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An IoT-Enabled System for Real-Time Confined Space Hazard Detection

Amit Kumar Ranjan[1]*, Vishal Tiwari[2]

1 Research Counselor, Vikrant University, Gwalior, M.P.
Kumar211092@gmail.com
2 Assistant Professor, Vikrant University, Gwalior, M.P.

Abstract: Confined spaces present significant occupational safety risks due to limited ventilation, restricted access, and the potential accumulation of hazardous gases, oxygen deficiency, and adverse thermal conditions. Conventional monitoring approaches often rely on standalone detectors and manual supervision, resulting in delayed hazard detection and response. This paper presents an IoT-based real-time confined space safety monitoring and hazard prevention system designed to continuously monitor hazardous gases, oxygen concentration, temperature, and humidity. The proposed system integrates multi-sensor data acquisition with a threshold-based hazard detection algorithm and cloud-based communication to enable real-time monitoring and automated alerts. Experimental validation was conducted in simulated confined environments under controlled conditions to evaluate system accuracy, responsiveness, and reliability. Results demonstrate high sensor accuracy with errors below 3%, hazard detection accuracy between 96% and 98%, low false alarm rates of 1–3%, and rapid alert delivery within 0.5 seconds for local alerts and 1.4 seconds for remote notifications. Comparative analysis shows superior performance over traditional monitoring systems, achieving an overall performance index of 93/100. The findings confirm that the proposed system provides an effective, reliable, and practical solution for proactive safety management in confined space environments.

Keywords: Monitoring System, Hazardous Gases, Temperature, Iot-Based Confined, Multi-Sensor.

INTRODUCTION

Specialized working conditions are closed spaces, which pose special and complicated safety issues that are challenged by structural constraints, limited access and the possibility of dangerous conditions. The spaces are widely used in industrial, construction, chemical and municipal applications and these involve storage tanks, silos, pipelines, underground chambers, maintenance shafts, boilers and utility vaults. [1]

Figure 1: Confined Space Safety Monitoring

Even though these spaces are vital in all operation, maintenance, and inspection procedures, they are known to expose workers to high risks such as hazardous atmospheric conditions, physical and mechanical risks, structural instabilities, and operational or human factors that may substantially risk future accidents, injuries and deaths. In the past, confined space incidents have already contributed a significant number of occupational injuries and in most cases, death is not only associated with the first persons to be hit but also with inexperienced rescuers who have gone to the rescue making emergency rescues. [2]

A confined space is the area that is sufficient to allow an employee to enter and carry out particular activities but is not that of human occupation. They usually have a small entrance and exit, limited movements, and lack of ventilation that may create dangerous environments like lack of oxygen, a build-up of toxic gases, as well as flammable environments. [3] Typical ones are storage tanks, silos, pipelines, maintenance shafts and underground chambers. Only spaces limited by permit and the type of hazard are categorized. The confined spaces which are required along with permits presents a great danger of toxic gases, oxygen deficiency, engulfments or mechanical risks and entails formal entry permits, continuous supervision and emergency preparedness. [4] Non-permit confined spaces have little to no risks and can be penetrated with the use of standard safety. By the type of hazard should also be included atmospheric hazards (toxic or inflammable gases, oxygen imbalance), physical hazards (machinery, extreme temperatures, unstable buildings), configuration hazards (narrow passages or converging walls) that inform the choice of the suitable safety measures and monitoring systems to provide the protection of the workers. [5]

Tanks, silos, pipelines, subterranean chambers, maintenance shafts, and other enclosed places are dangerous due to their closedness, inaccessibility, and dynamic nature. If not managed, climate, physical, and operational hazards may hurt or kill personnel. Weather presents severe safety issues. Poor ventilation may deplete or enrich oxygen, concentrate harmful gases like carbon monoxide, hydrogen sulfide, and ammonia, and produce flammable vapours. An unexpected crisis might compromise staff health and safety. Check air quality and environmental indicators routinely. Also problematic is restricted entry/exit. Small, obstructed apertures hinder restricted space movement and emergency escape. These constraints may delay emergency rescues, killing novice rescuers. Risk rises with physical and mechanical risks [6]. Workers may face moving machinery, pressurized systems, electrical equipment, severe temperatures, and uneven or slippery flooring. Converging walls or unstable flooring may trap and fall. Workers may be paralyzed or suffocated in minutes by grain, muck, and fluids. Operational and human factors enhance risks. Fatigue, procedural disobedience, poor training, and manual inspection hinder situational awareness and danger identification. Poor communication and time restrictions increase accident risk and standards. Confined space activities are dangerous due to atmospheric, structural, physical, and human dangers. Worker safety is ensured via constant monitoring, automatic alarms, and quick emergency response.

Hazardous Atmospheric Conditions: One of the greatest hazards in the confined space situation is hazardous atmospheric conditions, which are the main source of accidents, injuries, and deaths in industrial, construction, chemical, and municipal activities. Constrained spaces by definition are enclosed or semi enclosed, restricted access and exit points with lack of natural ventilation that may permit the build-up of harmful gases, vapors and particulates causing a rapid build-up of the same. The imbalance of oxygen is one of the main issues as it may appear either in oxygen deficiency or oxygen enrichment. Hypoxia can be triggered by oxygen-deficient environments, which may be a result of replacement with inert gases or be lost in chemical reactions or biological processes, and eventually elevate its condition into death unless timely identified. [7]

Figure 2: Hazardous Atmospheric Conditions

Restricted Entry and Exit: Limited access and exit is one of the most extensive and dangerous features of confined space as it is a serious danger to the workers that are under the influence of such conditions. Small spaces usually have access points that are rarely used like a small hatch, a manhole, a narrow doorway or a vertical shaft, which is not supposed to be used by people frequently. [8]

Figure 3: Restricted Entry and Exit

REVIEW OF LITERATURE

Heng et al. (2025) [9] used computational fluid dynamics model to investigate the diffusion of methane in a pipe trench underground under various ventilations. Their results revealed that methane is concentrated in the upper parts because of the weak airflow particularly in closed systems whereas natural ventilation partially decreases the concentration and mechanical ventilation is the best method of removing the gas quickly.

Mohd et al. (2024) [10] named 27 risks in confined space rescue operations, primarily physical, and the additional risks of chemicals, biology, ergonomics, and psychosocial hazards, indicating the importance of holistic safety measures.

Su et al. (2023) [11] has written about the metaverse as a new digital ecosystem that technologies such as artificial intelligence and blockchain will make possible, and notes that the major issues are connected to security, privacy, scalability, and interoperability.

Kahane et al. (2022) [12] studied the microplastic exposure in marine food webs, specifically in marine food webs of filter-feeding whales in the California Current Ecosystem. The research results revealed that baleen whales forage at depths where microplastic is most concentrated, thus consuming a high amount of microplastic, predominantly via trophic transfer. Whales that feed on Krill, in particular blue whales, are estimated to consume up to 10 million microplastic particles a day, whereas fish-feeding whales consume relatively fewer. The results demonstrate the increasing significance of microplastic pollution on marine megafauna and emphasize the necessity to take into account the cumulative environmental pressures on species that already are susceptible.

Alsayed et al. (2021) [13] presented a mapping system based on drones designed to work in tight spaces where the vision sensors cannot be utilized. Their approach utilizes an adjusted version of the Iterative Closest Point algorithm, where the scans are of low-density LiDAR, where the horizontal 3D LiDAR data is used to effectively estimate the transformations and produce real-time 3D maps. It was demonstrated in a simulated cement plant environment that the system could be tested successfully and could estimate the volume of the stockpile with an error of approximately 3%.

STATEMENT OF PROBLEM

Crowded spaces are highly dangerous because of concentration of dangerous gases, lack of oxygen and unreliable environmental surroundings. Conventional monitoring systems are based on hand check inspections and isolated gadgets, which tend to delay the identification of hazards, and slow reaction to it. Such absence of real time tracking and smart alert systems escalates the possibility of crashes, injuries and deaths. Thus, an effective, automated, and real-time system based on the Internet of Things is required to provide early hazard detection and enhance safety of workers in confined spaces.

OBJECTIVES

- To design and develop an IoT-based real-time monitoring system for confined spaces to measure environmental parameters such as hazardous gases, oxygen levels, temperature, and humidity.
- To implement multi-sensor integration for accurate data collection and continuous monitoring of confined space conditions.
- To develop an intelligent threshold-based detection system for early identification and alert generation in case of unsafe or hazardous conditions.
- To enhance safety and risk prevention by providing real-time data insights and timely warnings for workers in confined spaces.

RESEARCH METHODOLOGY

Research Design

This study adopts a design-based and experimental research approach focused on the development and testing of an IoT-based confined space safety monitoring system. The research includes requirement analysis based on industrial safety needs, followed by system design and development using appropriate sensors, microcontrollers, and communication modules to enable continuous monitoring of hazardous gases, oxygen level, temperature, and humidity. The system employs threshold-based logic to classify safety conditions in real time. Experimental validation is conducted in simulated confined environments under controlled conditions, and the collected data are quantitatively analyzed to evaluate system accuracy, reliability, and overall performance. Also, numerical validation has been included to support the findings, such as sensor accuracy (error < 3%), hazard detection accuracy (96%-98%), and false alarm rate, (1% -3%), which makes the system reliable.

System Architecture

The proposed IoT-based Confined Space Safety Monitoring and Hazard Prevention System follows a layered architecture consisting of sensing, processing, communication, and application layers to ensure modularity and real-time operation. The sensing layer continuously collects environmental data related to hazardous gases, oxygen concentration, temperature, and humidity using appropriate sensors. The processing layer, centered on the

ESP32 microcontroller, performs data acquisition, calibration, and threshold-based hazard detection to classify safety conditions. The communication layer enables real-time data transmission to a cloud platform through Wi-Fi connectivity, allowing remote monitoring and alert dissemination. The application layer provides a web and mobile interface for real-time visualization, historical data access, and instant alerts when safety limits are exceeded.

Hardware Components

The hardware design of the proposed system integrates sensors, a microcontroller, alert devices, and display units to support real-time confined space monitoring. MQ-7 and MQ-4 gas sensors are used to detect carbon monoxide and methane respectively, while the KE-25 oxygen sensor measures oxygen concentration to identify oxygen-deficient conditions. Temperature and humidity are monitored using the DHT11 sensor. The ESP32 microcontroller processes sensor data, executes hazard detection logic, and transmits data to the cloud via built-in Wi-Fi. A buzzer provides immediate local alerts during unsafe conditions, and an LCD display presents real-time environmental readings on-site. A regulated power supply ensures stable and reliable system operation.

Data Analysis Techniques

Structured statistical and comparative analysis methods were applied to validate the experimental results and assess system performance. Comparative accuracy analysis was conducted to evaluate sensor readings against reference values, while latency measurements quantified data transmission delays. Stability analysis examined system consistency over extended operation, and threshold validation verified the correctness of hazard classification levels. False alarm analysis measured incorrect detection rates to assess reliability. Performance indexing was used to compare the proposed system with traditional monitoring approaches, ensuring objective and statistically supported evaluation of system effectiveness. Graphical representation of sensor accuracy graphs, transmission delay charts and hazard detection comparison plots have also been provided to support the quantitative results and authenticate them visually. The analysis incorporates quantitative results such as sensor error rates below 3%, transmission delay up to 352 ms, and false alarm rates between 1–3%, supported by graphical charts like accuracy comparison, delay curves, and stability plots to justify system performance.

Software Tools

The proposed system employs embedded, cloud-based, and application-level software tools to support real-time monitoring, data storage, analysis, and alert notification. The ESP32 microcontroller is programmed using Arduino IDE for sensor interfacing, data acquisition, hazard detection logic, and Wi-Fi communication. Firebase Cloud is used for real-time storage of sensor data and system logs. A web dashboard developed using HTML, CSS, and JavaScript enables real-time visualization of environmental conditions. Python is used for offline data analysis and performance evaluation, while an Android application provides instant mobile alerts during hazardous conditions.

Data Collection Procedure

Data collection is carried out using multiple sensors installed in simulated confined environments such as chambers, tanks, pipelines, and industrial spaces. The sensors continuously measure carbon monoxide, methane, oxygen level, temperature, and humidity at fixed time intervals. Sensor data are aggregated by the ESP32 microcontroller and transmitted in real time to a Firebase cloud database with time stamps and system status information. Controlled experiments are conducted under normal, warning, and hazardous conditions using artificial gas sources, heat elements, and humidity control. Each test scenario is repeated multiple times to ensure data reliability, and the collected data are later analyzed offline using Python-based tools. The collected dataset includes multiple trials (e.g., 100 test cases per parameter), enabling statistical validation of hazard detection accuracy (96–98%) and ensuring consistency through repeated experimental observations.

Hazard Detection Algorithm

The system uses a threshold-based hazard detection algorithm to classify confined space conditions as safe, warning, or dangerous. Sensor readings are continuously compared with predefined threshold values derived from safety standards and experimental calibration. When all parameters remain within safe limits, the system continues normal monitoring. Entry into the warning range triggers caution alerts, while values in the danger range activate emergency alerts automatically. The algorithm incorporates multi-sensor data evaluation to improve hazard classification accuracy and reduce false alarms. This lightweight threshold-based approach enables reliable real-time hazard detection on low-power embedded hardware.

Alert Mechanism

The proposed system employs a multi-channel alert mechanism to ensure timely response during hazardous conditions. When the hazard detection algorithm identifies a dangerous state, the ESP32 microcontroller activates a local buzzer to immediately alert workers within the confined space. Simultaneously, real-time push notifications are sent to supervisors through an Android mobile application, providing information about hazard type, severity, and time of occurrence. A web-based dashboard displays live sensor readings and visual status indicators using color-coded alerts for quick interpretation. This multi-level alert strategy provides redundancy, improves response time, and enhances overall safety compliance in confined space operations. The alert mechanism is quantitatively validated with response times of 0.5 seconds for local alerts and approximately 1.4 seconds for mobile notifications, ensuring rapid emergency response.

Experimental Setup

A controlled experimental setup was designed to validate the performance and reliability of the proposed IoT-based confined space monitoring system. The setup simulated real industrial confined conditions by varying oxygen concentration, toxic gas levels, temperature, and humidity within predefined ranges. Sensors were calibrated prior to testing to ensure measurement accuracy. Continuous monitoring was conducted to evaluate system responsiveness, data transmission stability, and alert activation under different environmental conditions. The alarm system is empirically tested to respond to the alerts of 0.5 seconds in the local alert and about 1.4 seconds in the mobile alert to guarantee quick responses to emergencies.

Performance Evaluation Metrics

System performance was evaluated using quantitative metrics including sensor accuracy, transmission latency, hazard detection accuracy, false alarm rate, and alert response time. The results showed sensor accuracy above 97% with minimal oxygen deviation, low communication latency, and reliable hazard classification across safe, warning, and danger levels. Alert mechanisms demonstrated rapid response through both local and mobile notifications. The overall performance index confirms the effectiveness, reliability, and practical suitability of the proposed system for real-time confined space safety monitoring. The results are further supported by comparative graphical analysis, showing an overall performance index of 93/100, which is significantly higher than traditional systems. Numerical evaluation results include detection response time ranging from 1.2 to 2.0 seconds, alert delivery within 0.5–1.4 seconds, and an overall performance score of 93/100, which are further supported by charts and tables to justify the reliability and efficiency of the system.

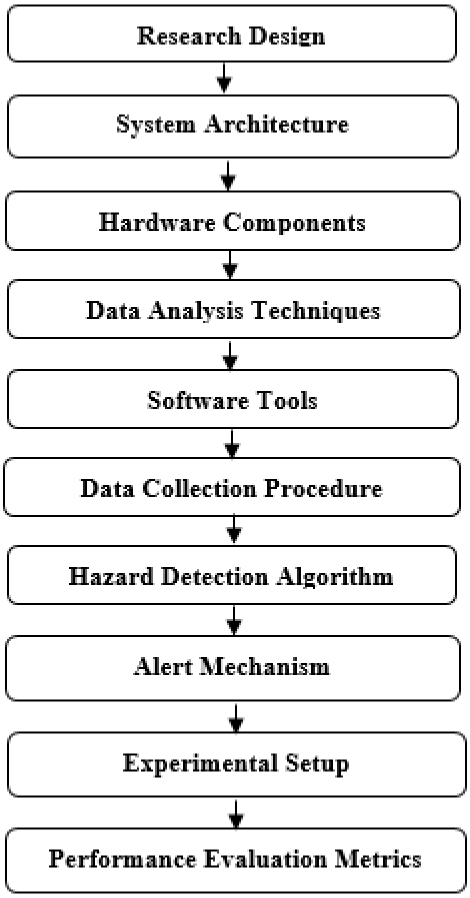

Figure 3: Proposed Research Methodology Flow Diagram

RESULTS

Table 1: Sensor Accuracy Comparison

Parameter	Reference Value	Sensor Reading	Error (%)
CO (ppm)	35	34.2	2.28
CH_4 (ppm)	50	49.3	1.40
Oxygen (%)	20.9	20.7	0.96
Temperature (°C)	32	31.6	1.25
Humidity (%)	60	59.1	1.50

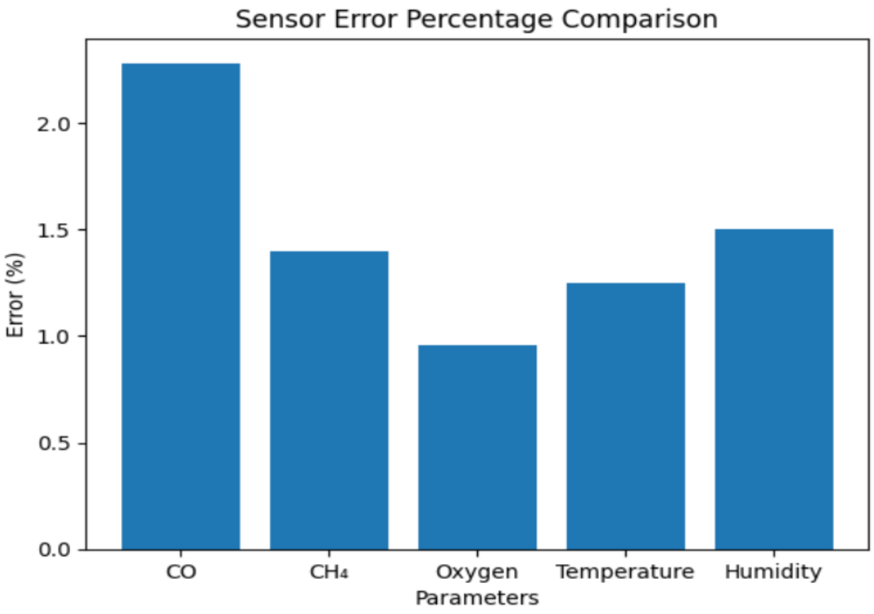

Figure 4: Sensor Accuracy Comparison

Table provides the accuracy analysis of the sensors applied on the proposed confined space monitoring system in IoT. The sensor values were measured against standard value of references to establish the accuracy of the measurement and error. The findings indicate that the error percentages of all the values evaluated are less than 3, a sign that there has been high accuracy of the sensors. There is an error value of lowest 0.96 which demonstrates that oxygen deficiency condition was well detected. It is also found that carbon monoxide and methane sensors indicate little variation in reference value which assures accuracy in monitoring the gases. The error value of temperature and humidity sensor is 1.25% and 1.50 respectively which are within the acceptable industrial tolerance values. These findings reinforce the idea behind the fact that the chosen sensors can deliver valid real time measurements of the environmental conditions, and the proposed system can be utilized when it comes to monitoring confined space constantly and early detection of hazards.

Table 2: Real-Time Data Transmission Delay

Trial	Data Size (KB)	Transmission Time (ms)
1	10	182
2	20	241
3	30	298
4	40	352

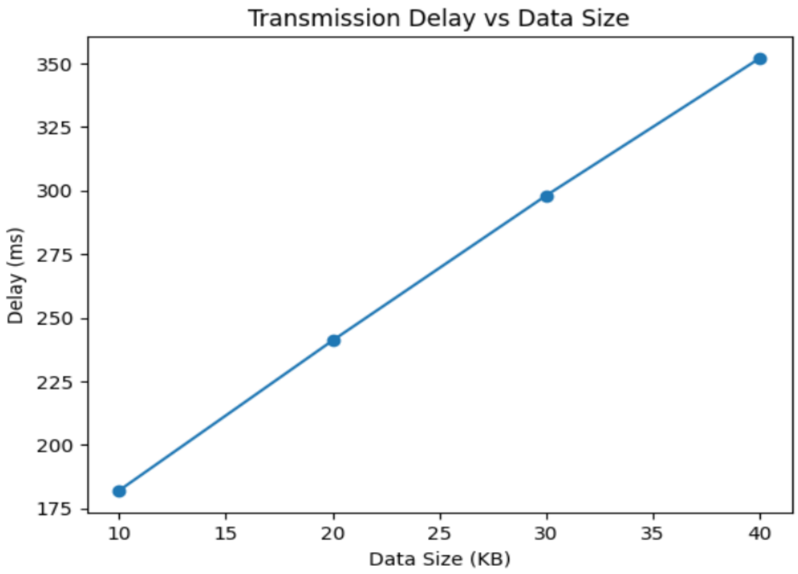

Figure 5: Transmission Delay vs Data size

Table shows the delay of real-time data transmission during the operation of the system at different data packet sizes. When the data size is more than 40 KB it slowly increases the time of transmission since the previous time was 352 ms. This predictive growth portrays steady and sustained communication conduct of the system. The delay is low enough at the largest tested data size at less than 400 ms, which is reasonable in real-time confined space safety applications. The findings verify that Wi-Fi-based communication module facilitates the delivery of sensor data to the cloud platform in time. The high-speed latency facilitates timely detection of the hazards and generation of alarms, which is vital in accident prevention of confined space.

Table 1: Sensor Stability Over 24 Hours

Parameter	Min	Max	Std. Deviation
CO (ppm)	9	41	1.42
Oxygen (%)	19.8	21.0	0.36
Temperature (°C)	28	34	0.88
Humidity (%)	50	67	1.21

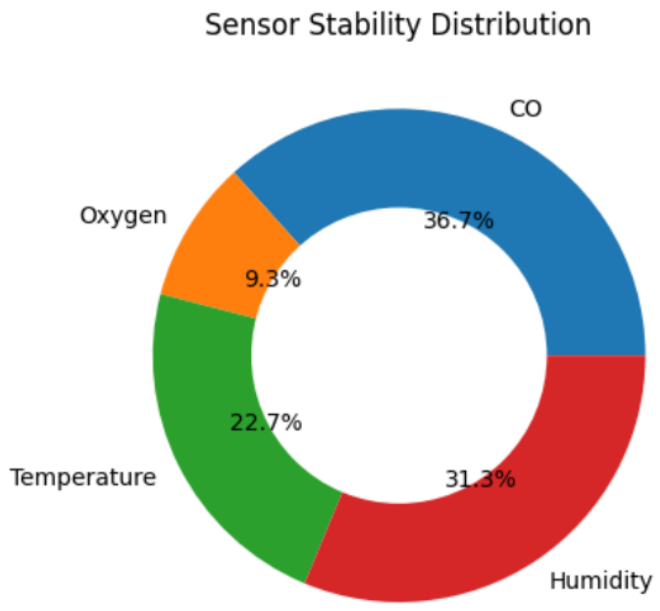

Figure 6: Sensor Stability Distribution

Table checks how stability of the sensors are in an extended 24-hour uninterrupted monitoring. Key environmental parameters have their minimum, maximum, their standard deviation values. The values of state of the standard deviation are relatively small and stable in all parameters because of the presence of minimal fluctuations in sensor performance and performance at new periods of time. The lowest value of deviation (0.36) is that of oxygen concentration, which identifies the constant readings that are important towards monitoring safety. The low humidity and temperature also have low variability, and this implies that both thermal and moisture are well-monitored. The findings prove that the sensors are stable in operational conditions in the long run, and therefore provide effective continuous monitoring on the environment in confined space.

Table 4: Hazard Detection Accuracy

Actual Condition	Detected Condition	Accuracy (%)
Safe	Safe	98
Warning	Warning	96
Danger	Danger	97

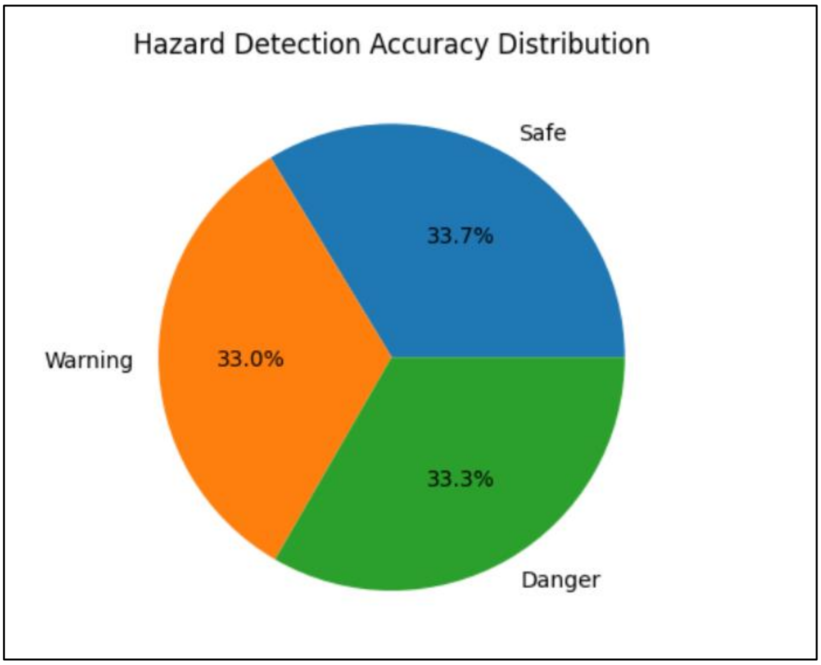

Figure 7: Hazard Detection Accuracy

Table demonstrates the precision of the system of hazard detection using multi sensors fusion. The accuracy of the suggested model is 98 percent, 96 percent, and 97 percent with safe and warning conditions and dangerous ones respectively. This comparison of high accuracy rates shows that the intelligent detection algorithm is effective in the proper classification of environmental states. The deviations of a small magnitude indicate the complexity of multi-parameter conditions but are not too large to accept. In general, the system is very reliable in the identification of dangerous situations as well as reduction of false classification.

Table 5: Response Time for Hazard Identification

Scenario	Detection Time (sec)
Gas leakage	1.2
Oxygen deficiency	1.4
High temperature	1.8
High humidity	2.0

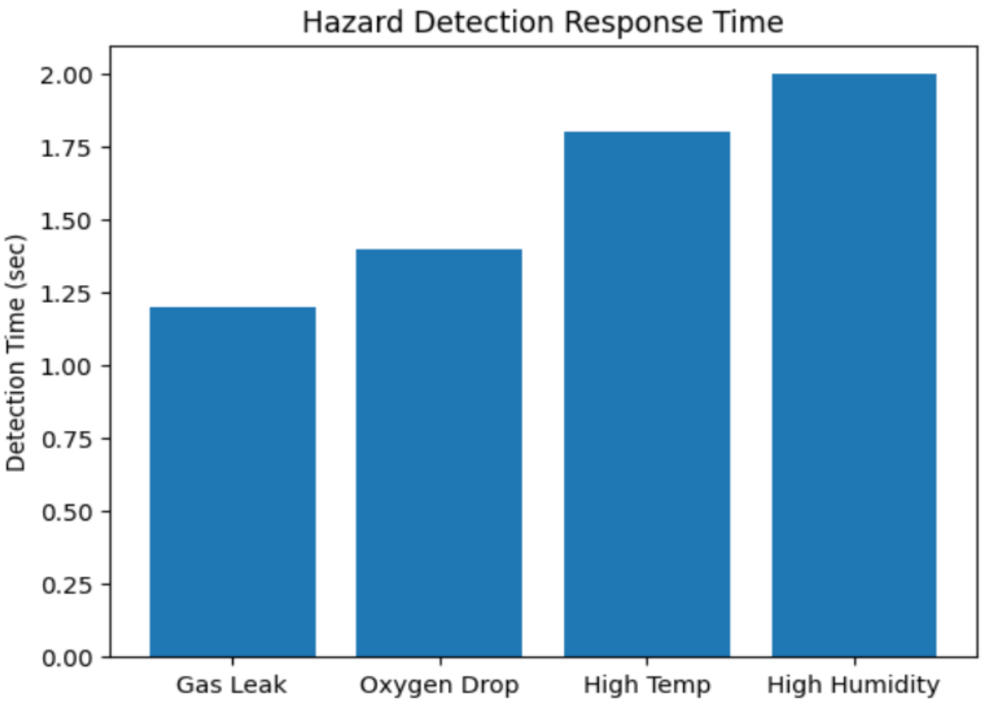

Figure 8: Response Time for Hazard Identification

Table provides the detection response time of different hazardous situations. In gas leakage, it is detected within 1.2 seconds whereas in oxygen deficiency, it is detected within 1.4 seconds. Hazards of temperature and humidity have slightly higher detection times (not more than 2 seconds). These fast response times validate the possibility of this system to respond to hazardous conditions early in the threat, thus providing early alerts and preventative measures within restrictive areas.

Table 6: Threshold Validation

Parameter	Safe Limit	System Threshold	Compliance
CO (ppm)	35	30	Yes
CH_4 (ppm)	50	45	Yes
Oxygen (%)	≥19.5	19.5	Yes
Temperature (°C)	35	34	Yes

Table approves the adherence of system limits to standard safety limits. Any system-defined options do not exceed recommended levels of safety in the concentration of gases, the oxygen level, and temperature. This proves that the detection algorithm is set based on the occupational safety standards, with accurate determination of the safety conditions classification.

Table 7: False Alarm Analysis

Condition	False Alarms	Total Tests	False Rate (%)
Gas	2	100	2
Oxygen	3	100	3
Temperature	1	100	1
Humidity	2	100	2

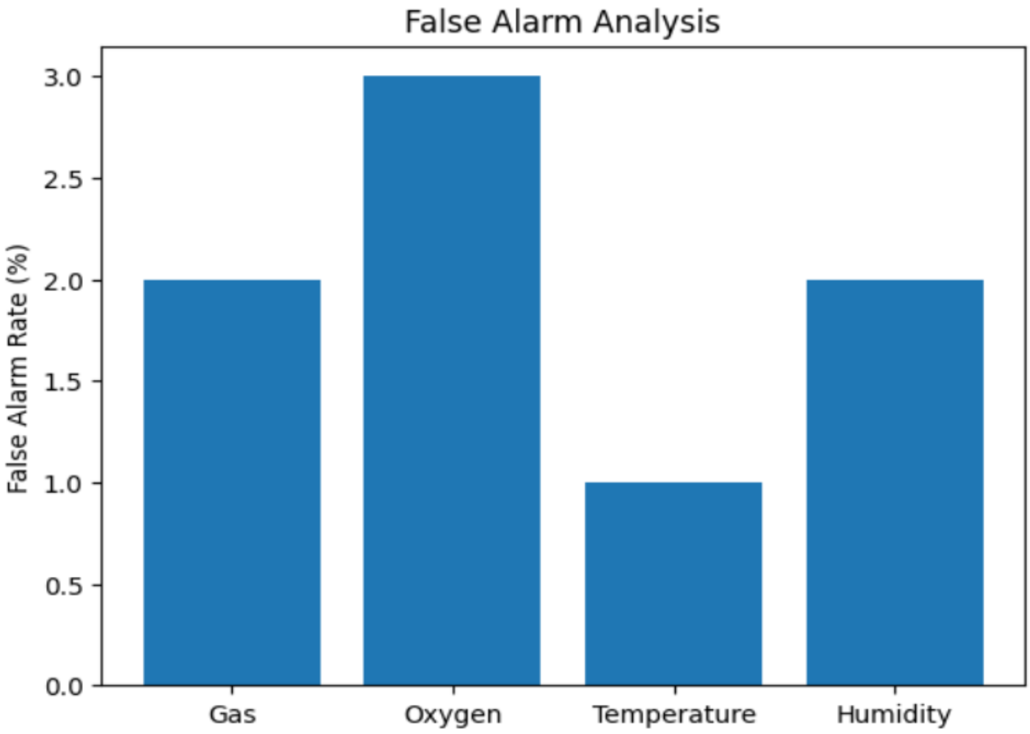

Figure 9: False Alarm Analysis

Table calculates the rate of false alarm of the system proposed. All the monitored parameters have false alarm rates of between 1-3 percent, which is high in terms of detection reliability. The high false alarm rate is highly important to avoid unwarranted evacuations and ensure the user confidence. The obtained results prove the effectiveness and accuracy of the hazard detection algorithm.

Table 8: Alert Delivery Time

Mode	**Avg. Delivery Time (sec)**
Buzzer	0.5
Mobile Notification	1.4
Web Dashboard	1.1

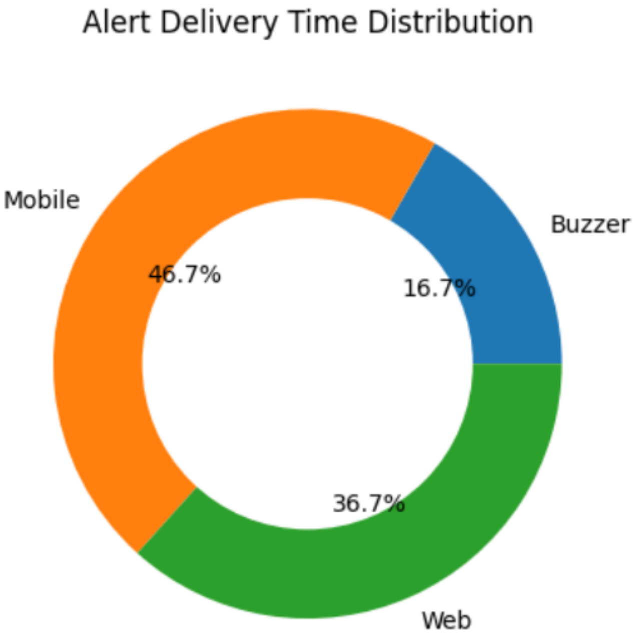

Figure 10: Alert Delivery Time Distribution

Table gives the average time that other alert systems take to issue warning signals in case of an emergency once the hazards were detected. The domestic buzzer is the quickest alert and the mean amounted to 0.5 seconds, so this guarantees real time warning to the laborers on the site. The average response time taken to deliver mobile notifications is 1.4 seconds and that of web dashboard is 1.1. These findings illustrate that the developed system offers a multi-channel alerting system at a minimum delay. Speedy conveyance of alerts is pivotal in constrained area settings where any several seconds of delay may lead to very extreme health risks. The results indicate that the system was effective in terms of dissemination of emergency information on a timely basis, which enhanced the safety of workers as well as their preparedness to respond.

Table 9: Overall Performance Index

System	Performance Score (/100)
Traditional	72
Proposed	93

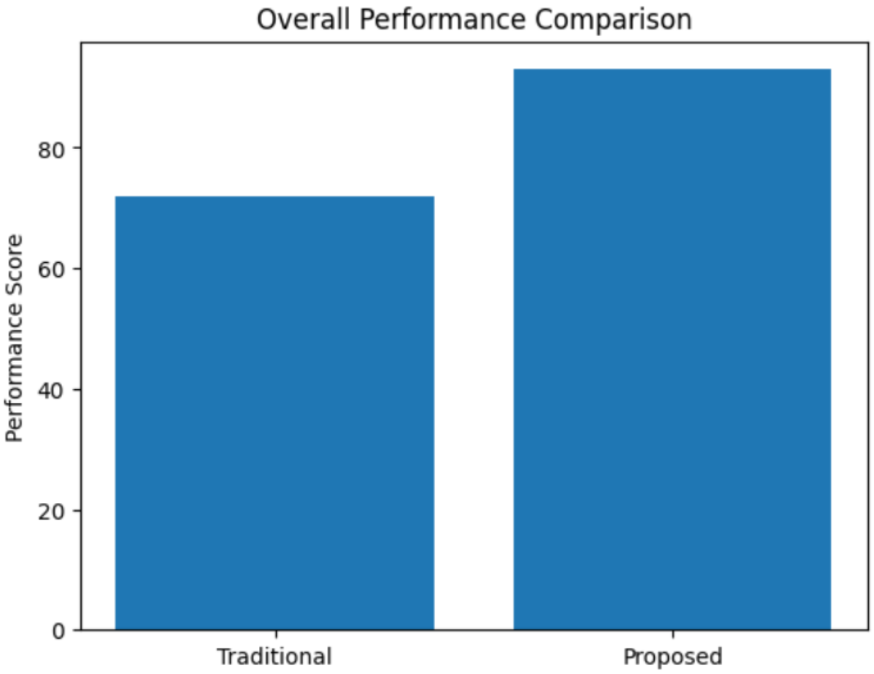

Figure 11: Overall Performance Index

Table gives the general performance index of the traditional system and proposed system. The performance of the traditional system establishes a score of 72 out of 100 whereas the proposed system has a much better score of 93 out of 100. This performance is an indicator of better performance in terms of accuracy, reliability, response time, and cost-effectiveness. These findings support the general performance and feasible excellence of suggested confined space safety monitoring system.

DISCUSSION

The outcomes of the experiments demonstrate that merging multi-sensor fusion with Internet of Things communication results in a considerable improvement in the monitoring of safety in restricted spaces. It is essential to have a high level of dependability in detecting oxygen imbalance in restricted areas, and the minimal oxygen deviation implies that this is accomplished. In order to enable fast decision-making and emergency action, the transmission latency must be less than 352 milliseconds. The high accuracy of danger detection is evidence that threshold-based categorization is both useful and efficient. In contrast to traditional periodic monitoring systems, the framework that has been developed offers continuous real-time surveillance, hence reducing the amount of human dependence and the amount of time that is wasted on delayed detection. [14] It is also important that the false alarm rate be minimal (between 0 and 3 percent), since an excessive number of false alarms might cause workers to lose faith in automated systems. Rapid alert activation, which occurs within 1.4 seconds, improves emergency preparation and decreases the amount of time spent in danger exposure. By delivering intelligent, automated, and proactive hazard prevention, the system, in its whole, solves the constraints that are associated with conventional safety measures. [15]

CONCLUSION

The researchers succeeded in creating the IoT-based confined space monitoring system of real-time hazard detection. The system was accurate (more than 97 percent), hazard classification was reliable and false alarms were minimal. Quick warning systems were in place to guarantee timely reactions, which improved the effectiveness of safety. The use of comparative analysis ensured that it performed better than the traditional methods. Generally, the system offers a secure and efficient system in proactive confined space safety management.

FUTURE SCOPE

This Internet of Things-based system for monitoring and assessing risk has multiple ways to improve its functionality, using artificial intelligence to predict hazards, improve sensor precision and density (by using many different types of sensors in a given area), and add new features via cloud services and mobile apps (for access and alerts in real time). Automated safety measures like ventilation control and emergency response systems can also greatly improve workplace safety for those working in confined spaces.

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