graphic animation, the user should press the ”finish” button to conclude the process.

5. Discussion

In the dynamic landscape of modern textile manufacturing, the convergence of cutting-edge technologies has inaugurated a new era of efficiency and innovation. The Internet of

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Things emerges as a fundamental force, connecting a myriad of devices to optimize processes and increase productivity in the textile manufacturing universe. The IoT manifests through interconnected sensors and smart devices, revolutionizing everything from inventory management to machine maintenance. A crucial companion to IoT is the concept of the Digital Twin, a virtual mirror reflecting the intricacies of physical objects or processes. In the textile sector, the Digital Twin is harnessed to create meticulous digital replicas, providing a platform for simulation, analysis, and optimization. This not only accelerates production but also elevates the quality and innovation in fabric and clothing design, all while preserving valuable time and resources.

The representation of processes, exemplified by models such as BPMN, lays the foundations for the seamless integration of intelligent systems. This representation becomes imperative as we delve into the era of Industry 4.0, where advanced technologies harmonize to create smarter, more efficient, and interconnected manufacturing environments.

Artificial Intelligence takes the lead, especially in the do- main of predictive maintenance. By leveraging real-time data captured by embedded sensors, AI algorithms predict potential faults, enabling proactive interventions before system failures occur. This predictive approach not only ensures the longevity of equipment but also optimizes operational efficiency. In the quest to comprehend and act upon the vast data generated by the Digital Twin, Augmented Reality and Virtual Reality emerge as transformative tools. VR immerses users in entirely simulated environments, fostering interactive experiences and facilitating a deeper understanding of complex data. On the other hand, AR overlays digital information onto the real-world environment, seamlessly blending the physical and digital realms. Together, AR and VR enhance user experiences and operational efficiency, marking their indispensability in the digital landscape of modern industries.

As textile manufacturing continues to evolve, the synergy of IoT, Digital Twin, process representation, AI-driven predictive maintenance, and immersive technologies paves the way for unprecedented advancements. This synergy not only propels efficiency but also opens doors to new frontiers of creativity and precision in the vibrant world of textiles.

Regarding the conducted experiment to investigate the use of Augmented Reality in industrial equipment maintenance, incorporating a digital twin model and Internet of Things technologies, has yielded valuable insights into the feasibility and effectiveness of this innovative approach. The selection of the Raspberry Pi 3 B+ as the central platform for environmental data collection has proven to be judicious. Its compact and efficient capabilities provided a robust solution for real-time data collection, specifically capturing temperature and humidity through the DTH11 sensor. The utilization of this platform underscored its versatility and adaptability for IoT applications, affirming its efficacy in industrial automation projects.

The implementation of MongoDB as a NoSQL database management system allowed for a flexible and document-oriented approach. This facilitated the efficient storage of

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complex and unstructured data from the sensors, demonstrating its adaptability to the specific requirements of the experiment. The agile deployment of the API using Node.js Express established an effective linkage between the database and the final Vuforia application. The synergy of these technologies facilitated the rapid and clear development of an interface that streamlines communication between the collected data and the augmented reality application.

The concluding application, developed with the Vuforia SDK and Unity game engine, successfully achieved its intended objectives, providing an engaging and realistic interactive simulation of industrial equipment maintenance. The developed simulation highlights the potential of augmented reality in optimizing industrial processes. In this context, the detection of a detrimental temperature triggers a maintenance request within the application, followed by a graphical representation of the machine and visual instructions for the maintenance procedure. It is imperative to note that this experiment represents an initial phase in the exploration of AR in industrial maintenance. Limitations, such as the simplicity of the maintenance step, should be considered for future iterations. Additionally, the application could and should be expanded to encompass multiple maintenance steps and more complex scenarios within a real-world context.

6. Conclusions

An increasingly prominent initiative within the industry is observed as it undergoes updates, driven by the growing integration of the digital twin concept to enhance operational efficiency and excellence. With this objective in mind, a research effort was initiated to explore the utilization of augmented and virtual reality in maintaining equipment within an entire manufacturing system, represented digitally by a digital twin model. To achieve this, an investigation into articles related to this theme and an examination of the encompassed fundamental concepts were conducted. Finally, a conclusive experiment was carried out to assess the application of the studied technologies. The results of the experiment indicate that the integration of various technologies offers benefits in optimizing industrial maintenance. The interactive simulation showcased the potential of augmented reality in improving processes, despite being conceptualized as an initial experiment. Even with a significant level of simplicity, it can be concluded that integrating augmented reality technologies in a manufacturing context that utilizes a digital twin model is not only beneficial for process optimization but also serves as a means to simplify necessary steps in the maintenance and conservation of various industrial equipment. Recognizing limitations, such as the simplification of the maintenance step, suggests potential future iterations to encompass more complex scenarios and multiple maintenance steps. In summary, this experiment has established a robust foundation for future, more intricate research, and experiments in this innovative area.

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6. Future Work

Considering the experiment conducted in this article, a proposal is made for its expansion. Given the intricate nature of industrial processes, broadening the simulation to encompass multiple maintenance stages and more challenging scenarios would provide a more faithful representation of situations encountered in practice. To clarify, this involves extending the application beyond the maintenance of a simple object to include various other objects and processes within a digital twin model. The incorporation of additional objects needs the comprehensive utilization of a diverse array of sensors, accommodating the distinct needs and characteristics of various machines. To achieve this, personnel with specialized training will be required to use the application for maintenance on one or multiple pieces of equipment. Regarding the final application, it is crucial to enhance the interaction between the user and the augmented reality application. Exploring more intuitive methods, user-friendly interfaces, and the integration of innovative input/output devices can enhance efficiency and user experience during simulated maintenance procedures. Additionally, the application, through the introduction of artificial intelligence technologies, should consider integrating predictive maintenance. Finally, it is imperative to test the application in real-world environments. Evaluating the feasibility of the application under actual operational conditions will validate the technology's effectiveness in dynamic and complex situations, providing practical insights.

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Conflicts of Interest: The authors declare no conflict of interest.

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