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Design and Implementation of an Augmented Reality-based Interactive and Real-time Wind Turbine Maintenance Auxiliary Platform System

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To achieve the goal of net zero emissions by 2050, Taiwan's government is committed to aggressively developing renewable energy sources, with wind power being among the top three. However, when wind turbines experience failures, it is common to shut them down and call for professional help to troubleshoot, leading to significant losses due to transportation costs and downtime. Traditional maintenance methods rely on expertise and are limited by paper manuals and screen-based tutorials. As Industry 4.0 progresses, IoT technology is being increasingly adopted across industries, leading to greater automation. Augmented reality (AR) technology is also gaining recognition as science and technology rapidly advance. AR technology adds virtual objects to the physical world and presents the potential to simplify tasks that once required significant time and effort. Additionally, it provides real-time information to technicians and has become an indispensable auxiliary system in various sectors. In this study, we aim to develop an AR-based, interactive, and real-time wind turbine maintenance auxiliary platform system using Unity3D and Vuforia. The system can control and repair wind turbines, monitor operational data and conditions in real time, and alert users to maintenance and repair tasks in the event of failures. This AR maintenance assistance platform also includes a remote expert system. When users are unable to troubleshoot issues themselves, they can connect with remote experienced experts for support, increasing wind farm efficiency and enabling real-time monitoring. The presented AR system can assist operations and maintenance (O&M) of a wind farm in reducing the maintenance cost and time, and thus increase the efficiency and output yield of the wind farm.

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1. Introduction

According to the Global Wind Power Report published by the Global Wind Energy Council in 2022, the cumulative installed capacity of global wind energy onshore and offshore wind turbines has reached 824 GW by the end of 2021, and the newly installed capacity has also reached 93.6 GW in 2021. This is the second-best year for the wind power industry, which is only 1.8% lower than the record in 2020.(1) Moreover, 2021 is also a record year for global offshore wind power. According to the 2022 global offshore wind power market report by the U.S. National Renewable Energy Laboratory, the capacity of newly installed offshore wind power has reached 17,399 MW, (2) and the growth continues to increase steadily every year.

Wind power generation in Taiwan has seen significant growth in recent years. According to the Energy Transformation White Paper 110-Year Implementation Report published by the Taiwan Ministry of Economic Affairs Bureau of Energy in 2021, the cumulative installed capacity of wind power generation reached 692 MW in 2017 and increased to 1,062 MW in 2021, representing a growth of approximately 53% compared with 2017. This growth can largely be attributed to the establishment of offshore wind demonstration projects.(3) To achieve the goal of renewable energy accounting for 20% of the total energy mix by 2025, the Taiwanese government has been actively promoting green energy development. Currently, there is a strong focus on promoting solar photovoltaic and wind power generation, with expected installed capacities of 20 GW for solar photovoltaic and higher than 5.7 GW for offshore wind power by 2025.(4) The development plan for offshore wind power has become a crucial component of the energy policy in recent years.

However, the core technologies and systems of the currently developed offshore wind power systems still rely heavily on foreign countries. This includes the drivetrain, generator, and control systems of the wind turbines themselves. Given the current situation, it is challenging for domestic industries to enter the market. The government has incorporated localization goals into the bidding process to address this, requiring investors to integrate certain technologies with domestic industries or adopt local products. The objective is to encourage domestic industry participation, establish a local supply chain, and provide significant employment opportunities. Recently, the casting of components such as the gearbox and nacelle, nacelle assembly, blades, and assembly of some subsystems has gradually been introduced, providing substantial benefits to domestic industries.

In the era of Industry 4.0, the workforce faces the need to adapt to technological advancements, with challenges such as COVID-19 accelerating the importance of technology transfer and knowledge sharing. Recent studies highlight the use of augmented reality (AR) in industries such as healthcare, education, shipbuilding, and wind turbine maintenance. Tailored AR solutions for wind turbines enable real-time access to information on mobile devices, streamlining manual reviews, wire inspections, and assistance calls.

While manuals and databases offer comprehensive information, complex problems can still arise, potentially leading to severe consequences. The incorporation of AR technology in wind turbine maintenance, even involving remote technicians, enhances functionality. An AR-guided remote assistance system facilitates real-time communication, improving collaboration, preventing issues, and offering solutions for generator failures. This system minimizes operation and maintenance costs, reduces on-site inspections, and enhances safety through step-by-step guidance during critical moments.

2. Related Work

2.1 Maintenance strategies of wind turbines

Wind power has solidified its standing in the renewable energy sector, progressively expanding its global electricity capacity share.[5] The pivotal role in this growth trajectory is the evolution of wind turbine technology, encompassing aerodynamics, mechanics, structural dynamics, and electrical engineering.[6] It has transformed from small kilowatt units to multi-megawatt turbines, with advancements in design and optimization, enhancing its reliability as a significant renewable energy source.[7]

Wind turbines, which convert wind's kinetic energy into rotational motion through optimally designed blades, have a complex yet crucial drivetrain system housed within the nacelle. This system comprises a gearbox increasing the blade's rotational speed, which is necessary for efficient power generation, and a protective braking mechanism. It facilitates the transmission of rotational force to the generator, where it undergoes conversion to electrical energy, later modified to suit various systems' needs. These turbines employ a yaw control system, which fine-tunes the orientation according to the wind direction to maximize energy capture efficiency.[8,9]

Maintenance strategies are paramount in securing the efficient operation and longevity of wind turbines. These strategies include scheduled maintenance such as vehicle servicing, which entails regular upkeep activities as dictated by operational times or conditions. Preventive maintenance, on the other hand, uses advanced tools for operational data analysis, thereby enabling the early detection of potential failures and facilitating timely interventions, enhancing the efficiency and safety of offshore wind farms.[10] The third strategy involves addressing unexpected failures, necessitating immediate troubleshooting and repair to minimize losses.

Given the offshore turbines' challenging accessibility and harsh maritime conditions, preventive maintenance takes precedence, helping avert critical issues before escalating to sudden failures. However, the occurrence of unexpected failures is sometimes inevitable. In such scenarios, leveraging remote synchronous maintenance support technology can be a game-changer. This technology aims to enhance the efficiency of maintenance strategies by providing real-time, specific failure data and online assistance from remote technicians, thereby curtailing substantial losses due to delayed or improper rectifications.[11]

In summary, we underscore the sophistication and progression of wind turbine technology, focusing on operational principles, diverse designs, and effective maintenance strategies. These elements are crucial in facilitating a global shift towards a sustainable and diversified energy portfolio, effectively integrating wind power into power systems, and contributing significantly to global energy transition efforts.

2.2 Cases of AR

AR technology has become a vital tool in the industrial sector, enhancing productivity, decreasing costs, and elevating product quality. Its applications span numerous fields, including medicine, education, and entertainment, with a notable role in improving maintenance operations. AR allows workers to replace traditional methods with advanced AR devices, promoting efficiency and safety through real-time alerts and reminders, thereby mitigating potential risks and accidents.

Industrial AR (IAR) was initiated in the 1990s, pioneered by Boeing Company[12] and later promoted by the German government through the ARVIKA project,[13,14] which fostered the creation of a significant IAR consortium comprising companies such as Airbus, BMW, and Audi. The project focused on advancing mobile IAR systems, although most developments remained prototypes, with the AR Welding Gun being a notable exception due to its user acceptance.[15]

Recently, the integration of AR with automation has revolutionized traditional industrial processes, enhancing efficiency and performance. Modern companies such as the historic Spanish shipbuilding firm Navantia are adopting Industry 4.0 and IAR principles[16] to update their facilities. Apart from aiding in maintenance, IAR is instrumental in training operators, offering simulation exercises for diverse professional skills and harsh environments. In the aviation sector, AR systems assist aircraft maintenance technicians by supplying supplementary data and facilitating task completion,[17] even expanding to pilot training and flight simulations.[18]

The use of AR applications has become widespread across many industries. The wind power industry also leverages AR for maintenance and training. Innovations include the utilization of optical see-through head-mounted displays for maintenance training on wind turbine motor parts[19] and a defect detection system using AR glasses integrated with neural networks for real-time analysis and interaction.[20] These technologies not only increase maintenance accuracy but also foster predictive maintenance platforms that enhance the safety and efficiency of wind turbine inspections.

2.3 Summary

Wind turbines necessitate frequent maintenance checks, which are traditionally time-consuming and error-prone. AR technology facilitates effective real-time communication between control centers and field staff, fostering collaborative problem-solving and reducing downtime. This remote assistance ensures the provision of accurate guidance at critical moments, enhancing overall safety and reducing potential hazards associated with traditional methods. The integration of AR systems thus stands as a catalyst for improved communication, collaboration, and error reduction in various industrial processes, marking a significant step towards modernization and safety in the industry.

3. Research Methodology

The structure of this study is shown in Fig. 1. We mainly utilize Unity3D as the open-source AR development environment, combined with Vuforia's open-source image recognition system as the target for scanning in AR. The system then displays the information collected by the programmable logic controller (PLC). We scan the icon to observe the operation of the wind turbine; the hardware side includes the PLC module for controlling the wind turbine and collecting data, as well as various internal sensing components of the wind turbine, simulating the internal control and data collection system of the wind turbine, and designing a wind turbine control simulation platform to simulate the actual wind turbine operation.

To simulate the state of a wind turbine, the research framework utilizes the sensing components found in the control box, which include an anemometer and temperature–humidity sensors. Additionally, the control components for the simulation are provided by the buttons of different levels designed in the box. By triggering these buttons, simulated signals are generated, which are subsequently read by the PLC. The PLC interprets and utilizes these signals to control various processes. Through the Modbus communication protocol, the PLC communicates with a

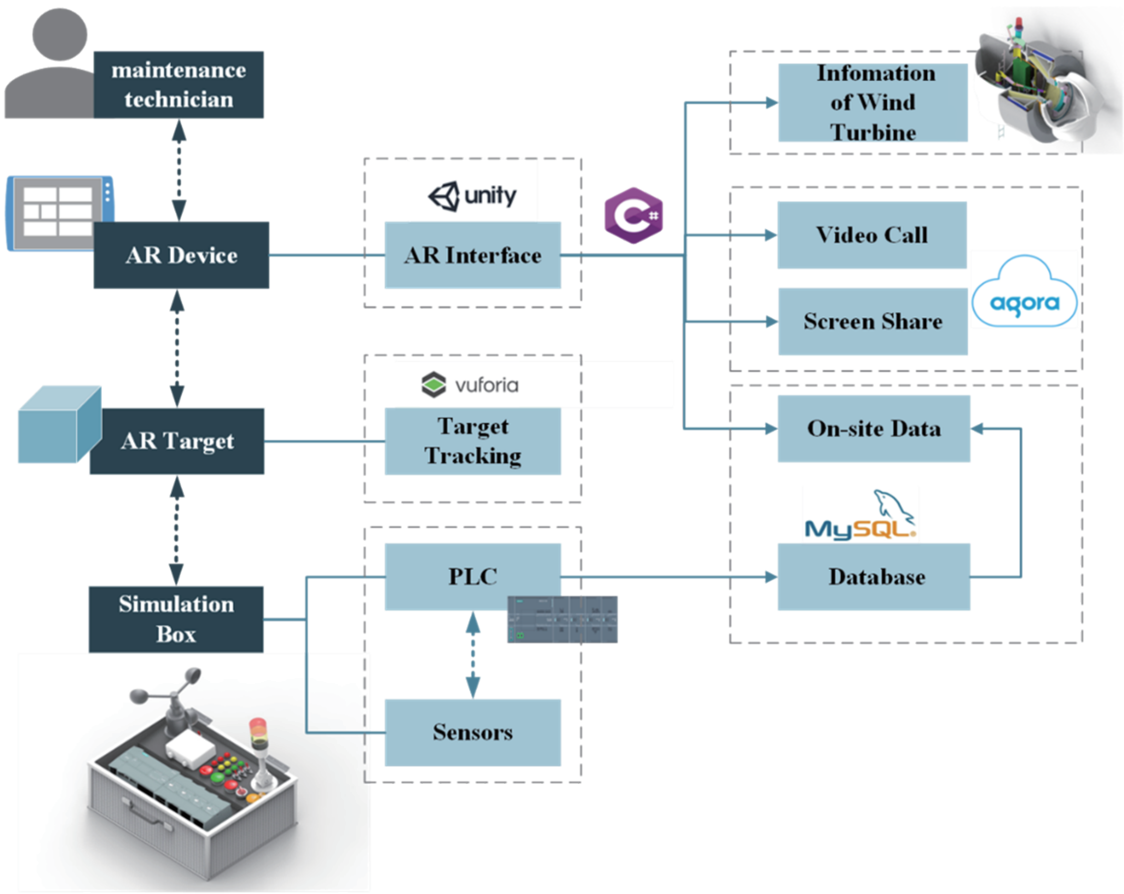

Fig. 1. (Color online) Research framework.

MySQL database, facilitating the transmission of data. The primary purpose of this interaction is to back up the signals collected by the PLC and modify the equipment status. This functionality enables users to observe historical records and query information in the event of a fault occurrence. Finally, these parts will be integrated into a complete AR system for wind turbine maintenance monitoring. In addition, in the expert collaboration system, the remote instant messaging function of Agora will play a key role. This expert collaboration system allows remote experts and team members to conduct instant audio and video communication, enabling real-time collaboration and knowledge sharing. This will considerably enhance communication and cooperation among team members, improving the efficiency and quality of wind turbine maintenance.

The AR device used in this experiment is the tablet, which serves as the hardware platform for AR collaboration. The experimental setup for simulating wind turbine operation includes the Siemens PLC module, an anemometer, and temperature–humidity sensors, among other sensing components, as shown in Fig. 2.

The design concept of the control box focuses on portability and ease of demonstration. Therefore, a portable case has been utilized as the external structure. Inside, the control box contains the Siemens PLC module, an anemometer, and various indicators and switches. The indicators simulate the start and stop states of different systems, while the switches simulate different scenarios. The display of different indicator lights corresponds to different scenarios, creating a simplified wind turbine control system simulation.

Finally, an estimation of the time and labor cost reduced for regular wind turbine maintenance and fault inspection will also be introduced to give a quantitative performance evaluation for the presented system.

Fig. 2. (Color online) Top view of control box.

4. Results and Discussion

In this study, the conditions of wind turbines are simulated using PLCs, and both error messages and troubleshooting guides are displayed on an AR maintenance assistance platform. The comprehensive alarm events mentioned in the Z72 maintenance manual are incorporated,[21] enabling users to immediately understand the current malfunction status of the wind turbine during maintenance. The platform further provides instructions, allowing for accurate judgments based on fault indicators. In situations where faults are challenging to resolve, the activation of a remote expert system is possible. This facilitates a faster and more efficient completion of maintenance tasks. The subsequent sections will detail the development process and results of this AR collaboration platform.

4.1 Case study

Our research subject is the wind turbine unit at the Taichung Port Wind Power Station in Taiwan. The unit originated from a design by the Dutch manufacturer Zephyros, a company that ceased operations in 2005. The model is Z72, with a rated power output of 2000 kW. There are 18 units in total at present. Table 1 shows the fundamental specifications of this wind turbine.

In this study, alarm lists for both the "Yaw System" and "Pitch System" are featured. These events are then incorporated into C# scripts, which display the event information on the AR interface. This includes the event ID, the message, an explanation of the message (highlighting possible causes), the event level, and the rectification methods used to address the events.

4.2 Development of AR platform

The AR wind power monitoring system was developed using Unity and Vuforia. Initiated by designing an image target essential for AR recognition, this target was incorporated into Vuforia—a platform offering an SDK for mobile devices and Unity integration. Developers can evaluate and refine the image recognition efficacy on this platform.

The foundational environment and user interface (UI) of the application were created using Unity. AR capabilities were solidified by combining Vuforia's game engine package with a target database and license. Backend development was facilitated using the C# scripting

Table 1
Specifications of Z72.

Rotor diameter	70.65 m
Rotor speed	Variable, nominal 23.5 rpm
Nominal power	2.0 MW
Transmission	Direct drive generator, single main bearing
Rated wind speed	13 m/s
Cut in and cut out wind speed	3–25 m/s
Survival wind speed	70 m/s
Rotor speed control	Blade pitch
Wind class	I and S, according to IEC 61400-1

language, allowing for interactions with the MySQL database. The result was an APK file that could be easily installed on mobile devices for user convenience.

The development of the AR system took place in six phases. First, a 3D CAD model displaying the wind turbine components was created. Next, a database populated with feature images for Vuforia was established to form the foundation for AR targeting. A standout feature of the system was the real-time display of data, which provided maintenance staff with instantaneous insights into the turbines. This data was collected from sensors housed in a wind turbine simulation setup and was funneled into a MySQL database via the PLC. C# and Python scripts were used to connect this data with the Unity framework. The Agora SDK was instrumental in creating the remote expert system. Finally, all components were assembled within Unity, and the system's final version was released as an Android app, which underwent extensive testing.

4.3 UI design of AR interface

In this research, the AR interface was developed using Unity3D version 2021.3.11f1 as the development environment. Unity is a cross-platform game engine that can be used to create standalone games for Windows, MacOS, and Linux, or mobile games for iOS and Android devices. The following sections present the Unity development environment for the AR maintenance platform, featuring the homepage, information page, wind turbine monitoring interface, and the additional feature of a remote expert assistance system.

The AR system offers multiple scenes, allowing users to toggle between pages using on-screen buttons. The information page showcases a 3D model of the wind turbine above the AR target, providing insights into its internal structure. This model can be interactively rotated for a comprehensive view.

The monitoring interface not only presents real-time turbine data, including the Yaw system, Pitch system, and power generation status, but also alerts users to malfunctions, referencing the Z72 turbine manual. These alerts come with repair instructions, streamlining the maintenance process.

In instances where on-screen guidelines fall short, the "Help Center" enables real-time expert consultations. Users can annotate directly on the AR interface, aiding remote experts in understanding issues and thereby boosting maintenance efficiency.

4.4 Device connection and real-time data display

To display real-time data, sensors and devices are connected using a PLC. Once all the components, including the PLC logic and the simulation control box, are integrated, the work states of the wind turbine can be simulated using the lights in the system.

When the operator presses the start button, the program starts to execute and then judges whether it is in the automatic mode. If it is in the automatic mode, it will be activated by the internal control logic of the PLC. If it is in the manual mode, the operator will operate it. The system will stop working, but when the emergency stop button is pressed, all the lights will turn red. The communication aspect is divided into two parts. First, we can utilize the Modbus module to collect signals from other devices. Additionally, we have established a Modbus TCP/IP server to communicate with the database and ultimately write the collected data into it.

To realize the function of displaying data in real time, MySQL is chosen as the database to store the data, and Python is the tool to retrieve the data. By developing Python programs, data retrieval is performed from the Siemens PLC using the Modbus TCP/IP protocol, and simultaneously, the retrieved data is written to the database for storage and backup purposes.

The primary purpose of establishing the database is to define and record the data points in a structured format, enabling easy data recording and backup. The historical data stored in the database allows for monitoring the changes of each data point over time.

4.5 Testing and final assessment

Initially, the user, utilizing an AR device (a tablet was employed in this study), launches the application. Once the AR device's camera detects the AR target, the designed interface, including 3D objects and information fields, is projected onto the target. The operation diagram is shown in Fig. 3.

The E-manual interface displays a 3D model of the wind turbine components along with their corresponding details. This feature enables users to familiarize themselves with the specifications of the wind turbine. Furthermore, they can freely manipulate the 3D model to observe its internal structure, offering an in-depth and comprehensive understanding of the turbine's layout and operation. Additionally, Fig. 4 shows the detailed 3D model illustration of the generator, along with the associated information, further expanding the depth of information accessible to the user.

In addition, the information interface presents the detailed specifications and a 3D model of the PLC. This is depicted in Fig. 5, which provides a view of the PLC's CPU model along with its relevant data. This comprehensive presentation of data ensures that users have all the essential information at their fingertips.

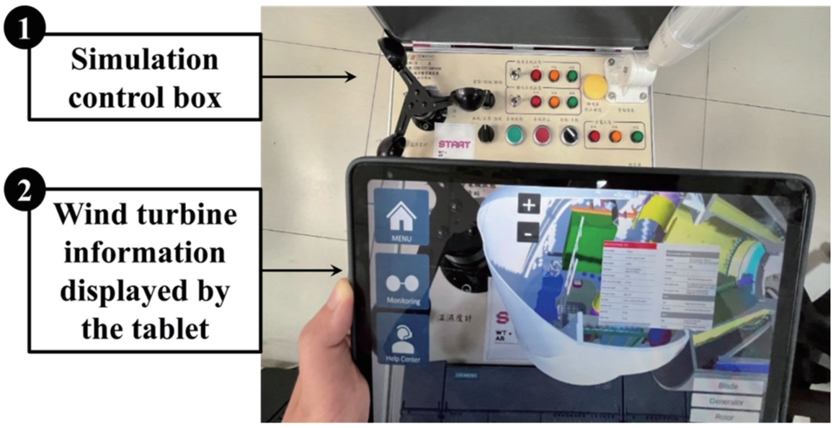

Fig. 3. (Color online) Operation diagram.

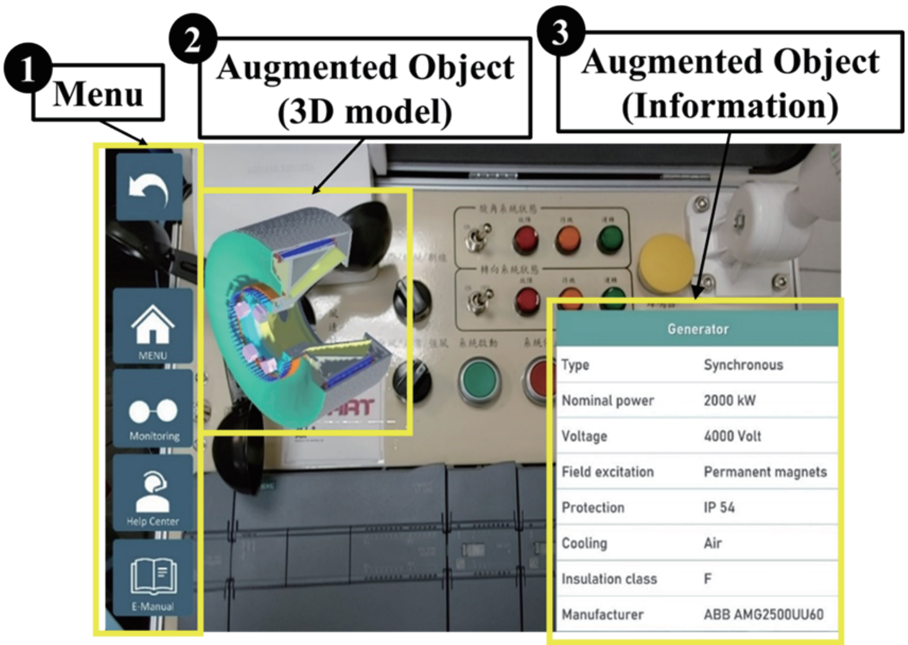

Fig. 4. (Color online) 3D diagram of generator and its information.

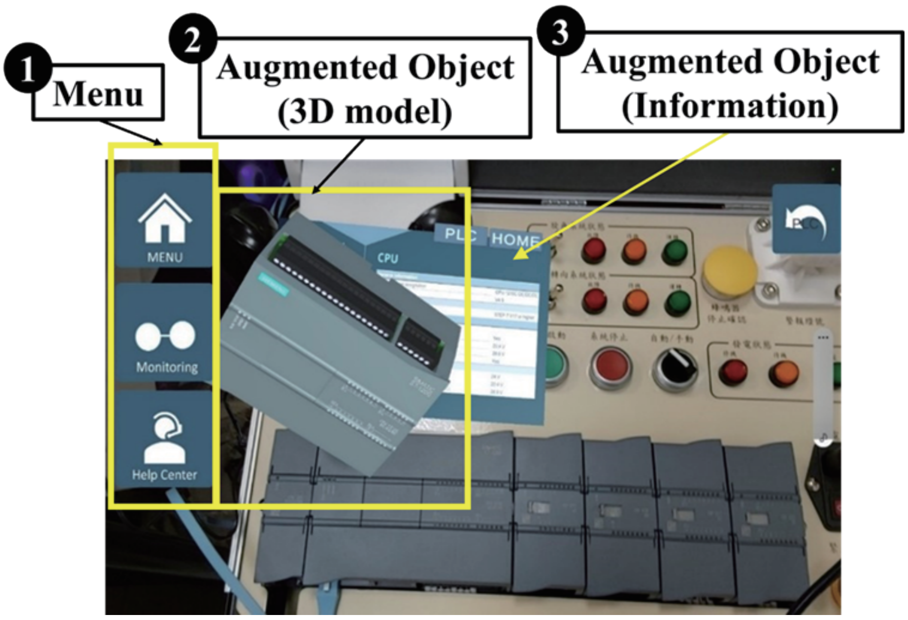

Fig. 5. (Color online) PLC's CPU model and its information.

Upon launching the application and viewing the main menu, the user can select the 'monitor' button, which directs them to the monitoring interface. The monitoring interface shown in Fig. 6 provides a real-time display of the wind turbine's operational status on the AR device. In its normal operational state, the wind turbine functions smoothly, with all systems running as

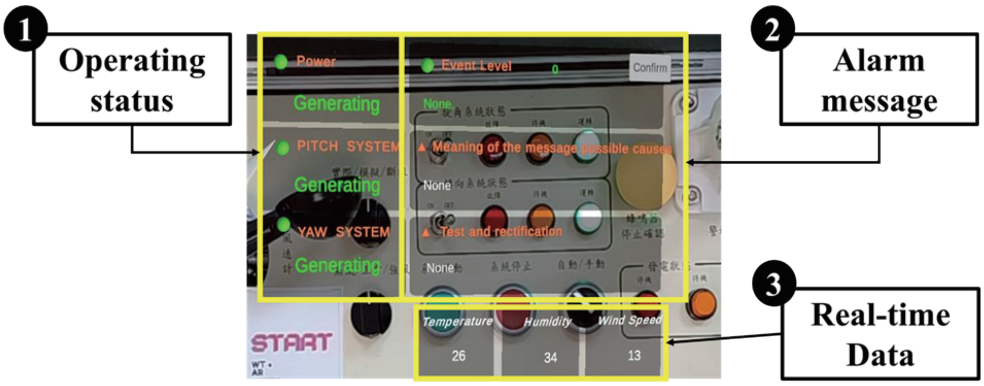

Fig. 6. (Color online) Wind turbine's normal operation screen display on AR device.

expected. However, should a malfunction occur, maintenance personnel can refer to the troubleshooting guide shown in the monitoring interface. For instance, if a shutdown status arises or alarm messages appear, these would be displayed as seen in Fig. 7.

If these issues persist despite following the provided instructions, the system seamlessly transitions to the remote expert system for immediate connectivity and further guidance. By utilizing video calls and the screen drawing feature to mark corresponding objects, both parties can enhance their understanding, leading to a more efficient communication and an effective problem resolution. The application of these features serves to expedite task completion, underscoring the platform's utility and effectiveness in AR-assisted maintenance tasks. Schematic diagrams of the remote expert system testing results are shown in Figs. 8 and 9.

Following the successful integration of features and the actual testing within the simulation experimental box, the AR maintenance assistance platform developed in this study was applied to a real wind turbine, confirming the results of this research development. The turbine for the test is a V47 turbine nacelle from Vestas with a capacity of 660 kW. Since it has been decommissioned, our team had full access to the nacelle for the test. The primary objective is to ensure the accuracy and efficiency of the system, rather than focusing exclusively on a specific turbine model.

Further expanding the platform's functionality, we show in Fig. 10 the annotation feature being demonstrated within an actual wind turbine. This feature allows field technicians to create drawings and annotations directly on the AR interface. This also allows remote experts to obtain a clearer understanding of the situation on-site and provide precise guidance on what actions should be undertaken. The addition of this feature demonstrates the AR maintenance assistance platform's adaptability and effectiveness in diverse operating environments.

4.6 Evaluation of the performance of the AR system on turbine maintenance

With the help of the developed AR system, maintenance efficiency can be improved in various tasks. As shown in Table 2, this system can be applied to not only maintenance and

Fig. 7. (Color online) Schematic diagram of shutdown status and alarm messages.

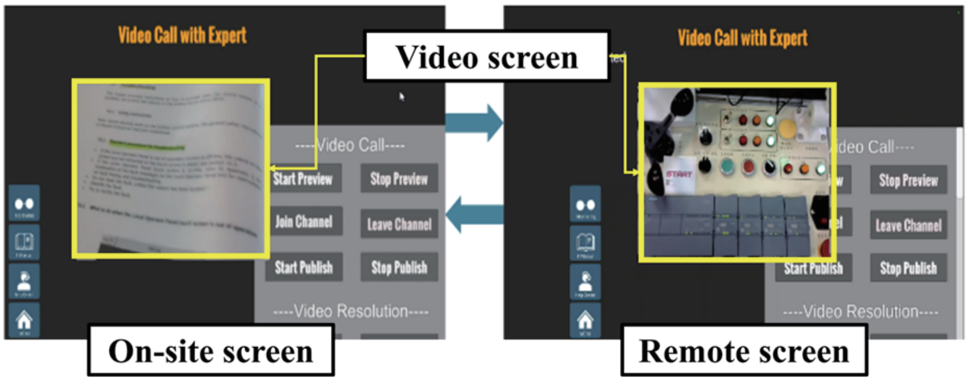

Fig. 8. (Color online) Schematic diagram of remote expert system testing.

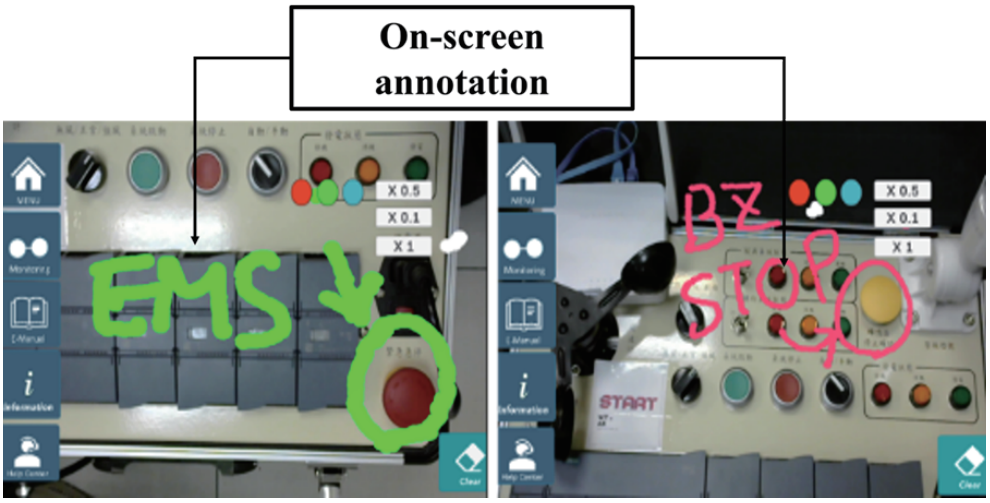

Fig. 9. (Color online) Schematic diagram of on-screen annotation test.

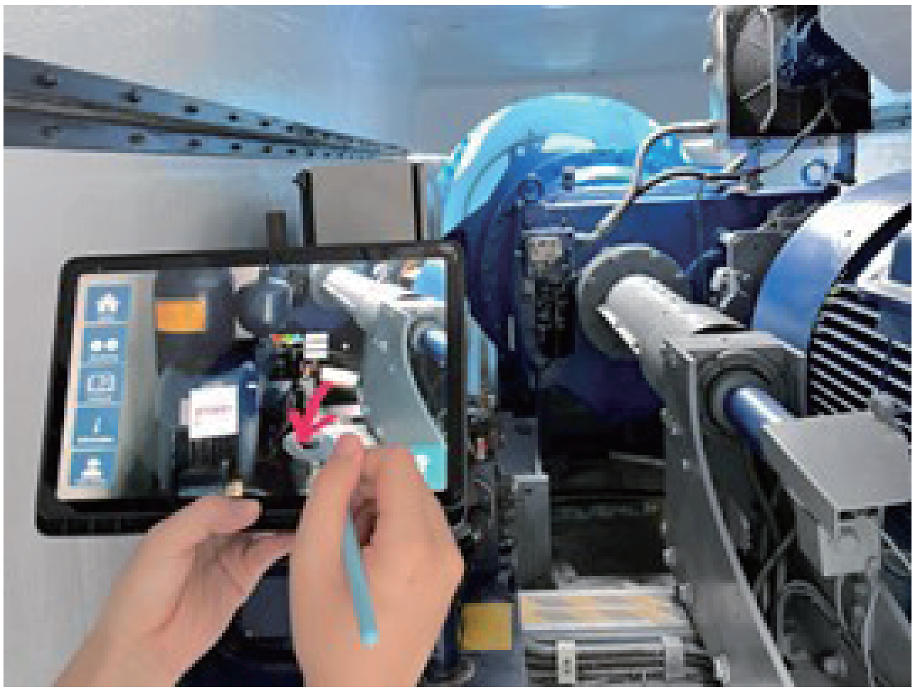

Fig. 10. (Color online) Demonstrating the annotation function in an actual wind turbine.

Table 2
Comparison of wind farm maintenance methods.

Aspect	Traditional Onsite Maintenance	AR-assisted Onsite Maintenance
Maintenance Task Efficiency	Longer time required to diagnose and execute repairs	Guided by AR instructions; quicker identification and execution of repairs
Training Time	Extensive training required for technicians	Reduced training time due to on-the-job AR guidance
Troubleshooting	Limited support for complex troubleshooting	Real-time remote assistance for complex troubleshooting
Data Retrieval	Manual retrieval of documentation and data	Instant access to relevant data and documentation through AR
Component Identification	Manual identification, potential for errors	Quick and accurate component identification with AR overlays
Safety Awareness	Safety precautions based on experience	Real-time safety warnings and reminders through AR
Documentation	Manual documentation, paperwork	Digital recording of maintenance activities with AR
Downtime Reduction	Longer onsite maintenance times lead to increased turbine downtime	Reduced onsite maintenance time leads to minimized turbine downtime
Total Onsite Time Reduction Potential	Variable, depending on technician's expertise and task complexity	Potential for significant reduction in onsite maintenance time, especially for complex tasks

troubleshooting, but also training, data retrieval, and component identification. The performance is notably better than those of the traditional methods; however, it can be challenging to achieve a consistent reduction in maintenance time because the complexity of each task varies and depends largely on the turbine manufacturers and the technician's expertise.

Table 3
Benefits of AR-assisted wind farm maintenance.

Maintenance Task	Description	Estimated Benefits
Blade Damage Inspection	Using AR technology to quickly inspect wind turbine blades for damage or cracks	Improves damage detection speed, saving approximately 2 h of inspection time
Lubricating Oil Replacement	Guiding the lubricating oil replacement process with AR technology to ensure accuracy and efficiency	Reduces human errors and saves around 1.5 h of maintenance time
Routine Turbine Check	Assisting routine inspections of various turbine components with AR technology	Enhances inspection efficiency, saving approximately 1.5 h of inspection time
Wind Sensor Calibration	Using AR technology to calibrate wind-side sensors to ensure the accuracy of wind direction measurements	Speeds up calibration and saves about 1 h of maintenance time
Anti-Corrosion Coating Maintenance	Employing AR technology to assist in maintaining the anti-corrosion coating of wind turbines	Improves maintenance efficiency, saving approximately 2.5 h of maintenance time
Remote Maintenance Cost Reduction (Estimation)	An offshore wind turbine maintenance with CTVs, an estimated 0.14 h required to reach the repair location. Utilizing AR for offshore wind turbine remote maintenance	Saving approximately 4 h and 1 labor workforce.

To estimate the potential benefits of AR in wind farm maintenance, we conducted a preliminary assessment using the Taiwan Power Company's Phase I offshore wind farm demonstration project as a case study. With an offshore distance of approximately 7.95 kilometers, crew transfer vessels (CTVs) operating at a speed of about 30 knots (approximately 56 km/h), and an estimated 0.14 h required to reach the repair location, we projected that the implementation of AR for remote maintenance can reduce the required workforce from 3 to 1–2 individuals, resulting in a significant 1/3 reduction in labor costs. The conservative estimate for traditional maintenance duration is 6 h, whereas AR technology has the potential to reduce it by 1/3, reducing the time to 4.14 h. This translates to substantial savings of 1.86 h compared with the traditional 6-h maintenance approach. This improvement can also be estimated in the following cases such as blade damage inspection, lubricating oil replacement, routine turbine check, wind sensor calibration, and anti-corrosion coating maintenance, as shown in Table 3.

5. Conclusions

AR technology can help streamline maintenance processes, increase efficiency, and reduce downtime, ultimately leading to cost savings and improved turbine performance. This research is underpinned by five core technologies: (1) the development of an AR monitoring system, (2) the utilization of industrial communication via Modbus technology, (3) the implementation of program logic control, (4) the incorporation of a remote expert system, and (5) the application of a MySQL database. These technologies work synergistically to shape a comprehensive AR monitoring system, which manifests in four crucial segments.

i. The initial segment incorporates a self-developed wind turbine control system, utilizing a control box. This phase employs the display of lights and the manipulation of switches to simulate the operations of a wind turbine, recreating various situations, such as excessive wind speed or disconnection events.
ii. The subsequent segment involves crafting the logic of the PLC. This is achieved by integrating the display of lights and switches from the first segment to establish an internal control logic, thereby simulating the operational scenarios of a wind turbine system.
iii. The third segment involves the creation of the AR interface using Unity and Vuforia. This phase involves programming the display interface and database connection using C#. Upon completion, the entire project is compiled into an APK file for display on tablets or smartphones.
iv. The final segment is dedicated to data backup. It communicates with the PLC through Modbus TCP/IP; the data obtained from this communication is written into a database for safekeeping.

Moreover, an auxiliary function of this research is the implementation of a remote expert system, which enables annotations and markings on real-world objects within the AR interface, made feasible through the AR camera lens.

The system will continue to evolve to simulate various scenarios and conditions that a wind farm may encounter and offer a comprehensive monitoring solution. This constant development aims to improve the efficiency of wind farm operations. Although a significant portion of the research was validated through operational tests in a real wind turbine, the testing was limited to multiple wind turbines. In the future, we plan to expand the application of this system to various wind turbines and conduct more customized designs. Additionally, we aspire to integrate a predictive maintenance system into our AR-assisted repair platform. The incorporation of machine learning algorithms will empower the system to predict potential faults based on historical data, thereby enabling preemptive measures.

On the hardware side, given the portability and popularity of smartphones and tablets, they were chosen as the development platform for this research. The cost of AR glasses is currently high and gesture recognition functionality is not as user-friendly as anticipated. However, our vision for the future involves migrating this project to AR glasses. Combined with precise gesture recognition, this would facilitate truly hands-free operation. Maintenance personnel could then benefit from the visual information displayed on the AR glasses, freeing their hands to focus more effectively on the repair tasks.

Considering the continual evolution of immersive technology, we also foresee an opportunity to extend our platform from merely an AR system to a broader concept of extended reality (XR). This would imply embracing elements of virtual and mixed realities, thereby enriching user interaction by creating more dynamic and responsive experiences between users and digital content. This incorporation of XR into our platform will not only provide a more immersive user experience but also ensure our project's relevance amidst future advancements in immersive technologies.

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