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An IoT-Based 360° Ultrasonic Obstacle Detection System for Real-Time Occupational Safety Monitoring

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ABSTRACT

Occupational safety remains a significant challenge in industrial and agricultural environments due to limited visibility and obstacle-related accidents. This study presents the development of an IoT-based 360° ultrasonic obstacle detection system for real-time hazard monitoring. The proposed system integrates an ESP32 microcontroller, an HC-SR04 ultrasonic sensor mounted on a 28BYJ-48 stepper motor, and the Blynk IoT platform to perform continuous 360° environmental scanning while enabling remote monitoring. A multi-level alert mechanism consisting of green, yellow, and red LEDs, together with an audible buzzer, was implemented to notify users based on predefined obstacle distance thresholds. The prototype was evaluated under Safe, Warning, and Danger operating conditions to assess its obstacle detection performance, response time, and system reliability. Experimental results demonstrated that the system successfully performed continuous obstacle detection, correctly activated the corresponding notification mechanisms, and maintained synchronized real-time monitoring through the Blynk dashboard and radar visualization interface. The system also achieved a response time of less than 500 ms, enabling timely hazard notification. Overall, the proposed system offers a low-cost, reliable, and practical solution for improving situational awareness and enhancing occupational safety in construction, warehouse, and agricultural environments.

Keywords: Internet of Things (IoT), Obstacle Detection, Ultrasonic Sensor, Occupational Safety, Real-Time Monitoring

INTRODUCTION

The rapid advancement of the Internet of Things (IoT) has transformed industrial monitoring and occupational safety by enabling real-time sensing, wireless communication, and remote supervision of critical environments. The integration of IoT technologies into industrial applications has significantly improved situational awareness, allowing safety-related information to be collected, transmitted, and analyzed continuously (Ashton, 2009). More recently, IoT platforms integrated with embedded microcontrollers such as the ESP32 have enabled the development of low-cost, intelligent monitoring systems capable of providing real-time alerts and cloud-based visualization for safety-critical applications. Recent reviews have further highlighted that IoT-based monitoring systems are becoming an essential component of modern occupational health and safety (OHS) by improving hazard detection, reducing response time, and supporting data-driven safety management (Zikas et al., 2026).

Occupational safety remains a major concern in construction sites, manufacturing facilities, warehouses, and agricultural environments where workers operate alongside heavy machinery and moving vehicles. According to previous studies, struck-by incidents continue to be among the leading causes of workplace injuries because operators often experience limited visibility and blind spots while performing daily operations (Cheng & Teizer, 2011). Conventional safety practices primarily rely on manual observation, warning signs, or fixed-position sensors that monitor only limited areas. Consequently, hazards approaching from outside the sensing region may remain undetected, reducing the effectiveness of existing safety monitoring systems. Recent studies have emphasized that smart sensing technologies and connected monitoring platforms are increasingly adopted to enhance workplace safety through continuous environmental monitoring and early hazard notification (Zikas et al., 2026).

Obstacle detection technologies have evolved considerably over the past decades. Vision-based systems provide detailed environmental information but require high computational resources and are highly dependent on illumination conditions, camera positioning, and image-processing algorithms (Sivaraman & Trivedi, 2013). Likewise, LiDAR-based systems achieve high measurement accuracy but involve considerably higher implementation costs, making them less attractive for low-cost industrial safety applications. In contrast, ultrasonic sensors offer an economical and reliable alternative for obstacle detection because they operate independently of ambient lighting conditions while providing satisfactory distance measurement accuracy for short-range applications (Borenstein & Koren, 1988). Recent reviews on obstacle detection systems also indicate that ultrasonic sensors remain widely adopted due to their low cost, ease of implementation, and satisfactory performance in short-range detection, particularly when integrated with IoT technologies (Joseph et al., 2023; Xu et al., 2023).

Recent advances in embedded systems have further enhanced ultrasonic sensing by integrating wireless communication and cloud-based monitoring. ESP32 microcontrollers combined with the Blynk IoT platform have demonstrated promising performance in various real-time monitoring applications, including smart home security, railway crossing monitoring, and automated safety systems. These implementations highlight the practicality of IoT-enabled monitoring for providing instant notifications, remote visualization, and improved operational awareness while maintaining relatively low implementation costs (Lovella & Yuhendri, 2024; Syahrani et al., 2025).

Despite these developments, several limitations remain in existing obstacle detection systems. Many ultrasonic-based monitoring systems employ fixed sensors that provide only a limited field of view, resulting in blind spots that reduce environmental coverage. Although camera-based systems can provide wider scene information, their performance deteriorates under poor lighting or dusty industrial conditions. Furthermore, many existing IoT monitoring systems focus primarily on transmitting sensor readings without integrating comprehensive environmental scanning together with multi-level local warning mechanisms. Current reviews also identify limited adoption of cloud-based visualization and integrated sensing architectures in occupational safety applications, indicating opportunities for developing more comprehensive and scalable monitoring systems (Zikas et al., 2026).

To address these limitations, this study proposes an IoT-Based 360° Ultrasonic Scanning System with Real-Time Monitoring and Alert Notification. The proposed prototype integrates an ESP32 microcontroller, an HC-SR04 ultrasonic sensor, and a 28BYJ-48 stepper motor to perform continuous 360-degree environmental scanning. A multi-level alert mechanism comprising green, yellow, and red LEDs together with an audible buzzer provides immediate visual and acoustic feedback according to predefined safety thresholds. Simultaneously, obstacle information is transmitted through Wi-Fi to the Blynk cloud platform, allowing operators to remotely monitor obstacle locations and system status using mobile devices or personal computers. In addition, a radar-style visualization interface is developed to improve users' situational awareness by displaying obstacle positions in real time.

The main contributions of this study are summarized as follows:

i) Development of a low-cost IoT-enabled prototype capable of performing continuous 360° ultrasonic obstacle detection.
ii) Integration of real-time cloud monitoring using the ESP32 microcontroller and Blynk IoT platform.
iii) Implementation of a multi-level alert notification system combining visual and audible warning indicators.
iv) Experimental evaluation of the proposed system in terms of obstacle detection capability, response behaviour, and suitability for occupational safety monitoring.

The proposed system demonstrates that integrating ultrasonic sensing, embedded IoT technologies, and real-time monitoring provides a practical and scalable solution for enhancing occupational safety while maintaining low implementation cost. The developed prototype also establishes a foundation for future intelligent safety systems incorporating artificial intelligence, sensor fusion, and predictive hazard analysis.

METHODOLOGY

System Architecture

The proposed IoT-based 360° ultrasonic scanning system was developed to provide continuous obstacle detection and real-time hazard monitoring in dynamic environments. The system consists of four major subsystems: (i) sensing module, (ii) control module, (iii) alert module, and (iv) IoT communication module, as illustrated in Figure 1. The ESP32 microcontroller serves as the central processing unit, coordinating data acquisition, motor control, local notifications, and wireless communication.

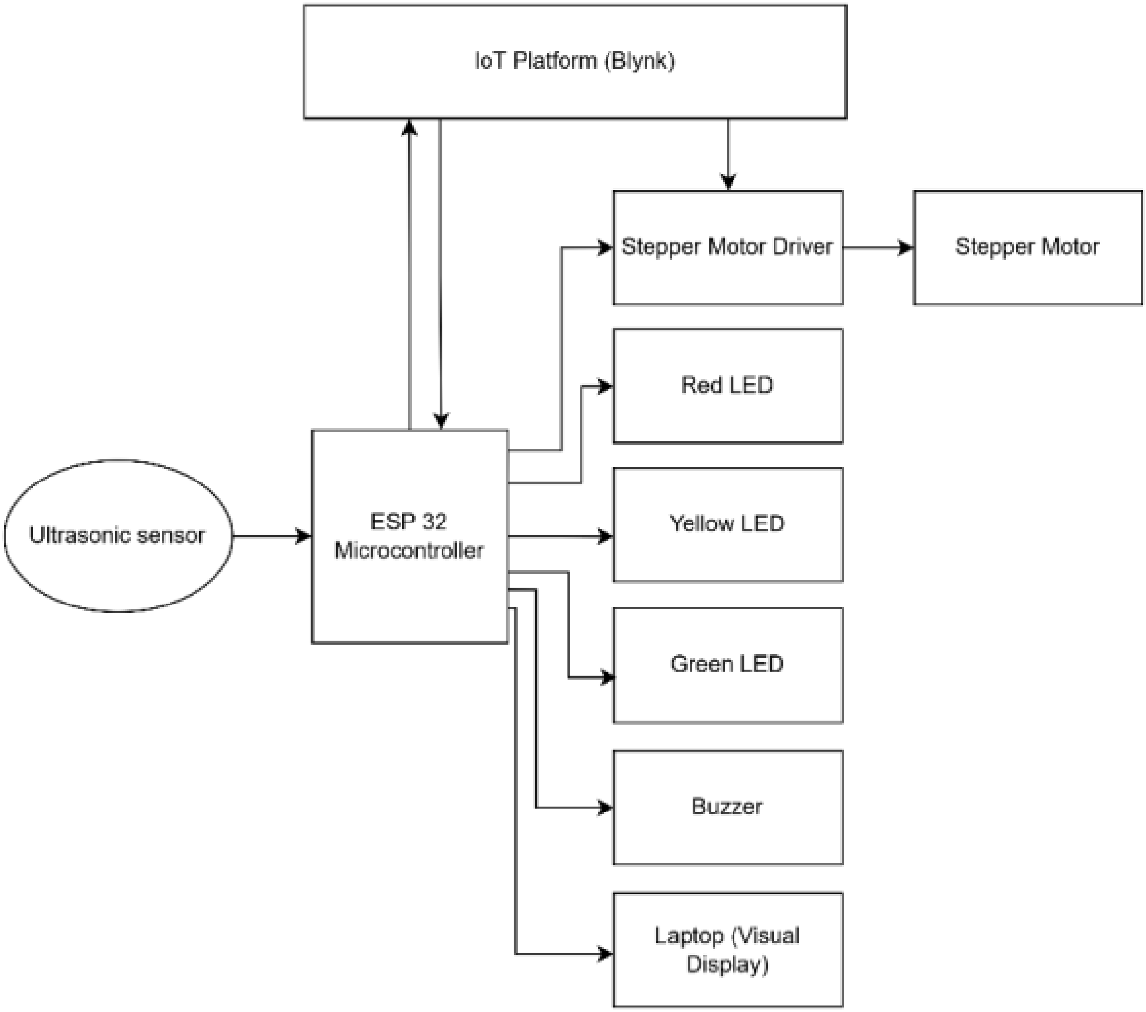

Figure 1: Proposed Architecture of the IoT-Based 360° Ultrasonic Scanning System

The sensing module comprises an HC-SR04 ultrasonic sensor mounted on a 28BYJ-48 stepper motor. The rotating mechanism enables the sensor to perform continuous 360° environmental scanning by collecting distance measurements at multiple angular positions. The measured distance values are transmitted to the ESP32 for processing, where obstacle distances are evaluated against predefined safety thresholds.

The alert module consists of three coloured LEDs (green, yellow, and red) together with an active buzzer to provide immediate visual and audible warnings. Simultaneously, processed sensor data are transmitted via the built-in Wi-Fi capability of the ESP32 to the Blynk IoT cloud platform, allowing users to monitor system status remotely using smartphones or personal computers. In addition, a radar-style visualization interface developed using the Processing software displays obstacle positions in real time, improving operators' situational awareness.

Hardware Configuration

The prototype was constructed using commercially available electronic components to achieve a low-cost and scalable monitoring solution. Table 1 summarizes the major hardware components employed in the proposed system.

Table 1: Hardware Components of the Proposed System

Component	Function
ESP32 NodeMCU	Main controller and Wi-Fi communication
HC-SR04 Ultrasonic Sensor	Distance measurement and obstacle detection
28BYJ-48 Stepper Motor	Continuous 360° sensor rotation
ULN2003 Driver Module	Stepper motor control interface
Green, Yellow and Red LEDs	Visual safety indication
Active Buzzer	Audible warning notification
5 V Power Supply	System power source
PCB Board	Permanent hardware implementation

The ESP32 microcontroller was selected because it provides sufficient processing capability together with integrated Wi-Fi communication, enabling simultaneous sensor acquisition, motor control, and cloud connectivity. The HC-SR04 ultrasonic sensor performs non-contact distance measurement using the time-of-flight principle, while the 28BYJ-48 stepper motor rotates the sensor incrementally to achieve full 360° environmental coverage. The ULN2003 driver module supplies the required driving current for the stepper motor without overloading the ESP32 output pins.

Software Development and System Operation

The software was developed using the Arduino Integrated Development Environment (Arduino IDE). The control algorithm initializes the ESP32, establishes a Wi-Fi connection with the Blynk cloud platform, and continuously rotates the stepper motor through a complete 360° scanning cycle. During each scanning position, the ultrasonic sensor transmits an ultrasonic pulse and measures the echo return time to calculate the obstacle distance.

The measured distance is compared with two predefined threshold values to classify the surrounding environment into three safety levels:

- Safe Zone: Green LED ON; buzzer OFF.
- Warning Zone: Yellow LED ON; buzzer OFF.
- Danger Zone: Red LED ON; buzzer ON.

The processed distance information, alert status, and scanning angle are transmitted to the Blynk platform via Wi-Fi for remote monitoring. Simultaneously, the distance data are sent through serial communication to the Processing application to generate a radar-style visualization of the detected obstacles in real time. This dual-monitoring mechanism enables both local and remote supervision of the monitored environment.

Prototype Development

The prototype development process consisted of four sequential stages: literature review, circuit simulation, printed circuit board (PCB) fabrication, and hardware integration.

Initially, the proposed circuit was designed and verified through simulation to ensure correct functionality before hardware implementation. Following successful verification, a custom PCB was designed, fabricated, and assembled using standard PCB manufacturing procedures, including layout preparation, ultraviolet exposure, chemical etching, drilling, and component soldering. The completed hardware was then integrated with the developed software to produce a fully functional prototype.

To ensure safe laboratory practices throughout fabrication and assembly, appropriate personal protective equipment (PPE) was used during PCB manufacturing, drilling, soldering, and testing activities.

Experimental Procedure

The prototype was evaluated under controlled laboratory conditions using obstacles positioned at various distances from the rotating ultrasonic sensor. During each experiment, the stepper motor continuously rotated the ultrasonic sensor through 360°, while the ESP32 collected distance measurements and classified each obstacle according to the predefined safety thresholds.

System performance was evaluated based on three criteria:

i) Obstacle detection capability during continuous 360° scanning.
ii) Alert notification performance, including LED activation, buzzer response, and IoT notification.
iii) Real-time monitoring capability, evaluated using both the Blynk IoT dashboard and the radar visualization interface.

Experimental observations focused on verifying the reliability of obstacle detection, the responsiveness of the notification system, and the consistency of data transmission during continuous operation. The collected results are presented and discussed in the following section.

RESULTS AND DISCUSSION

Results of the Proposed System

The developed IoT-based 360° ultrasonic scanning system was successfully implemented and evaluated under different obstacle distances to verify its obstacle detection capability, alert mechanism, and IoT monitoring performance. The system was tested using three predefined safety conditions: Safe, Warning, and Danger.

(i) Simulation Results

Figure 2 to Figure 4 present the simulation results obtained during system verification. The simulation was conducted to validate the embedded control algorithm before hardware implementation.

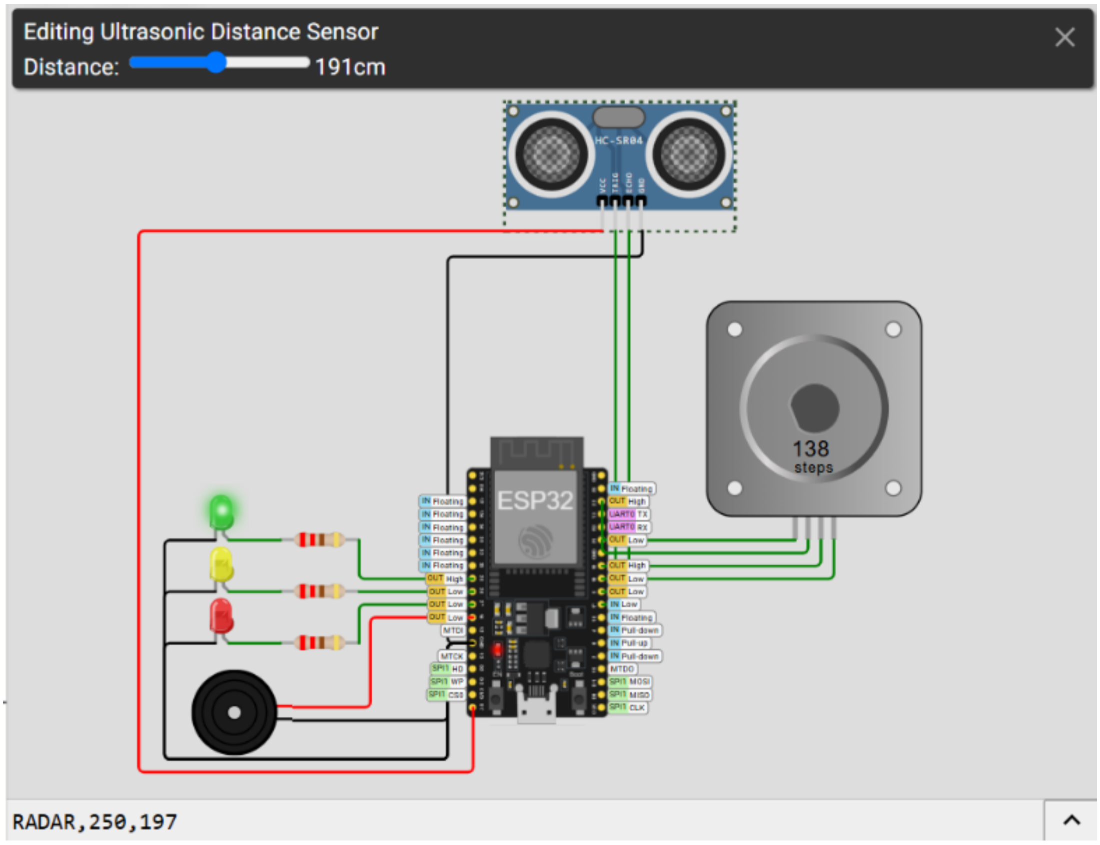

Figure 2: Simulation Result Under the Safe Condition (191 cm)

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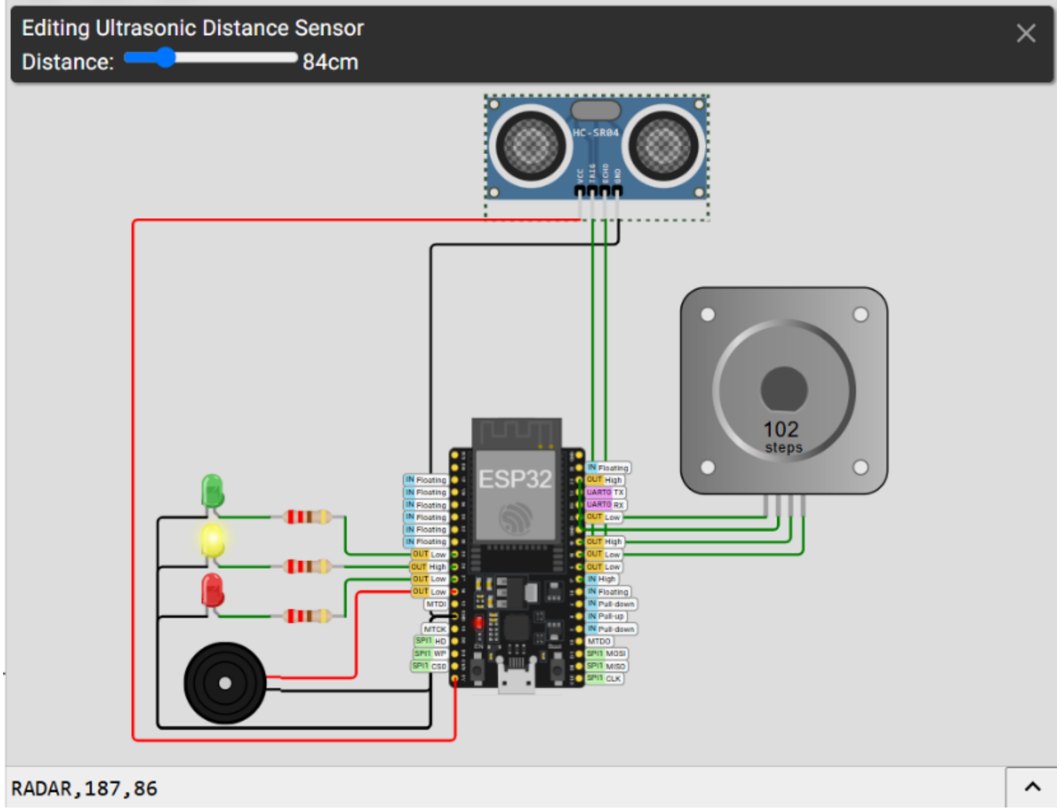


Figure 3: Simulation Result Under the Warning Condition (84 cm)

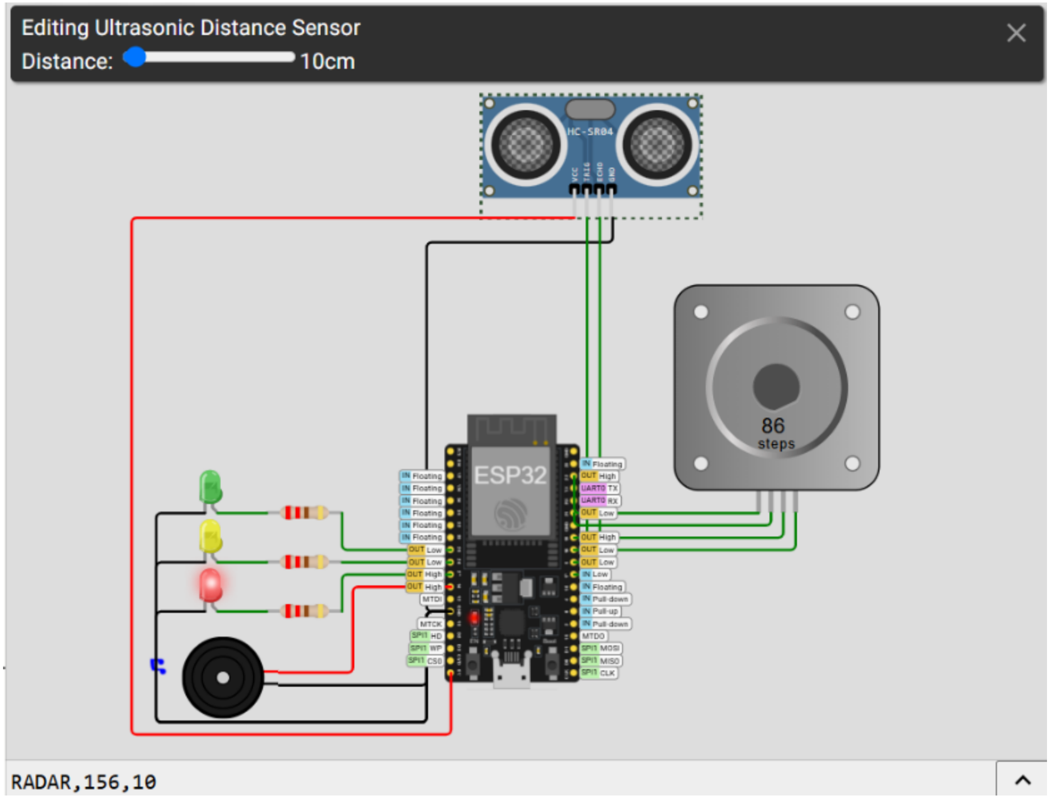


Figure 4: Simulation Result Under the Danger Condition (10 cm)

Figure 2 shows the system operating under the Safe condition, where the detected obstacle was approximately 191 cm from the sensor. The green LED was activated to indicate that no immediate hazard was present.

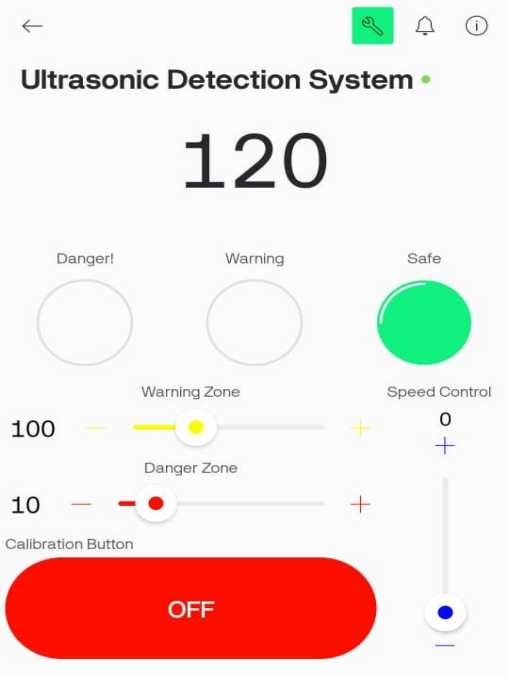
Figure 3 illustrates the Warning condition. As the obstacle approached the sensor, the measured distance decreased to approximately 84 cm. The system successfully switched from the green LED to the yellow LED, indicating that the obstacle had entered the predefined warning zone.

Figure 4 shows the Danger condition, where the obstacle was detected at approximately 10 cm. The system immediately activated the red LED to indicate a hazardous situation. The simulation results verified that the developed control algorithm correctly classified obstacle distances according to the predefined safety thresholds before hardware implementation.

(ii) Experimental Results

The experimental performance of the developed prototype was evaluated using the Blynk IoT dashboard, the physical prototype, and the Processing-based radar visualization.

Figure 5 show the system operating under the Safe condition. The Blynk dashboard displayed the measured distance in real time, while the prototype activated the green LED to indicate a safe operating condition. The radar visualization also showed that no obstacle was detected within the critical safety region.



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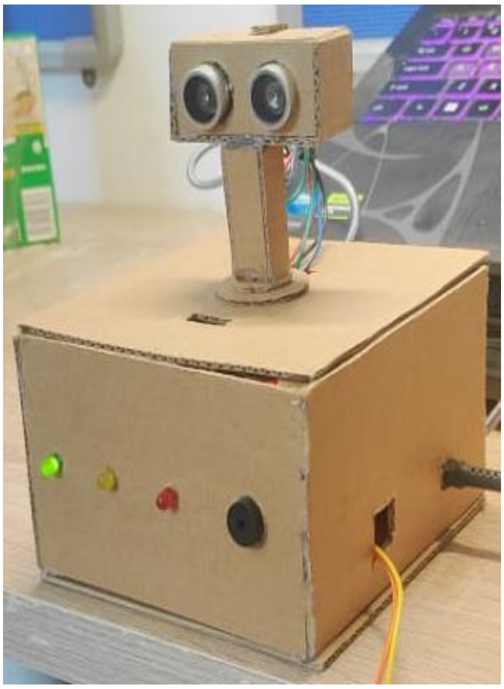

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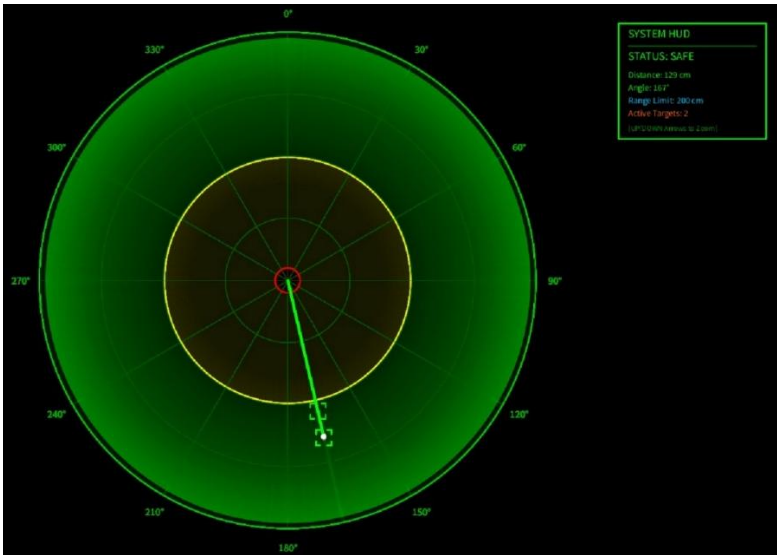

(c)

Figure 5: System Response Under the Safe Condition: (a) Blynk Dashboard Displaying the Measured Distance, (b) Prototype Indicating the Safe Condition (Green LED), and (c) Radar Visualization of the Detected Obstacle

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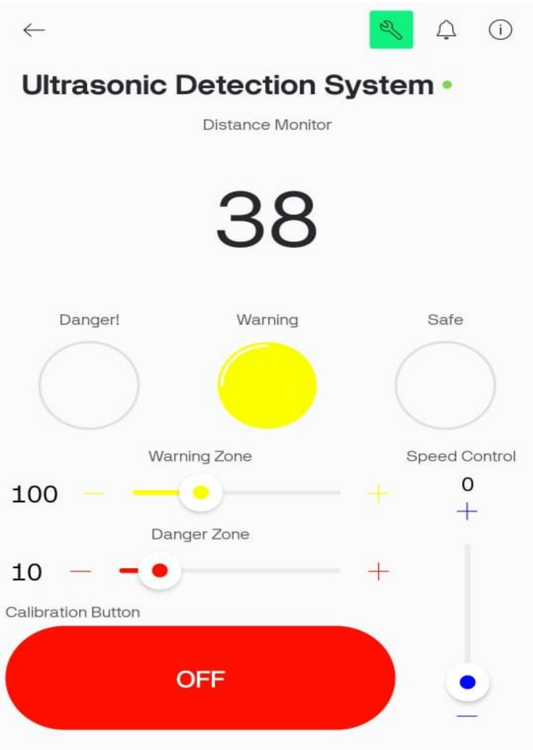
Figure 6 illustrate the Warning condition. As the obstacle moved closer to the sensor, the measured distance was updated on the Blynk dashboard and the yellow LED was activated. The radar visualization accurately identified the obstacle position, demonstrating successful synchronization between the sensing unit and the visualization interface.



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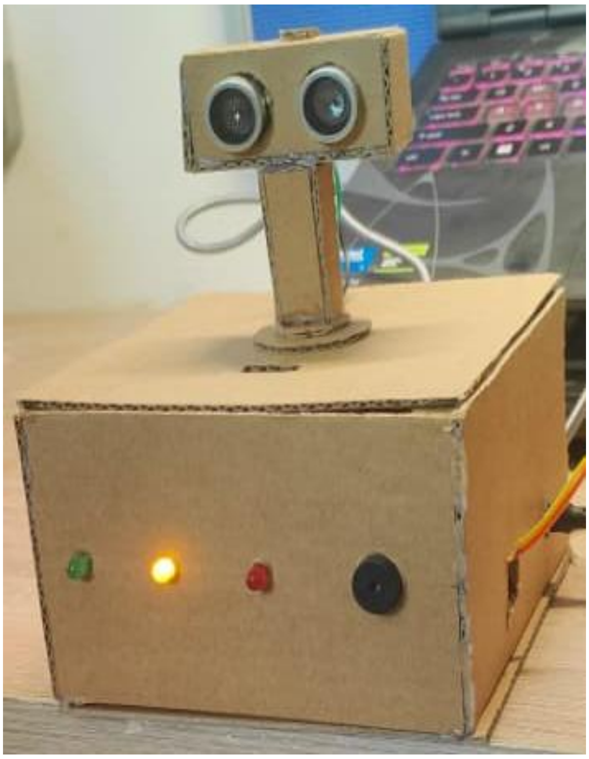

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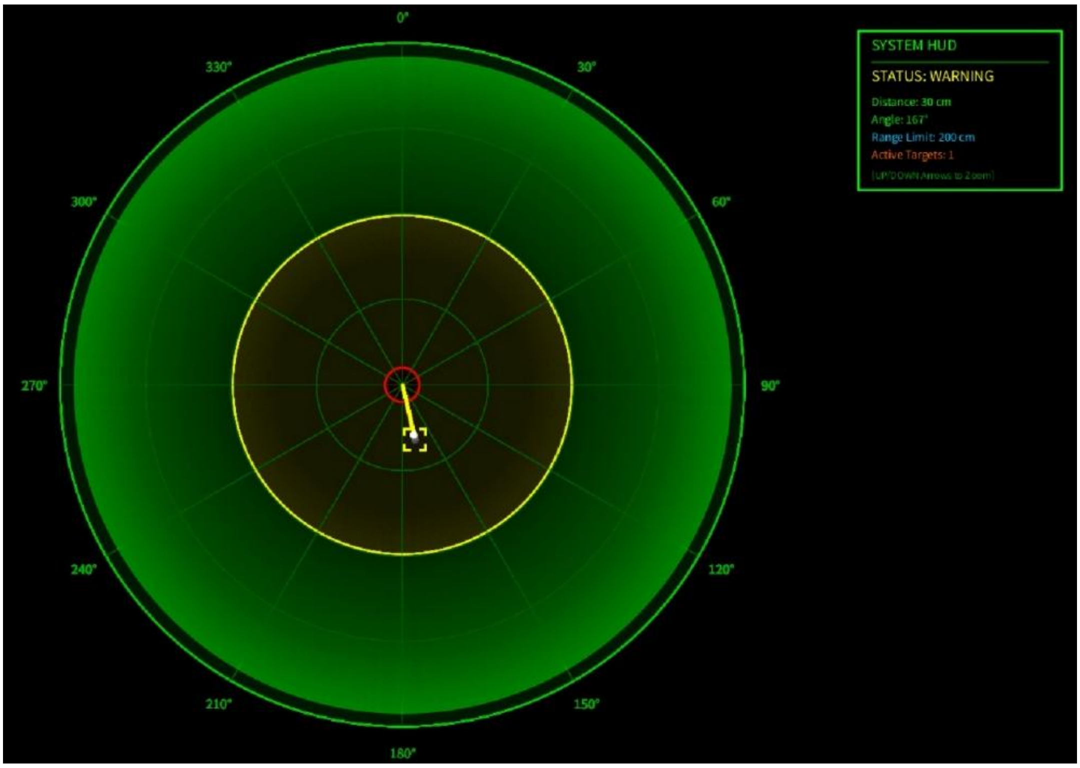

(c)

Figure 6: System Response Under the Warning Condition: (a) Blynk Dashboard Displaying the Measured Distance, (b) Prototype Indicating the Warning Condition (Yellow LED), and (c) Radar Visualization of the Detected Obstacle

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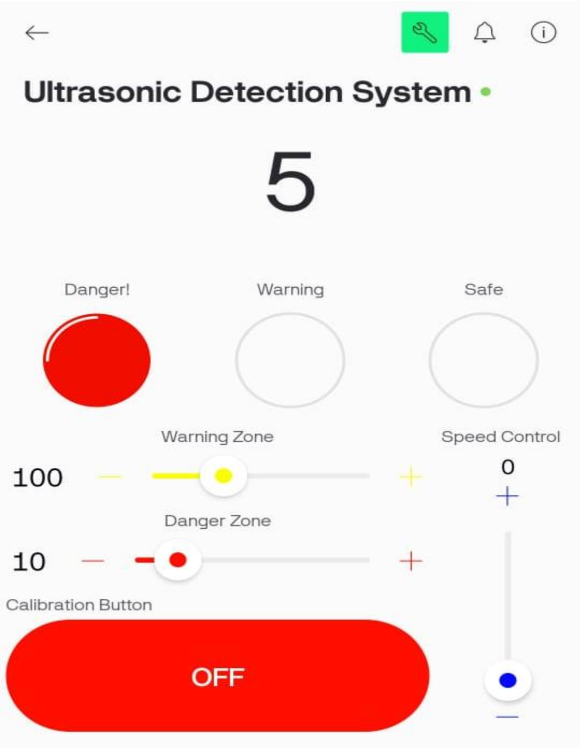
Figure 7 present the Danger condition. When the obstacle entered the critical detection range, the prototype activated the red LED together with the buzzer to provide immediate warning. Simultaneously, the Blynk dashboard updated the obstacle distance and warning status, while the radar interface displayed the obstacle within the danger zone. The results demonstrate that the physical alerts and cloud-based monitoring operated simultaneously throughout the experiment.



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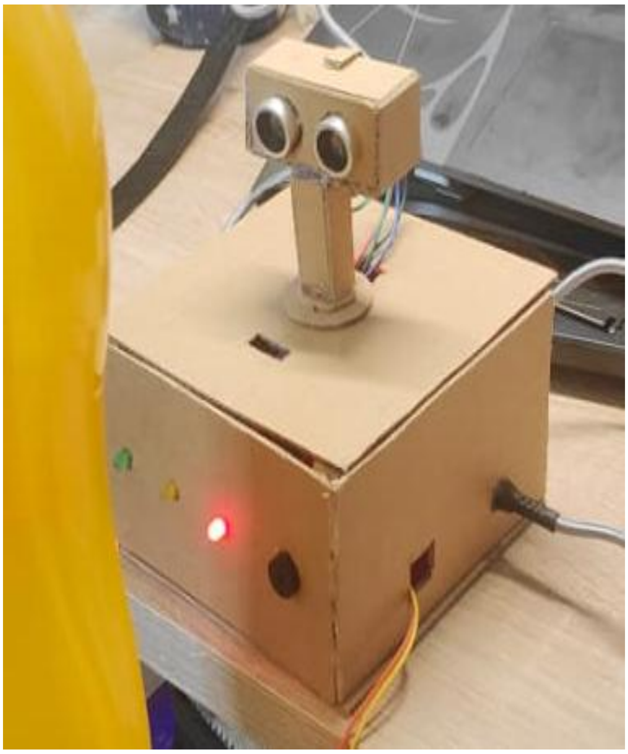

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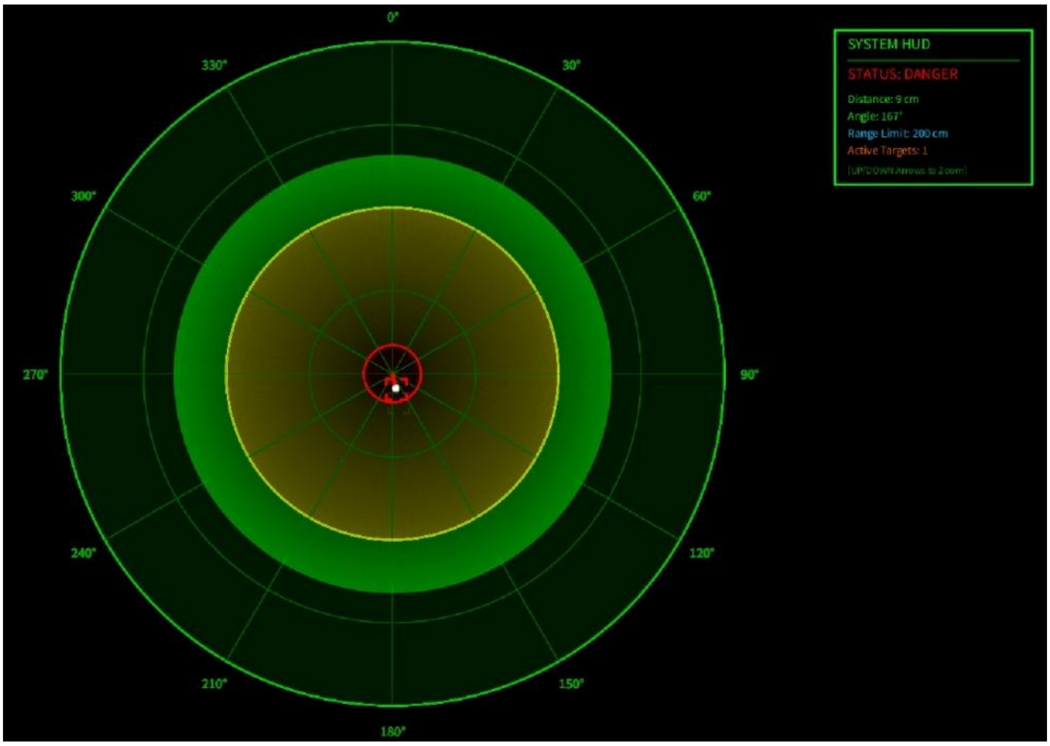

(c)

Figure 7: System Response Under the Danger Condition: (a) Blynk Dashboard Displaying the Measured Distance, (b) Prototype Indicating the Danger Condition (Red LED), and (c) Radar Visualization of the Detected Obstacle

Table 2 summarizes the system responses under the three operating conditions.

Table 2: Experimental Observations Under Different Operating Conditions

Condition	Measured Distance (cm)	LED Status	Buzzer	Blynk Status	Radar
Safe	191	Green	OFF	Safe	No nearby obstacle
Warning	84	Yellow	OFF	Warning	Obstacle detected
Danger	10	Red	ON	Danger	Critical obstacle

The results demonstrate that the proposed system consistently differentiated obstacle proximity using predefined threshold values while maintaining synchronization between the physical alerts and the IoT monitoring platform.

System Performance Evaluation

The proposed system was evaluated based on three performance criteria: obstacle detection performance, response time, and system reliability.

(i) Obstacle Detection Performance

The obstacle detection performance of the proposed system was evaluated under three predefined operating conditions: Safe, Warning, and Danger. The evaluation focused on the system's ability to detect obstacles continuously during 360° scanning and activate the corresponding notification mechanisms.

As summarized in Table 2, the prototype successfully detected obstacles at different distances and correctly classified them according to the predefined threshold values. Under the Safe condition, the system maintained the green LED while the buzzer remained inactive, indicating that no immediate hazard was present. When the obstacle entered the warning region, the system automatically switched to the Warning condition by activating the yellow LED. As the obstacle moved closer to the sensor, the system correctly identified the Danger condition by activating the red LED together with the audible buzzer.

In addition to the local notifications, the Blynk dashboard continuously displayed the obstacle status and measured distance, while the radar visualization accurately represented the obstacle position during each operating condition. The synchronization between the sensing module, local alert system, cloud-based monitoring platform, and radar visualization demonstrates the effectiveness of the proposed system in providing continuous real-time obstacle detection and hazard notification.

Overall, the experimental results confirm that the proposed system successfully performed continuous 360° obstacle detection and consistently responded to changes in obstacle proximity. These findings indicate that the developed prototype is suitable for real-time occupational safety monitoring, particularly in applications where early hazard detection and immediate user notification are essential.

(ii) Response Time

The response time of the proposed system was evaluated by observing the time required for the system to react after an obstacle entered the predefined detection zone. The response included obstacle detection by the HC-SR04 ultrasonic sensor, processing by the ESP32 microcontroller, activation of the corresponding LED indicator and buzzer, and the transmission of obstacle information to the Blynk IoT platform. Experimental observations indicated that the overall response time remained below 500 ms, demonstrating the capability of the system to provide timely hazard notification.

The short response time can be attributed to the efficient integration of the ESP32 microcontroller, ultrasonic sensing, and Wi-Fi communication. During testing, the LED indicators, buzzer, Blynk dashboard, and radar visualization responded consistently with minimal observable delay after obstacle detection. This synchronized operation enables users to receive immediate local and remote notifications, thereby improving situational awareness in safety-critical environments.

Although the proposed system demonstrated satisfactory real-time performance, the overall response time is influenced by the mechanical scanning process of the rotating ultrasonic sensor. Since the sensor scans the environment sequentially, obstacles that appear immediately after a scanning cycle may only be detected during the next scan. Nevertheless, the observed response time remained sufficiently low for the intended short-range occupational safety applications, indicating that the developed prototype is capable of providing effective real-time hazard monitoring.

(iii) System Reliability

Continuous testing demonstrated stable operation throughout the evaluation period. The stepper motor rotated continuously without mechanical failure, while the ESP32 maintained reliable communication with the Blynk platform. No significant interruption in cloud synchronization or radar visualization was observed during testing, confirming the reliability of the proposed system for continuous monitoring.

DISCUSSION

The experimental results demonstrate that the proposed IoT-based 360° ultrasonic obstacle detection system successfully achieved the objectives of this study. The integration of the HC-SR04 ultrasonic sensor with the 28BYJ-48 stepper motor enabled continuous 360° environmental scanning, thereby improving monitoring coverage compared with conventional fixed-position ultrasonic sensors. Furthermore, the implementation of a multi-level alert mechanism consisting of visual indicators, an audible buzzer, and cloud-based monitoring through the Blynk platform provided synchronized local and remote notifications, enhancing users' situational awareness in real time.

Compared with conventional obstacle detection systems that employ a single fixed ultrasonic sensor, the proposed system offers wider environmental coverage without significantly increasing hardware complexity or implementation cost. The use of commercially available components resulted in a total hardware cost of approximately RM114.90, demonstrating that the proposed prototype is a practical and economical solution for occupational safety applications in construction sites, warehouses, manufacturing facilities, and agricultural environments. In addition, the successful synchronization between the sensing module, alert system, Blynk dashboard, and radar visualization confirm the feasibility of integrating embedded IoT technologies into low-cost safety monitoring systems.

Despite these promising results, several limitations should be acknowledged. First, the sensing capability is constrained by the operating characteristics of the HC-SR04 ultrasonic sensor, which has a limited detection range and may exhibit reduced performance when detecting irregularly shaped objects or surfaces with low ultrasonic reflectivity. Consequently, the current prototype is more suitable for short-range obstacle detection in controlled or semi-controlled environments. Second, the rotating scanning mechanism introduces a finite scanning interval because the ultrasonic sensor acquires measurements sequentially rather than simultaneously in all directions. As a result, rapidly approaching obstacles may only be detected during the subsequent scanning cycle, depending on the rotational speed of the stepper motor. Nevertheless, the experimental results demonstrated that the overall response time remained below 500 ms, indicating that the system can provide timely hazard notifications for the intended applications.

Furthermore, the prototype was evaluated under controlled laboratory conditions. Factors commonly encountered in real industrial and outdoor environments, such as temperature variations, humidity, airborne noise, dust, and the acoustic properties of obstacle surfaces, may influence ultrasonic signal propagation and measurement reliability. Therefore, additional experimental validation under diverse environmental conditions is necessary to comprehensively evaluate the robustness and practical deployment of the proposed system.

Overall, the findings demonstrate that integrating ultrasonic sensing with embedded IoT technologies provides an effective and affordable approach for real-time occupational safety monitoring. The proposed prototype establishes a foundation for future intelligent safety systems that incorporate enhanced sensing technologies, adaptive scanning strategies, and advanced data analytics to improve hazard detection performance in complex industrial environments.

CONCLUSIONS

This study presented the development and evaluation of an IoT-based 360° ultrasonic obstacle detection system for real-time occupational safety monitoring. The proposed system successfully integrated an ESP32 microcontroller, an HC-SR04 ultrasonic sensor mounted on a 28BYJ-48 stepper motor, and the Blynk IoT platform to provide continuous 360° environmental scanning, multi-level alert notifications, and cloud-based remote monitoring. The developed prototype demonstrates the feasibility of combining embedded systems, wireless communication, and real-time visualization into a low-cost safety monitoring solution.

Experimental evaluation confirmed that the proposed system successfully detected obstacles under the predefined Safe, Warning, and Danger operating conditions. The synchronized operation of the LED indicators, buzzer, Blynk dashboard, and radar visualization enabled timely local and remote hazard notification, while the overall response time of less than 500 ms demonstrated the capability of the system to support real-time monitoring. These findings indicate that the proposed system can enhance situational awareness and contribute to improving occupational safety in environments such as construction sites, warehouses, manufacturing facilities, and agricultural operations.

Although the prototype demonstrated satisfactory performance, several limitations remain. The sensing capability is constrained by the characteristics of the HC-SR04 ultrasonic sensor, and the rotating scanning mechanism introduces a finite scanning interval that may affect the detection of rapidly approaching obstacles. In addition, the current evaluation was conducted under controlled laboratory conditions, and further investigation is required to assess the system performance under varying environmental conditions commonly encountered in practical industrial applications.

Future work will focus on enhancing the sensing capability through sensor fusion, such as integrating LiDAR, infrared sensors, or multiple ultrasonic sensors to improve detection accuracy and environmental coverage. Adaptive scanning strategies may also be investigated to reduce blind time by dynamically prioritizing high-risk sectors during the scanning process. Furthermore, the incorporation of lightweight artificial intelligence or machine learning algorithms for object classification and differentiation between stationary and moving obstacles, together with advanced communication technologies such as LoRaWAN, has the potential to further improve the intelligence, scalability, and reliability of the proposed system for next-generation occupational safety monitoring.

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