Design and Implementation of an IoT-Based Multi-Sensor Carbon Monoxide and Combustible Gas Leakage Detection System for Residential Safety Using ESP32

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Abstract: Carbon monoxide (CO) and combustible gas leaks represent significant hazards in residential environments, often leading to severe health consequences and fatal accidents due to their colorless and odorless nature. Recent incidents have highlighted the urgent need for reliable, real-time monitoring systems capable of early hazard detection and rapid emergency response. This paper presents the design and implementation of an Internet of Things (IoT)-based smart safety system for detecting carbon monoxide, combustible gas leakage, and abnormal temperature conditions using the ESP32 microcontroller. The proposed system integrates multiple sensors, including a ZE03 electrochemical CO sensor, an MQ-2 semiconductor gas sensor, and a DS18B20 digital temperature sensor, to provide reliable environmental monitoring. The system continuously acquires sensor data and processes it locally using the ESP32. Once a hazardous condition is detected, the controller follows a priority-based safety strategy in which the gas supply is immediately shut off through a normally closed solenoid valve, followed by activation of the audible alarm and transmission of wireless notifications to the user via Wi-Fi. Experimental results demonstrated reliable real-time operation of the proposed system. The measured response times of the ZE03 carbon monoxide sensor and the MQ-2 combustible gas sensor were 38 s and 43 s, respectively. The ESP32 processing time was approximately 22 ms, while the total delay for wireless user notification was approximately 19 s. These results confirm the effectiveness of the proposed priority-based protection strategy for rapid hazard detection and automatic emergency response in residential safety applications. The proposed system provides a scalable and practical IoT solution for early gas hazard detection and automatic emergency protection in residential environments.

Keywords: Internet of Things (IoT), ESP32, Carbon Monoxide Detection, Combustible Gas Leakage Detection, Real-Time Monitoring, Automatic Gas Shutoff, Residential Safety.

1. INTRODUCTION

Ensuring safety in residential and industrial environments has become increasingly important due to the growing risks associated with carbon monoxide (CO) poisoning, combustible gas leakage, and fire-related incidents. Carbon monoxide is particularly hazardous because it is colorless, odorless, and highly toxic. Even relatively short exposure to elevated CO concentrations may result in severe poisoning or fatal consequences. Likewise, leakage of combustible gases such as liquefied petroleum gas (LPG) or methane can lead to explosions and fires if not detected at an early stage. Consequently, reliable real-time monitoring systems capable of rapidly detecting hazardous conditions and initiating immediate protective actions have become an important research topic [7], [19], [20].

Recent fatal accidents reported in Algeria, involving families affected by carbon monoxide poisoning caused by domestic water heaters and combustion appliances, further emphasize the necessity of deploying intelligent safety systems capable of preventing such incidents through early detection and automatic intervention.

The rapid development of the Internet of Things (IoT) has enabled a new generation of smart monitoring systems that integrate sensing units, embedded processing, wireless communication, and remote supervision into a single platform. Compared with conventional

standalone detectors, IoT-based safety systems provide continuous environmental monitoring, remote notifications, and automated emergency responses, thereby improving reliability and user protection [9], [10], [13], [14].

Recent studies have proposed various IoT-based gas monitoring systems using different sensing technologies and communication platforms. However, many existing solutions mainly focus on detecting either carbon monoxide, combustible gases, or fire conditions independently. In addition, several reported systems rely on single-sensor architectures, which may suffer from limited detection reliability, reduced fault tolerance, and increased susceptibility to false alarms under variable environmental conditions [15], [16], [17]. Furthermore, many existing approaches provide only warning notifications without integrating automatic protective mechanisms capable of reducing the hazard at its source.

To overcome these limitations, this paper presents the design and implementation of an IoT-based smart safety system using the ESP32 microcontroller for integrated monitoring of carbon monoxide concentration, combustible gas leakage, and abnormal temperature variations. The proposed system combines a ZE03 electrochemical CO sensor, an MQ-2 semiconductor combustible gas sensor, and a DS18B20 digital temperature sensor to achieve complementary multi-sensor monitoring. The ZE03 sensor was selected due to its higher selectivity toward carbon monoxide and improved stability compared with general-purpose semiconductor gas sensors, while the MQ-2 sensor provides combustible gas detection capability [3], [5]. The ESP32 platform was selected because it provides adequate processing capability, integrated Wi-Fi connectivity, and a compact embedded architecture suitable for real-time IoT safety applications [1], [2].

Unlike many existing systems, the proposed safety strategy gives the highest operational priority to automatic gas isolation through a normally closed solenoid valve immediately after the detection of a hazardous condition. Audible alarms and wireless notifications are subsequently activated to inform nearby occupants and remote users. This priority-based protection approach follows the principles of safety-oriented systems, where rapid mitigation of the hazard source is essential for reducing risks and limiting the consequences of abnormal events [22].

The main contributions of this work are summarized as follows:

- Design and implementation of a multi-sensor IoT-based safety system integrating carbon monoxide, combustible gas, and temperature monitoring.

- Development of a priority-based emergency response strategy in which automatic gas shutoff is performed as the first protective action, followed by alarm activation and wireless notification.

- Integration of real-time local processing using the ESP32 microcontroller with Wi-Fi-based remote monitoring capabilities.

- Experimental validation of the proposed prototype under different hazardous operating conditions to evaluate its practical feasibility for residential safety applications.

The remainder of this paper is organized as follows. Section II presents the overall system architecture and hardware implementation. Section III describes the software design and control algorithm. Section IV discusses the experimental setup and performance evaluation. Finally, Section V concludes the paper and outlines future research directions

2. RELATED WORK

Recent advances in the Internet of Things (IoT) have significantly accelerated the development of intelligent gas monitoring and residential safety systems. Numerous studies have investigated the integration of gas sensors, embedded controllers, and wireless communication technologies to enable

continuous environmental monitoring, early hazard detection, and remote supervision.

Several researchers have proposed IoT-based gas leakage detection systems using MQ-series sensors combined with wireless communication modules for monitoring and alarm notification. These solutions demonstrate the feasibility of low-cost gas detection platforms; however, many reported approaches mainly depend on single-sensor configurations and focus primarily on warning generation rather than implementing automatic protective mechanisms capable of reducing the hazard source [9]– [12].

More recent studies have focused on improving detection reliability through multi-sensor integration, intelligent data processing, and machine learning techniques. Approaches based on sensor fusion, cloud monitoring, and lightweight artificial intelligence methods have been investigated to enhance detection accuracy and reduce false alarms under different environmental conditions [13]– [16]. Nevertheless, these methods often require higher computational resources, increased system complexity, and additional hardware, which may limit their adoption in low-cost residential safety applications.

Other works have explored integrated fire and gas monitoring systems by combining gas sensors, temperature measurement, and IoT communication technologies. These systems improve environmental awareness by simultaneously monitoring multiple hazardous parameters [17], [18], [21]. However, many existing solutions still emphasize detection and notification functions, while limited attention is given to rapid automatic intervention strategies such as gas isolation or actuator-based protection. Safety-oriented systems require not only hazard identification but also effective mitigation actions to reduce the consequences of abnormal events [22].

From the hardware perspective, the ESP32 microcontroller has become a widely adopted platform for IoT safety applications due to its integrated Wi-Fi connectivity, adequate processing capability, low-power operation, and compact architecture [1], [2]. Combined with electrochemical and semiconductor gas sensors, ESP32-based systems provide an effective framework for developing intelligent and connected safety devices.

Despite these developments, several limitations remain in existing literature. First, many reported systems rely on limited sensing architectures, which may reduce detection reliability under practical operating conditions. Second, a significant number of studies concentrate on monitoring and notification functions without integrating automatic emergency response mechanisms. Third, complete quantitative evaluation of the safety chain, including sensor response, decision processing, actuator activation, and wireless communication delay, is still insufficiently reported.

To address these limitations, this work proposes an IoT-based multi-sensor safety system integrating a ZE03 electrochemical carbon monoxide sensor, an MQ-2 combustible gas sensor, and a DS18B20 temperature sensor with an ESP32 microcontroller. Unlike conventional monitoring approaches, the proposed system adopts a priority-based protection strategy in which the normally closed solenoid valve is activated as the first emergency response to isolate the gas source, followed by audible alarm activation and wireless notification. This approach aims to reduce hazard duration while maintaining reliable real-time monitoring and practical implementation suitability for residential safety applications.

3. SYSTEM ARCHITECTURE

The proposed IoT-based safety system is organized into four functional layers: the sensing layer, the processing and control unit, the actuation layer, and the communication and user interface. This modular architecture enables continuous environmental monitoring, rapid hazard detection, and automatic emergency response while maintaining a compact and scalable implementation suitable for residential safety applications.

A. Hardware Implementation

The hardware prototype integrates sensing, processing, communication, and protection components into a single embedded platform. The ESP32 microcontroller is used as the central processing unit due to its integrated Wi-Fi connectivity, multiple analog and digital input/output channels, and sufficient computational capability for real-time data acquisition and decision-making [1], [2].

The developed prototype consists of three environmental sensors, a normally closed solenoid valve controlled through a relay module, an audible buzzer, and a Thin-Film Transistor (TFT) display for local visualization of system parameters. These components are interconnected through an embedded prototype platform to ensure reliable signal acquisition and coordinated system operation.

Figure 1 illustrates the functional block diagram of the proposed system, showing the interaction between the sensing units, ESP32 controller, protection devices, and wireless communication interface. Figure 2 presents the implemented hardware prototype used for experimental validation.



Fig. 1. Block diagram of the IoT-based gas and fire detection system.

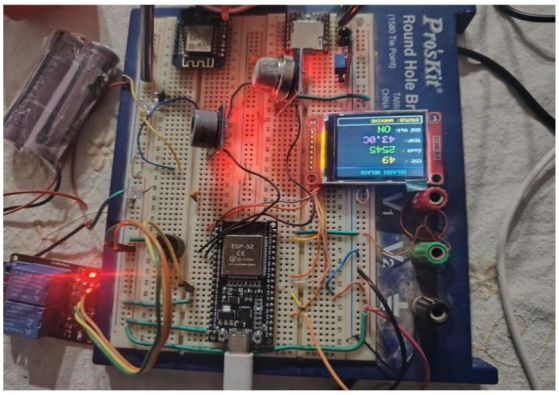


Fig. 2. System Architecture Prototype

B. Sensing Layer

The sensing layer continuously monitors the surrounding environment using three complementary sensing devices.

The ZE03 electrochemical CO sensor is employed for carbon monoxide measurement due to its high selectivity toward CO, stable response characteristics, and suitability for safety-oriented monitoring applications [3], [4]. Compared with general-purpose semiconductor sensors, electrochemical sensing technology provides improved specificity and helps reduce the influence of interfering gases and environmental variations.

The MQ-2 semiconductor gas sensor is used for detecting combustible gases such as LPG, methane, and smoke-related gases [5]. Unlike the ZE03 sensor, which is dedicated to CO measurement, the MQ-2 provides a complementary detection capability for combustible gas leakage, enabling the proposed system to monitor different categories of hazards.

The DS18B20 digital temperature sensor continuously measures ambient temperature. In this system, it is not considered a direct fire detector; instead, it provides an additional safety indicator by identifying abnormal temperature increases that may indicate overheating conditions or potential fire development [6], [7].

The integration of these heterogeneous sensing technologies enables multi-parameter monitoring and improves the reliability of

hazard assessment by reducing dependence on a single sensing source.

C. Processing and Protection Unit

The ESP32 continuously acquires measurements from all connected sensors and compares the obtained values with predefined safety thresholds stored in the controller.

When a hazardous condition is identified, the controller executes a priority-based protection strategy. The first and highest-priority action is the activation of the relay controlling the normally closed solenoid valve, which immediately isolates the gas supply and limits the propagation of leakage.

After initiating gas isolation, the controller activates the audible alarm to provide a local warning. Subsequently, a wireless notification containing the system status and measured parameters is transmitted through the Wi-Fi interface to the remote monitoring application.

This sequential decision strategy prioritizes hazard mitigation before user notification, reducing the exposure time to dangerous conditions and improving the effectiveness of the proposed safety system.

D. Communication and User Interface

The integrated Wi-Fi capability of the ESP32 enables wireless transmission of sensor measurements and alarm status to a mobile monitoring application, allowing users to remotely supervise the protected environment and receive notifications when hazardous conditions occur [1], [2].

For local monitoring, a Thin-Film Transistor (TFT) display provides real-time visualization of carbon monoxide concentration, combustible gas status, ambient temperature, and overall system condition. Under normal operation, the display continuously updates the measured parameters, whereas hazardous conditions generate warning messages and activate the corresponding protection sequence.

The combination of local visualization, wireless communication, and automatic actuation improves user awareness and enables rapid response during safety-critical events.

4. METHODOLOGY

The proposed safety system operates through continuous environmental monitoring, real-time data acquisition, and priority-based emergency decision-making. The methodology integrates multi-sensor measurements, threshold evaluation, and sequential protective actions to rapidly detect hazardous conditions and minimize potential risks in residential environments [9], [13], [14].

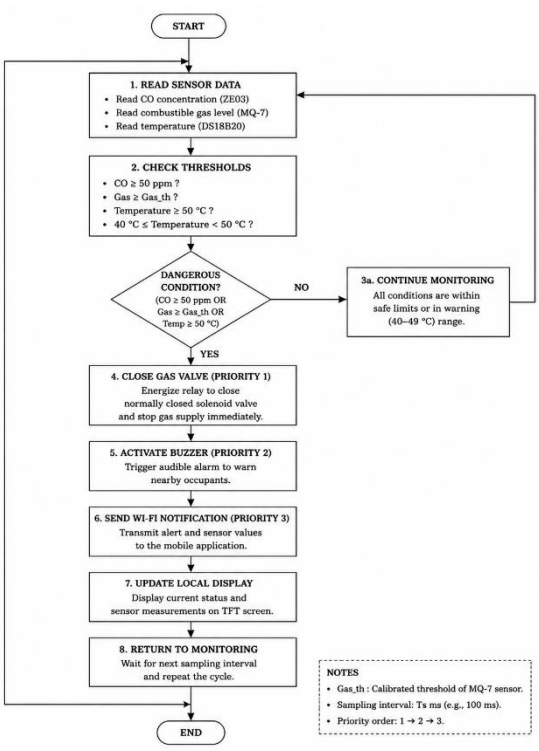


Fig. 3. Flowchart of the proposed priority-based monitoring and protection algorithm.

As illustrated in Fig. 3, the ESP32 continuously acquires measurements from the connected sensors using a fixed sampling interval of 1000 ms (1 s). During each acquisition cycle, the controller reads the carbon monoxide concentration from the ZE03 electrochemical CO sensor, the combustible gas level from the MQ-2 semiconductor gas sensor, and the ambient temperature from the DS18B20 digital temperature sensor. The acquired measurements are locally processed by the ESP32 before executing any protection decision [1]– [6].

The selected sampling interval provides an appropriate compromise between real-time monitoring capability and stable controller operation while avoiding unnecessary computational overhead. This acquisition period allows continuous supervision of the residential environment and enables rapid detection of abnormal conditions.

The measured parameters are compared with predefined safety thresholds established according to sensor specifications, indoor air quality recommendations, safety guidelines, and experimental calibration results [3], [5], [7], [19], [20].

Table I. Safety Threshold Levels Used in the Proposed System

Parameter	Normal Condition	Warning Condition	Hazard Condition
Carbon monoxide concentration (ZE03)	CO < 50 ppm	—	CO ≥ 50 ppm
Combustible gas concentration (MQ-2)	Gas < Gas_{th}	—	Gas ≥ Gas_{th}
Ambient temperature (DS18B20)	T < 40 °C	40 °C ≤ T < 50 °C	T ≥ 50 °C

The combustible gas threshold (Gas_{th}) represents the calibrated activation level of the MQ-2 sensor. Since the MQ-2 sensor provides an electrical response related to gas concentration rather than a direct calibrated ppm output, the threshold value is experimentally determined during the calibration process. This approach ensures reliable combustible gas leakage detection while reducing false alarm activation caused by environmental variations.

The DS18B20 temperature sensor provides an additional safety layer in the proposed system. Although temperature measurement alone cannot confirm the presence of a fire, a rapid and abnormal temperature increase may indicate overheating conditions or the early development of a fire event, particularly in environments containing gas-powered appliances. Therefore, temperature monitoring is included as an independent safety parameter capable of triggering the emergency protection sequence.

A. Decision Logic and Hazard Evaluation

During each monitoring cycle, the ESP32 evaluates the three sensing parameters independently. The proposed decision logic is based on an OR-based hazard detection strategy, meaning that exceeding the critical threshold of any single parameter is sufficient to classify the condition as hazardous.

The hazard condition is mathematically expressed as:

$$Hazard = (CO \geq CO_{th}) \vee (Gas \geq Gas_{th}) \vee \quad (1)$$

where CO_{th}, Gas_{th}, and T_{th}represent the predefined threshold values for carbon monoxide concentration, combustible gas level, and temperature, respectively.

The operating state of the system is defined as:

$$State = \begin{cases} \text{Safe}, & \text{if } CO < 50,\ Gas < Gas_{th},\ T < 40°C \\ \text{Warning}, & \text{if } 40°C \leq T < 50°C \\ \text{Hazard}, & \text{if } CO \geq 50 \text{ or } Gas \geq Gas_{th} \text{ or } T \geq 50°C \end{cases} \quad (2)$$

where *CO* represents the carbon monoxide concentration measured by the ZE03 sensor, *Gas* represents the MQ-2 sensor output, Gas_{th} denotes the calibrated combustible gas threshold, and *T* represents the temperature measured by the DS18B20 sensor.

When the system remains in the Safe state, the ESP32 continues normal monitoring and starts a new acquisition cycle. During the Warning state, caused by a moderate temperature increase, the controller continues monitoring while updating the system status on the TFT display without activating emergency actions.

When a Hazard state is detected, the ESP32 immediately executes the predefined emergency response sequence.

B. Priority-Based Emergency Response

The proposed protection strategy follows a priority-based sequence designed to eliminate the hazard source before informing the user.

The first and highest-priority action is the activation of the relay controlling the normally

closed solenoid valve. Energizing the relay interrupts the gas supply immediately, thereby reducing the duration of gas leakage and limiting the possibility of fire or explosion propagation [15], [18], [22].

After gas isolation, the controller activates the audible buzzer to provide a local warning to occupants in the protected area.

Finally, the ESP32 transmits a wireless notification containing the detected hazard type, sensor measurements, and system status through its integrated Wi-Fi interface to the remote monitoring application [1], [2], [10], [17].

This sequential strategy ensures that the system performs an effective protective action before user notification. Therefore, the proposed approach reduces dependence on human intervention and improves the response capability of residential safety systems.

The monitoring cycle is continuously repeated, allowing real-time environmental supervision and adaptation to changing operating conditions. This cyclic decision-making process improves system reliability and maintains continuous protection throughout system operation [9], [13], [21].

5. EXPERIMENTAL RESULTS AND DISCUSSION

This section presents the experimental evaluation of the proposed IoT-based carbon monoxide, combustible gas leakage, and abnormal temperature monitoring system. The prototype was tested under controlled laboratory conditions to evaluate sensor response, emergency decision performance, and the effectiveness of the automatic protection strategy.

A. Combustible Gas Detection Performance

The combustible gas detection capability was evaluated using the MQ-2 semiconductor gas sensor under controlled gas exposure conditions. The sensor output was recorded for different gas leakage levels to analyze the variation of the electrical response with increasing gas presence.

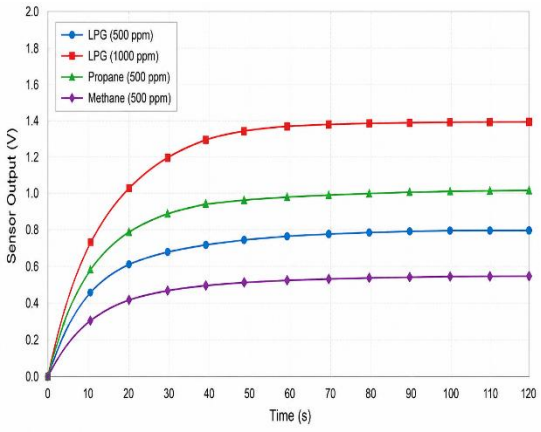


Fig. 4. MQ-2 gas sensor response under different gas exposure conditions.

As illustrated in Fig. 4, the MQ-2 sensor exhibits an increasing response when exposed to higher combustible gas concentrations. The observed behavior confirms the ability of the sensor to detect abnormal gas leakage conditions and provide sufficient information for threshold-based safety decisions.

Unlike electrochemical sensors, semiconductor gas sensors such as MQ-2 do not directly provide a calibrated gas concentration value. Therefore, the proposed system uses the experimentally determined threshold Gas_{th} from the sensor response to identify hazardous leakage conditions. This approach allows reliable gas detection while reducing false alarms caused by environmental variations [5].

The MQ-2 sensor was selected because it provides a broad response to combustible gases such as LPG, methane, and smoke-related gases, complementing the selective CO measurement provided by the ZE03 electrochemical sensor.

B. Carbon Monoxide Detection Performance

The carbon monoxide detection performance was evaluated using the ZE03 electrochemical CO sensor. The sensor provides direct CO concentration measurements in ppm, allowing comparison with predefined safety limits.

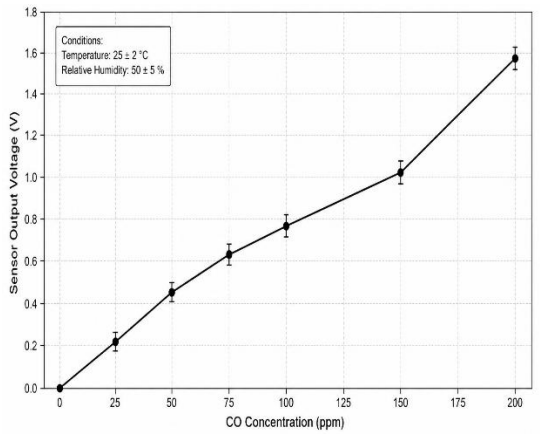


Fig. 5. ZE03 carbon monoxide measurement response under different CO levels.

The experimental results show that the ZE03 sensor provides stable CO measurements and rapidly identifies hazardous concentration levels. The use of an electrochemical sensor improves reliability because of its higher selectivity toward carbon monoxide compared with general semiconductor gas sensors [3], [4].

When the measured CO concentration exceeds the predefined threshold of 50 ppm, the ESP32 immediately classifies the condition as hazardous and initiates the emergency protection sequence.

C. Temperature Monitoring Performance

The DS18B20 temperature sensor was evaluated under different temperature conditions to verify its suitability as an additional safety indicator.

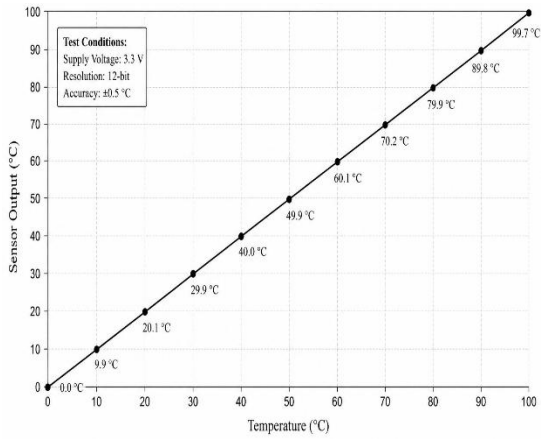


Fig. 6. Temperature measurement response versus temperature variation.

The obtained results demonstrate stable temperature tracking with a consistent response over the tested range. The temperature information is not used as a direct fire confirmation signal; instead, abnormal temperature elevation is considered an early indication of possible overheating or fire development.

When the measured temperature exceeds the critical threshold of 50 °C, the controller activates the same emergency response strategy used for gas and CO hazards.

D. Response Time Measurement

To evaluate the real-time capability of the proposed system, the response time was measured from the instant a hazardous condition was introduced until the corresponding protective action was initiated. The measurements were performed under controlled laboratory conditions for combustible gas leakage, carbon monoxide exposure, and abnormal temperature rise.

The overall response time can be expressed as:

$$T_{response} = T_{sensor} + T_{processing} + T_{communication} \quad (3)$$

where:

- represents the sensor detection delay required for the measured parameter to exceed its predefined safety threshold.
- represents the ESP32 processing time, including threshold comparison, decision-making, relay activation, and solenoid valve control.
- represents the delay associated with transmitting the alarm notification through the Wi-Fi interface to the remote monitoring application.

The response time was experimentally evaluated for each sensing stage by measuring the elapsed time between hazard exposure and activation of the corresponding protection sequence. The measured response times of the main components of the proposed system are summarized in Table II.

Table II. Measured Response Time of the Proposed System

Parameter	Measured Time
ZE03 CO detection response	38 s
MQ-2 combustible gas detection response	43 s
ESP32 processing time	22 ms
Wireless notification delay	19 s

Table II shows that the overall response time is primarily governed by the sensing characteristics of the employed sensors, whereas the ESP32 executes the protection algorithm within only 22 ms after threshold crossing. The measured detection times of 38 s for the ZE03 sensor and 43 s for the MQ-2 sensor mainly reflect the physical sensing and gas diffusion processes under the experimental conditions. Once a hazardous condition is confirmed, the controller immediately initiates the priority-based protection sequence by closing the normally closed solenoid valve, activating the audible alarm, and transmitting a wireless notification. The measured notification delay of approximately 19 s demonstrates the capability of the proposed system to provide timely remote alerts for residential safety applications.

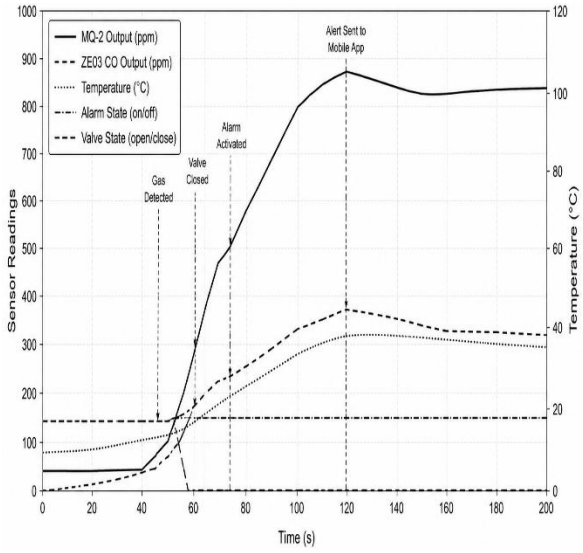


Fig. 7. Time sequence of the proposed priority-based emergency response algorithm.

Figure 7 illustrates the chronological execution of the proposed priority-based emergency response strategy. Once a hazardous condition is detected by any of the three sensing elements (ZE03, MQ-2, or DS18B20), the ESP32 immediately processes the acquired measurements and evaluates the predefined safety thresholds. If any threshold is exceeded, the controller first actuates the normally closed solenoid valve to isolate the gas supply, followed by activation of the audible alarm and transmission of a wireless notification to the remote monitoring application. This sequential execution ensures that hazard mitigation is prioritized over user notification, thereby minimizing gas leakage duration and improving the overall safety of the protected environment [1], [2], [10], [17].

E. System Response Analysis

Table III summarizes the operating behavior of the proposed protection algorithm under different environmental conditions.

Table III. System Response Under Different Hazard Conditions

Condition	Sensor Input	System Decision	Protective Action
Normal operation	CO < 50 ppm, Gas < Gas_{th}, T < 40 °C	Safe	Continuous monitoring
Temperature warning	40 °C ≤ T < 50 °C	Warning	Display update
CO hazard	CO ≥ 50 ppm	Hazard	Valve OFF → Alarm → Notification
Gas leakage	MQ-2 ≥ Gas_{th}	Hazard	Valve OFF → Alarm → Notification
High temperature	T ≥ 50 °C	Hazard	Valve OFF → Alarm → Notification

The obtained results demonstrate that the proposed decision algorithm correctly classifies the monitored environment into safe, warning, and hazardous operating states according to the predefined thresholds. Once any hazardous condition is detected, the controller immediately executes the priority-

based protection sequence by first interrupting the gas supply through the normally closed solenoid valve, followed by activation of the audible alarm and transmission of the wireless notification. This strategy minimizes the duration of hazardous gas leakage while ensuring rapid user awareness [8], [20], [26].

F. Comparison with Existing Gas Detection Systems

To evaluate the effectiveness of the proposed architecture, a comparison with representative IoT-based gas monitoring systems reported in the recent literature is presented in Table IV.

Table IV. Comparison with Existing IoT-Based Gas Detection Systems

System / Study	Sensors Used	Communication	Automatic Gas Shutoff	Monitoring
[9]	MQ-series sensor	IoT/GSM	No	Remote
[12]	MQ-based gas sensor	IoT	No	Remote
[18]	Gas + temperature sensors	IoT	Limited	Local
Proposed System	ZE03 + MQ-2 + DS18B20	Wi-Fi (ESP32)	Yes	Local + Remote

The comparison indicates that the proposed system integrates three complementary sensing technologies with a priority-based protection mechanism that automatically isolates the gas supply before issuing alarm notifications. In contrast to many existing systems that primarily focus on monitoring and warning functions, the proposed design combines real-time decision-making, automatic actuation, and wireless communication within a compact embedded platform. These characteristics improve its suitability for residential safety applications requiring rapid emergency intervention [15], [22], [25].

In addition to the functional advantages summarized in Table IV, the quantitative performance results presented in Table II further demonstrate the effectiveness of the proposed system. The prototype achieved carbon monoxide and combustible gas detection response times of 38 s and 43 s, respectively, while the ESP32 completed the protection decision within approximately 22 ms after threshold crossing. The wireless notification was successfully delivered within approximately 19 s. These results confirm that the proposed architecture provides timely hazard detection, automatic emergency protection, and reliable remote monitoring, making it well suited for residential safety applications.

G. Error and Reliability Analysis

Table V. Estimated Hardware Cost of the Proposed System

Component	Quantity	Approximate Cost (USD)
ESP32 Development Board	1	5.00
ZE03 Electrochemical CO Sensor	1	24.00
MQ-2 Gas Sensor	1	1.97
DS18B20 Temperature Sensor	1	2.00
Relay Module	1	0.80
Normally Closed Solenoid Valve	1	15.00
TFT Display	1	3.00
Buzzer	1	0.45
Miscellaneous Components	—	8.00
Total Estimated Cost		**≈ 60.22 USD**

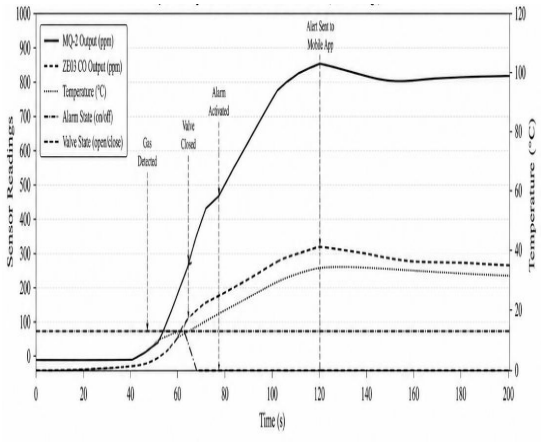


Fig. 8. Measurement error percentage under different operating conditions.

An error analysis was conducted to evaluate the stability and repeatability of the proposed sensing system under controlled operating conditions. The measured variations remained within acceptable limits for residential safety applications and were mainly attributed to sensor characteristics, environmental conditions, and calibration uncertainty.

The use of complementary sensing technologies improves the overall reliability of the proposed system. The ZE03 electrochemical sensor provides accurate and selective carbon monoxide measurement, while the MQ-2 semiconductor sensor enhances combustible gas detection. The DS18B20 temperature sensor supplies an additional safety indicator for detecting abnormal thermal conditions associated with potential fire initiation. The integration of these sensors with the ESP32-based decision algorithm reduces dependence on a single sensing element and improves the robustness of the overall protection system [3], [5], [6], [26].

Overall, the experimental evaluation demonstrates that the proposed IoT-based safety system provides reliable real-time monitoring, rapid emergency response, and automatic protective actions, making it a practical solution for smart residential safety applications.

H. Cost and Power Consumption Analysis

To further assess the practical feasibility of the proposed residential safety system, a cost and power consumption analysis was conducted. The prototype was designed using commercially available components with low hardware cost while maintaining reliable sensing, processing, and communication capabilities.

Table VI. Estimated Power Consumption

Component	Typical Power Consumption
ESP32	0.8–1.2 W
ZE03 CO Sensor	0.15 W
MQ-2 Gas Sensor	0.75 W
DS18B20	<0.01 W
TFT Display	0.4 W
Relay Module	0.35 W
Total (Monitoring Mode)	**≈2.5 W**

The estimated results indicate that the proposed prototype can be implemented using low-cost commercially available components while maintaining modest power consumption suitable for continuous operation in residential environments. The electrochemical ZE03 sensor provides high selectivity and measurement stability for carbon monoxide detection, whereas the MQ-2 sensor offers an economical solution for combustible gas monitoring. Combined with the ESP32 microcontroller, the overall system achieves a favorable balance between detection performance, implementation cost, and energy efficiency. These characteristics make the proposed architecture suitable for practical deployment in smart residential safety applications [1], [3], [5], [6], [10].

6. CONCLUSION AND FUTURE WORK

This paper presented the design and implementation of an Internet of Things (IoT)-based residential safety system for the detection of carbon monoxide, combustible gas leakage, and abnormal temperature conditions using an ESP32 microcontroller.

The proposed architecture integrates a ZE03 electrochemical carbon monoxide sensor, an MQ-2 semiconductor gas sensor, and a DS18B20 digital temperature sensor to provide continuous environmental monitoring through complementary sensing technologies.

A priority-based protection strategy was developed in which the gas supply is immediately isolated by actuating a normally closed solenoid valve once a hazardous condition is detected. Following this protective action, the system activates an audible alarm and transmits wireless notifications through the ESP32 Wi-Fi interface, ensuring both local and remote emergency awareness. This sequential decision-making process minimizes the duration of hazardous gas leakage while improving the overall safety of residential environments.

The experimental evaluation demonstrated the feasibility of the proposed system for real-time monitoring and automatic emergency response under different hazardous operating conditions. The combination of electrochemical and semiconductor sensing technologies enhances detection reliability by enabling selective carbon monoxide measurement together with combustible gas detection, while temperature monitoring provides an additional safety indicator for identifying abnormal thermal conditions associated with the early stages of fire development. The proposed architecture offers a practical, scalable, and cost-effective solution for smart residential safety applications by integrating sensing, embedded processing, wireless communication, and automatic protective actuation within a compact IoT platform.

Future work will focus on extending the proposed system through cloud-based data logging, long-term field validation, and intelligent data analysis using machine learning techniques to improve hazard prediction and reduce false alarms. Additional developments will include optimization of power consumption, integration with smart home platforms, and support for additional environmental sensors. In particular, future versions of the system will investigate the integration of a flame sensor to complement carbon monoxide, combustible gas, and temperature monitoring by enabling direct flame detection during the early stages of fire development. This additional sensing capability is expected to further improve the robustness, reliability, and overall effectiveness of the proposed residential safety system.

References

[1] Espressif Systems, *ESP32 Series Datasheet*, Version 5.x, Espressif Systems, Shanghai, China, 2024.

[2] Espressif Systems, *ESP32 Technical Reference Manual*, Espressif Systems, Shanghai, China, 2024.

[3] Zhengzhou Winsen Electronics Technology Co., Ltd., *ZE03 Electrochemical Carbon Monoxide Sensor User Manual*, Zhengzhou, China.

[4] Zhengzhou Winsen Electronics Technology Co., Ltd., *ZE03 Electrochemical Gas Sensor Specification*, Zhengzhou, China.

[5] Hanwei Electronics Co., Ltd., *MQ-7 Semiconductor Sensor for Carbon Monoxide, Technical Datasheet*, Zhengzhou, China.

[6] Analog Devices (Maxim Integrated), *DS18B20 Programmable Resolution 1-Wire Digital Thermometer Datasheet*, 2023.

[7] World Health Organization, *WHO Guidelines for Indoor Air Quality: Selected Pollutants*, Geneva, Switzerland.

[8] National Fire Protection Association, *NFPA 72: National Fire Alarm and Signaling Code*, Latest Edition.

[9] M. Sreerama Murty, “Smart Gas Leakage Detector Using IoT Sensors,” *International Journal of Intelligent Systems and Applications in Engineering*, vol. 12, no. 4, 2024.

[10] R. Sarkar *et al.*, “Elevating Gas Safety Standards: ESP32-Based Detection Systems with Blynk Integration,” in *Proc. IEEE Region 10 Symposium (TENSYMP)*, 2024, doi: 10.1109/TENSYMP61132.2024.10752183.

[11] R. J. Jadhav, P. Radhakrishnan, D. A. Jadhav, B. Ashreetha, J. Divya, and S. Mukherjee, “Internet of Things Enabled Gas Leakage Detection Over Industrial Areas Using Powerful MQ Series Sensor and Controller,” in *Proc. IEEE ICICT*, pp. 1679–1686, 2024.

[12] G. N. Sai, K. P. Sai, K. Ajay, and P. Nuthakki, “Smart LPG Gas Leakage Detection and Monitoring System,” in *Proc. 5th International Conference on Smart Systems and Inventive Technology (ICSSIT)*, 2023.

[13] T. Babu, R. R. Nair, S. Kishore, and M. Vineeth, "Enhancing Gas Leak Detection with IoT Technology: An Innovative Approach," *Procedia Computer Science*, vol. 235, pp. 961–969, 2024, doi: 10.1016/j.procs.2024.04.091.

[14] "IoT-HGDS: Internet of Things Integrated Machine Learning Based Hazardous Gases Detection System for Smart Kitchen," *Internet of Things*, vol. 28, Art. no. 101396, 2024, doi: 10.1016/j.iot.2024.101396.

[15] M. Alharbi *et al.*, "Gas Leakage Detection Using Tiny Machine Learning," *Electronics*, vol. 13, no. 23, Art. no. 4768, 2024.

[16] D. Khongorzul, M.-H. Kim, and K. Jo, "NDAMA: A Novel Deep Autoencoder and Multivariate Analysis Approach for IoT-Based Methane Gas Leakage Detection," *IEEE Access*, 2023, doi: 10.1109/ACCESS.2023.3340240.

[17] I. E. Khahar, F. Affandi, and D. Fachrezi, "A Real-Time LPG Leakage Detection System Based on ESP32 with Alerts via Buzzer and Telegram," *Indonesian Journal of Electrical Engineering and Electronics*, vol. 2, no. 1, 2025, doi: 10.54378/ijeee.v2i1.10268.

[18] N. Ibrahim, "Gas Leakage and Fire Detector Based on Internet of Thing (IoT) Network," *American Journal of Engineering, Mechanics and Architecture*, vol. 1, no. 9, pp. 52–60, 2023.

[19] U.S. Environmental Protection Agency, *Carbon Monoxide's Impact on Indoor Air Quality*, Washington, DC, USA.

[20] International Organization for Standardization, *ISO 7240: Fire Detection and Alarm Systems*, Latest Edition.

[21] N. Wibowo, H. Zarory, D. Mursyitah, and A. Ullah, "Fire Detection Design Based on Gas Leakage Accompanied by Fire Location Point Using ESP32 Based on IoT," *Protek: Jurnal Ilmiah Teknik Elektro*, vol. 12, no. 1, pp. 60–66, 2025, doi: 10.33387/protk.v12i1.7744.

[22] N. Boudjoghra and F. Innal, "Safety Lifecycle of Safety Instrumented System: Case Study of Diesel Storage Tank," *Algerian Journal of Signals and Systems*, vol. 10, no. 3, pp. 104–110, 2025.

[23] I. Bouleghlimat, S. Boudouda, and S. Bouleghlimat, "A Lightweight Intrusion Detection for Attacks in IoT Big Data Networks," *Algerian Journal of Signals and Systems*, vol. 10, no. 1, pp. 40–47, 2025.