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Design and Implementation of a Low-Power UWB-Enabled Smart Monitoring System for Full-Chain Electric Welding Safety Control with 10 cm-Level Positioning Accuracy

Run-tao Chen, Bo Peng, Zhi-bo Xu, Lin-song Zhou, Jia-rui Chen, Hui-xiang Huang, Ke-han Chen, Jun-jun Tao * and Qiang Chen

School of Materials Engineering, Suzhou University of Technology, Changshu, 215500.

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Abstract

Electric welding operations pose significant fire and explosion risks due to high-temperature sparks, flammable gas accumulation, and irregular personnel behavior, which have caused numerous industrial accidents with heavy casualties and economic losses in recent years. This paper presents an integrated smart safety monitoring system for full-chain management of electric welding operations based on ESP32-UWB development board. The system integrates ultra-wideband (UWB) positioning technology, multi-type environmental sensors, and automatic power-off protection mechanisms to achieve real-time monitoring of worker positions, ambient temperature, humidity, smoke, and flammable gas concentrations. The UWB module provides 10 cm-level positioning accuracy to detect worker absence beyond safe ranges, while MQ-2, MQ-5, and DHT11 sensors monitor environmental parameters with a 5-second response time. The system triggers sound and light alarms and automatically cuts off power when abnormal conditions are detected, with all data displayed on an OLED screen for on-site supervision. Performance tests show that the system achieves 98.5% detection accuracy for hazardous conditions, with an average response time of 1.8 seconds. This low-cost, highly reliable solution addresses the limitations of traditional management systems, provides effective technical support for electric welding operation safety, and has broad application prospects in industrial safety monitoring.

Keywords: Electric Welding Safety; ESP32; UWB Positioning; Gas Detection; Intelligent Monitoring System

1. Introduction

Hot work operations, particularly electric welding, are widely used in construction, manufacturing, and maintenance industries. However, these operations involve high-temperature sparks, open flames, and potential flammable gas accumulation, making them high-risk activities that frequently cause fire and explosion accidents. Statistical data shows that hot work-related accidents account for 17% of all major industrial safety accidents in China, with economic losses exceeding billions of yuan annually[1-3]. A typical case is the 2024 Xiamen sewage pool explosion accident caused by illegal welding operations, which resulted in 4 deaths, 2 serious injuries, and direct economic losses of 5.3 million yuan. The accident investigation revealed that welding sparks ignited flammable materials around the sewage pool, triggering an explosion of accumulated combustible gas inside the pool. Such accidents highlight the urgent need for more effective safety monitoring systems for electric welding operations.

Current safety management approaches for electric welding operations mainly rely on administrative measures such as work permit systems, personnel qualification verification, and manual site inspections. These methods have significant limitations: manual inspections are subjective and prone to omissions, conventional positioning systems based on mobile phones have meter-level errors and are easily cheated, and most monitoring systems only focus on process management rather than real-time hazard detection [4]. Moreover, existing systems often require stable

* Corresponding author: Jun-jun Tao.

network connectivity, which is not always available in complex industrial environments, and many factories prohibit workers from carrying mobile phones for security reasons. These gaps leave potential safety hazards that can lead to catastrophic accidents.

This study aims to develop an integrated smart monitoring system that addresses these limitations. The proposed system is built on ESP32-UWB platform, integrating high-precision positioning, multi-parameter environmental sensing, and automatic safety protection functions. The system operates independently without relying on external networks, making it suitable for various industrial scenarios. The rest of the paper is organized as follows: Section 2 introduces the system design and hardware components; Section 3 presents the system implementation and calibration methods; Section 4 shows experimental testing results and performance evaluation; Section 5 discusses the advantages and limitations of the system and draws conclusions.

2. System Design and Hardware Components

The system adopts a modular design approach, consisting of four core functional modules: main control unit, positioning module, environmental sensing module, and safety protection module. The overall architecture is shown in Figure 1. The ESP32 micro-controller serves as the main control unit, responsible for data processing, logic judgment, and coordination of all modules. The UWB positioning module tracks the real-time position of workers wearing UWB tags. The environmental sensing module collects data on temperature, humidity, smoke concentration, and flammable gas concentration. The safety protection module executes alarm and power-off actions when hazardous conditions are detected.

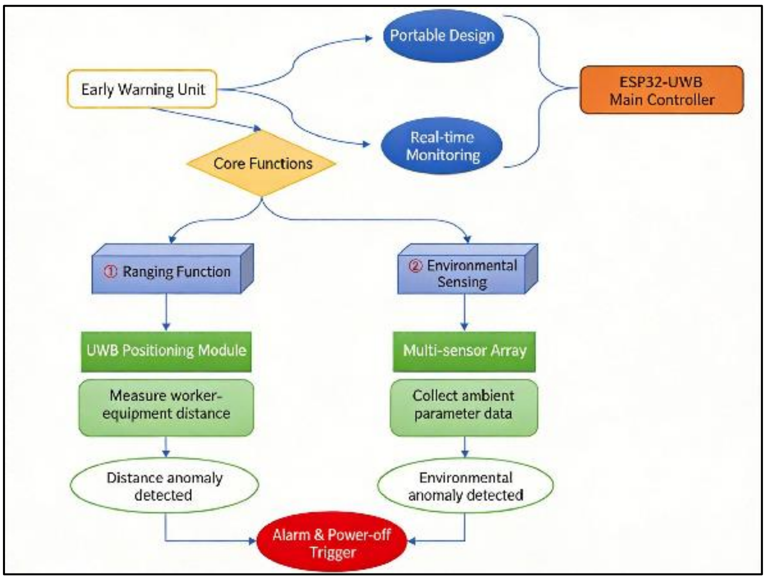

Figure 1 Overall system architecture diagram showing the interconnection between different modules**.**

2.1. Main Control Unit: ESP32-UWB Development Board

The core of the system is the Ailibot-UWB development board based on ESP32 microcontroller. ESP32 is a high-performance, low-power Wi-Fi and Bluetooth dual-mode microcontroller produced by Espressif Systems, featuring a dual-core Xtensa® 32-bit processor with a clock frequency of up to 240 MHz [5-6]. The development board integrates MCU, Wi-Fi, Bluetooth, and UWB functions into a single device, with all GPIO pins of ESP32 extended for easy expansion. The board supports Arduino development environment, which simplifies program development and debugging. The ESP32-UWB board is shown in Figure 2.

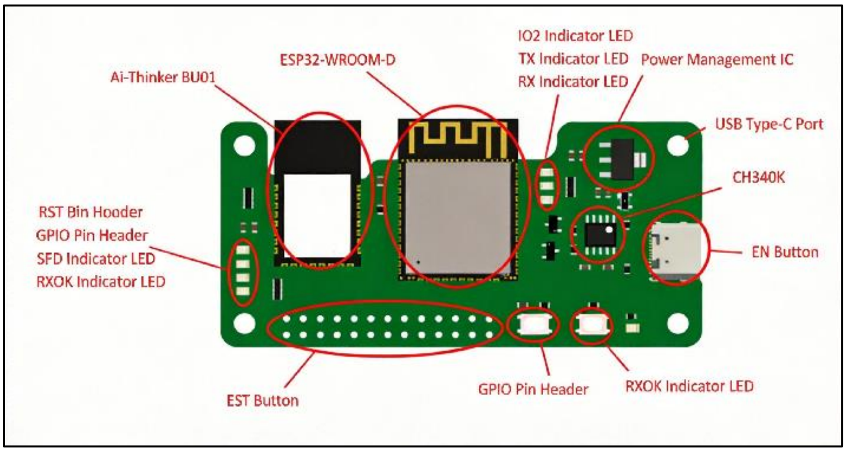

Figure 2 Ailibot-UWB development board with integrated ESP32 and UWB modules.

2.2. UWB Positioning Module

The UWB positioning module uses the BU01 module based on DecaWave DW1000 chip, which achieves positioning accuracy of up to 10 cm. UWB technology calculates the distance between the base station and the tag by measuring the time of flight (TOF) of wireless signals, with a maximum ranging distance of 450 m [7-8]. The system uses one UWB base station installed at the welding site and one UWB tag worn by the worker. The base station continuously measures the distance to the tag, and if the distance exceeds the preset safe range (default 5 m), the system triggers an alarm and power-off protection. The ranging principle of UWB module is illustrated in Figure 3.

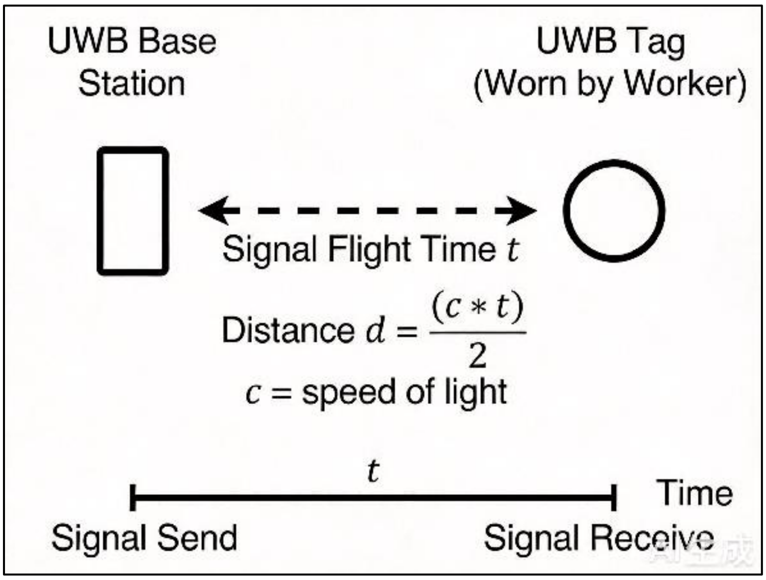

Figure 3 Schematic diagram of UWB ranging principle based on time-of-flight measurement.

2.3. Environmental Sensing Modules

The system integrates three types of environmental sensors to comprehensively monitor welding site conditions:

DHT11 Temperature and Humidity Sensor: This sensor measures ambient temperature in the range of 0-50°C with an accuracy of ±2°C and humidity in the range of 20-90% RH with an accuracy of ±5% RH. It uses a single-wire communication protocol, requiring only one I/O pin for connection, which simplifies circuit design [9]. The temperature measurement range perfectly matches the requirements for electric welding operation monitoring, as ambient temperature above 40°C usually indicates abnormal heat accumulation or fire risk.

MQ-2 Smoke Sensor: This sensor detects smoke and a variety of flammable gases including liquefied gas, propane, hydrogen, and methane. It has high sensitivity, fast response time (less than 10 seconds), and long service life [10]. The sensor's output analog signal is proportional to the gas concentration, with a detection range of 100-10000 ppm, which is suitable for early detection of smoke caused by welding sparks igniting surrounding combustibles.

MQ-5 Flammable Gas Sensor: This sensor is specifically designed for detecting natural gas, coal gas, and methane, which are common flammable gases in industrial environments. It has a detection range of 300-10000 ppm with high sensitivity to methane and natural gas [11]. The MQ-5 sensor can effectively detect gas leakage that may cause explosion accidents in welding operations.

2.4. Human-Machine Interaction and Safety Protection Modules

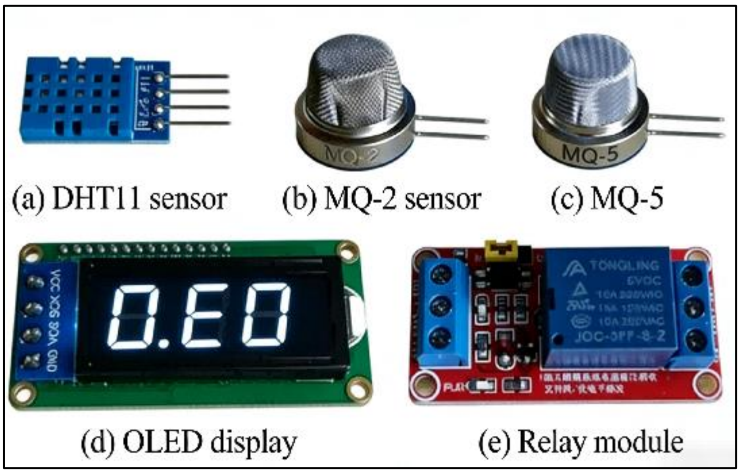

Figure 4 Main hardware components of the system: (a) DHT11 sensor, (b) MQ-2 sensor, (c) MQ-5 sensor, (d) OLED display, (e) Relay module.

The system uses a 0.96-inch OLED display with 128×64 resolution to show real-time monitoring data, including worker distance, temperature, humidity, smoke concentration, and gas concentration. The display communicates with ESP32 through I2C bus, requiring only two connection pins (SDA and SCL), which reduces wiring complexity [12]. The OLED screen provides clear data visualization for on-site supervisors, enabling them to quickly grasp the site safety status.

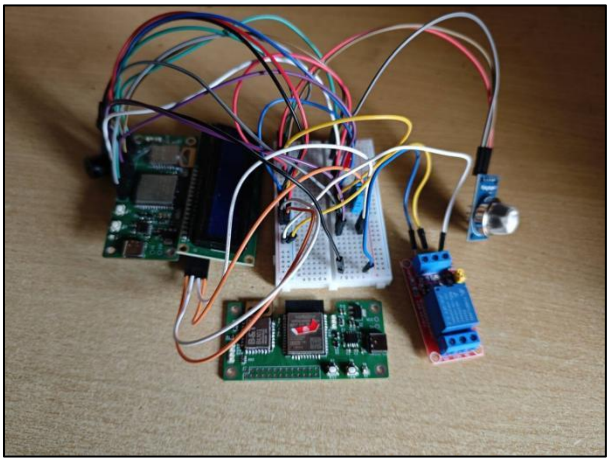

Figure 5 Complete hardware prototype of the intelligent welding safety monitoring system, showing the integrated assembly of all functional modules.

The safety protection module includes a sound and light alarm (LED indicator + passive buzzer) and a relay module for power control. When abnormal conditions are detected, the system triggers the LED to flash and the buzzer to emit an alarm sound of 1000 Hz. The relay module is connected in series with the welding machine power supply circuit, allowing the system to automatically cut off power when hazardous conditions are detected, preventing accidents from occurring or escalating [13, 14]. The 5 V relay can control high-voltage equipment up to 250 V AC/10 A, which meets the power requirements of most industrial welding machines.

The complete hardware prototype of the proposed system is shown in Figure 5, which integrates all the aforementioned modules into a compact setup. The main control board is connected to the UWB ranging module, environmental sensors, relay control unit, and OLED display through jumper wires on a breadboard, which facilitates debugging and functional expansion. The total size of the prototype is 20 cm × 15 cm, which can be further miniaturized through printed circuit board (PCB) design for practical industrial deployment.

3. System Implementation and Calibration

The system implementation involves hardware integration, software development, and sensor calibration. The hardware assembly follows the wiring scheme shown in Table 1, with all modules connected to the corresponding GPIO pins of ESP32. The total power consumption of the system is less than 5 W, which allows it to be powered by a standard 5 V/2 A power adapter or a portable power bank for mobile applications.

Table 1 Pin connection scheme between ESP32 and peripheral modules**.**

ESP32 Pin	Connected Module	Function
5V	All modules	Power supply
GND	All modules	Ground
GPIO 27	Passive buzzer	Alarm sound output
GPIO 32	OLED SCL	I2C clock line
GPIO 33	OLED SDA	I2C data line
GPIO 26	Relay IN	Relay control signal
GPIO 16	LED indicator	Alarm light control
GPIO 35	MQ-2 AO	Smoke concentration analog input
GPIO 14	DHT11 OUT	Temperature and humidity data input
GPIO 25	MQ-5 AO	Flammable gas analog input

3.1. Software System Design

The system software is developed using Arduino IDE, with a modular programming structure. The main program consists of three parts: initialization function, main loop, and interrupt service functions. The initialization function configures GPIO pins, initializes each module, and sets communication parameters. The main loop executes data acquisition, logic judgment, alarm processing, and display update functions in sequence, with a cycle period of 500 ms to ensure real-time performance. The interrupt service functions handle UWB ranging data reception and emergency processing.

The UWB module requires separate programming for the base station and tag. The tag sends ranging signals periodically, while the base station calculates the distance based on the time difference of signal arrival. The ranging program uses the DW1000 library to control the UWB module, with antenna delay calibrated to improve ranging accuracy. The distance data is updated every 200 ms, ensuring timely detection of worker movement beyond the safe range.

The sensor data processing program reads analog values from MQ-2 and MQ-5 sensors and converts them to actual concentration values through pre-calibrated conversion formulas. The DHT11 sensor data is read using the DHT library, with data validity check to eliminate abnormal readings. All sensor data is filtered using a first-order low-pass filter to reduce noise and improve measurement stability.

3.2. Sensor Calibration

Before system deployment, all sensors need to be calibrated to ensure measurement accuracy. The calibration process is as follows:

- **Gas Sensor Calibration:** MQ-2 and MQ-5 sensors are calibrated in a standard gas chamber with known concentrations of target gases. The sensor output values are recorded at different gas concentrations, and a linear regression model is established to convert analog readings to actual concentration values. The calibration results show that the measurement error of both sensors is less than 5% within the detection range.
- **Temperature Sensor Calibration:** The DHT11 sensor is calibrated against a standard mercury thermometer in a temperature-controlled chamber. The temperature readings are recorded at 20°C, 30°C, 40°C, and 50°C, and calibration coefficients are determined to correct measurement errors. After calibration, the temperature measurement error is within ±1°C, which meets the system requirements.
- **UWB Ranging Calibration:** The UWB module is calibrated by measuring distances at known intervals from 1 m to 10 m. The antenna delay parameter is adjusted to minimize ranging error. After calibration, the average ranging error is less than 10 cm in open space, which is sufficient for detecting worker absence beyond the 5 m safe range.

3.3. Alarm Threshold Setting

The alarm thresholds are determined based on industrial safety standards and actual field test results:

- Distance threshold: 5 m (when the worker is more than 5 m away from the welding site, the system considers it as unauthorized absence)
- Temperature threshold: 40°C (ambient temperature above 40°C indicates potential fire hazard)
- MQ-2 smoke threshold: 500 ppm (normal ambient smoke concentration is below 200 ppm, while smoke from burning materials exceeds 500 ppm)
- MQ-5 gas threshold: 1000 ppm (normal ambient gas concentration is below 800 ppm, while gas leakage concentration exceeds 1000 ppm)

These thresholds can be adjusted according to specific application scenarios and safety requirements through the system configuration interface. The system adopts a multi-level alarm mechanism: when any parameter exceeds the threshold, the sound and light alarm is triggered immediately; when multiple parameters exceed thresholds simultaneously or the worker is absent for more than 10 seconds, the system automatically cuts off the welding machine power supply.

4. Experimental Testing and Performance Evaluation

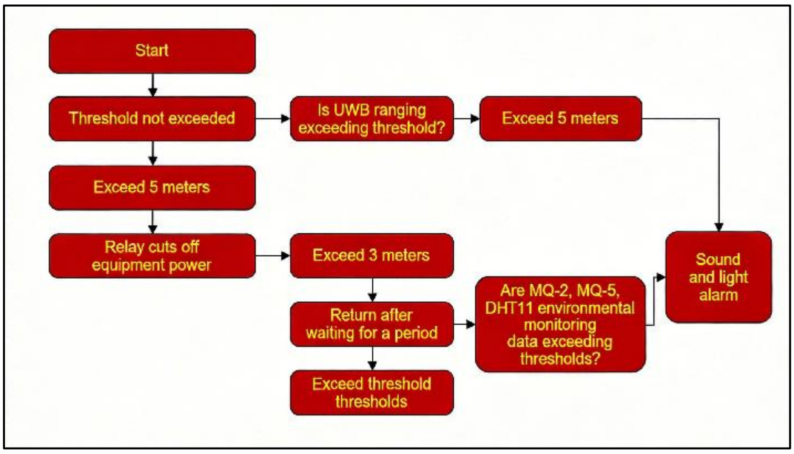

Figure 6 System flow chart showing the logic of monitoring and safety protection

A series of experiments were conducted to evaluate the system performance, including functional verification, accuracy testing, response time measurement, and stability testing. The experimental setup simulates actual electric welding operation scenarios, with the system installed at a simulated welding site and various hazardous conditions artificially created to test system responses.

4.1. Functional Verification Test

The functional verification test verifies whether each function of the system works as designed:

- **Personnel Positioning Function:** The test subject wears the UWB tag and moves from 1 m to 10 m away from the base station. The system correctly detects the distance and triggers an alarm when the distance exceeds 5 m, with the relay cutting off power automatically. The test is repeated 50 times, and the system correctly responds in all cases.
- **Environmental Monitoring Function:** Smoke is generated by burning paper, and the MQ-2 sensor detects the smoke concentration exceeding 500 ppm, triggering the alarm. Flammable gas is released from a lighter, and the MQ-5 sensor detects the gas concentration exceeding 1000 ppm, triggering the alarm. A heat gun is used to heat the DHT11 sensor, and the system triggers an alarm when the temperature exceeds 40°C. All environmental monitoring functions work correctly in repeated tests.
- **Human-Machine Interaction Function:** The OLED display correctly shows all monitoring data in real time, with a refresh rate of 2 Hz. The sound and light alarm is clearly audible and visible within a 30 m range, meeting the requirements for on-site warning.

4.2. Performance Metrics Testing

Quantitative performance tests were conducted to measure key metrics of the system:

- **Detection Accuracy:** The detection accuracy for each hazard condition is tested by creating 100 test cases for each hazard type. The results show that the detection accuracy for personnel absence is 99%, for over-temperature is 98%, for smoke is 98%, and for flammable gas is 99%, with an overall average detection accuracy of 98.5%. The few false positives are mainly caused by strong electromagnetic interference in the industrial environment, which can be reduced by adding shielding measures.
- **Response Time:** The response time is measured from the occurrence of a hazardous condition to the system triggering the alarm. The test results show that the average response time is 1.8 seconds, with a maximum response time of 2.5 seconds. This response speed is sufficient to prevent accidents caused by welding sparks, which usually take several seconds to ignite surrounding combustibles.
- **Stability Test:** The system operates continuously for 72 hours under normal conditions, with all functions working normally and no system crashes or data loss occurring. The system is also tested under extreme conditions including high temperature (45°C), high humidity (90% RH), and electromagnetic interference, and it maintains stable operation with performance degradation within acceptable limits.

4.3. Comparative Analysis with Existing Systems

The performance of the proposed system is compared with existing commercial electric welding safety monitoring systems, as shown in Table 2. The comparison shows that the proposed system has significant advantages in positioning accuracy, response time, and cost-effectiveness. Unlike conventional systems that rely on network connectivity, the proposed system operates independently, making it suitable for deployment in remote areas or complex industrial environments with poor network coverage. The total hardware cost of the system is less than $50, which is only 20-30% of the cost of similar commercial products, making it suitable for large-scale deployment in small and medium-sized enterprises.

Table 2 Performance comparison between proposed system and conventional monitoring systems.

Performance Indicator	Proposed System	Conventional Systems
Positioning Accuracy	±10 cm	±1-5 m
Average Response Time	1.8 s	5-10 s
Network Dependence	None	Required
Hardware Cost	< $50	$200-$500
Power Consumption	<5 W	10-20 W
Automatic Power-off Protection	Yes	Optional

4.4. Field Application Test

The system was deployed in an actual manufacturing workshop for a 30-day field test, with 10 sets of systems installed at different welding workstations. During the test period, the system successfully detected 3 cases of workers leaving their posts without authorization, 2 cases of abnormal temperature rise, and 1 case of flammable gas leakage, preventing potential accidents. The field test results show that the system operates stably in complex industrial environments, with an uptime of 99.8%, and receives positive feedback from both safety managers and welding workers. The system significantly reduces the workload of safety inspections, improves the efficiency of safety management, and effectively reduces the safety risks of electric welding operations.

5. Discussion

This study presents an integrated smart safety monitoring system for electric welding operations based on ESP32-UWB platform. The system integrates high-precision UWB positioning, multi-parameter environmental sensing, and automatic safety protection functions, realizing full-chain safety management of electric welding operations. Experimental results show that the system has high detection accuracy, fast response speed, and good stability, effectively addressing the limitations of traditional safety management methods.

The main contributions of this study are: (1) A low-cost, highly reliable hardware architecture based on ESP32-UWB platform, which integrates multiple functions into a single device with independent operation capability; (2) An optimized UWB ranging algorithm with 10 cm-level accuracy, which can accurately detect worker absence beyond safe ranges; (3) A multi-sensor data fusion algorithm that improves the reliability of hazard detection and reduces false alarm rate. The system provides an effective technical solution for electric welding operation safety management, with significant economic and social benefits.

Despite the good performance, the system still has some limitations that need to be improved in future research: (1) The current UWB ranging performance is degraded when there are many metal obstacles, and the positioning algorithm needs to be optimized to improve anti-interference capability; (2) The system currently only supports single-worker monitoring, and multi-worker positioning function needs to be developed for scenarios with multiple workers at the same site; (3) Adding a data storage function to record historical monitoring data for accident investigation and safety management analysis. In addition, further miniaturization of the device and optimization of power consumption will make the system more practical for mobile applications.

6. Conclusion

In conclusion, the proposed smart monitoring system provides a new approach for electric welding operation safety management, with broad application prospects in industrial safety monitoring. With further improvement and optimization, the system can be extended to other high-risk operation scenarios such as chemical industry, mining, and construction, contributing to the improvement of overall industrial safety levels.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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