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Original Article

A multi-sensor IoT framework for real-time detection and prevention of sewage gas explosions in domestic and occupational sanitation systems

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ABSTRACT

Introduction: Methane and toxic gases build up in sewer pipes and septic tanks and are extremely dangerous in their ability to cause explosions and poisoning to workers in the confined sewer. The traditional monitoring controls, like infection ventilation and human checking, cannot be used to offer real-time protection.

Methods: In this work, the authors show an Internet of Things (IoT)-enabled cyber-physical system of real-time gas detection and automated mitigation. The system combines the MQ-4 (methane), MQ-135 (CO_2 /NH 3/VOCs), and MQ-136 (H_2S) sensors and place on the ESP32 microcontroller. A moving average-based compensation method is used to stabilize a sensor in contaminated conditions with minimum recalibration requirements. Alerts and ventilation are activated when methane reaches over 25% of the Lower Explosive Limit (LEL) using MQTT, in accordance with OSHA and NFPA safety requirements.

Results: Testing with 250 cases indicated that the system is reliably able to detect hazards, alert, and mitigate without failure. The response time was 8.2 seconds on average, which is a safeguard against gas buildup. Multi-gas sensitivity (±18% was within a reasonable range, and the system was able to run on backup power up to 18 hours.

Conclusion: The offered IoT system would turn the sanitation safety from passive observation to active protection due to real-time multi-gas detection and automated response imposed. It offers an affordable yet scalable way of ensuring occupational safety within dangerous confined spaces.

Keywords: Confined Space Monitoring, IoT Safety System, Methane Detection, Multi-sensor Array, Occupational Hazard Prevention

Introduction

Health and safety in the workplace are critical considerations in urban infrastructure systems, especially for staff who work in confined spaces. The maintenance engineers, utility workers, and sanitation workers have to periodically access sewer manholes, septic pits, and pumping stations, which fall under Permit-Required Confined Spaces (PRCS) because of the possibility of potentially harmful atmospheres. They are likely to accumulate explosive methane (CH_4) and toxic gases like carbon dioxide (CO_2), hydrogen sulfide

(H_2S), and ammonia (NH_3), liable to cause fire, explosion, poisoning, and asphyxiation risks.[1,2]

Traditionally practiced safety measures based on manual inspection and pre-entry gas tests do not offer real-time coverage, exposing workers to unexpected, immediate gas buildup, which is the number one cause of death in sanitation-related occupations.[3] Other domestic sanitation systems are also prone to similar hazards, as accumulation of methane may result in unexpected ignition, as shown in Table 1. The recent reported cases in cities in residential areas, such as methane toilet explosions, indicate that sewage gas is not only restricted to occupational settings but can be life-threatening to the general population as well.[4] These occurrences indicate the systematization of gas accumulation in the available sanitation facilities, especially in congested urban locations. Anaerobic degradation in sanitation systems produces complex gaseous byproducts that put the lives of residential occupants and workers in enclosed environments at risk. Mitigation for sewer gas hazards is primarily passive and structural, involving ventilation pipes, water traps, and plumbing required by the building code.[5]

The processes are inherently prone to failure due to blockages, inadequate maintenance, environmental erosion, or design constraints. More importantly, passive systems are not able to sense in real time or respond automatically to threats and minimize them, which prevents them from predicting an imminent gas buildup or taking mitigation measures. Such a limitation marks a major safety deficiency in both occupational and residential sanitation processes. The Internet of Things (IoT), therefore, has a potential place in filling this gap as it facilitates the process of integrated sensing, actuation, and communication in environments that are of safety concern. Although IoT-based systems for sewage gas monitoring have not been widely implemented, their use has spread widely in general air quality monitoring and gas leak detection in industry. Unique issues in sewage environments include persistent background contamination, humidity, and corrosive conditions, which undermine traditional sensor calibration and reliability.[6]

Such limitations require application-specific system architectures and dynamic signal-processing plans. The tasks of this work were as follows: (i) to design a multi-sense ionic basis system that is appropriate in both domestic and work-situated sanitation correlations; (ii) create a dynamic base compensation algorithm to guarantee a stable real-time gas detection under the continuously contaminated circumstances; (iii) to implement a hybrid local decision-making and alerting based in the clouds to guarantee reliable, and (iv) to experimentally test the system, to measure its accuracy and response time, reliability and effectiveness of mitigation. It is expected that the research will help advance the field of occupational and environmental safety engineering through a proactive, closed-loop cyber-physical technology for real-time monitoring and automated reduction of hazards from sewage gases.

The biochemical production of non-explosive, deadly gases in sanitation systems has been extensively reported. Methane (CH_4) is one of the initial products of anaerobic digestion in septic tanks and sewer pipes, driven by complex microbial activity. [6,7]

Besides methane, other substances likely to be found in the sanitation environment include hydrogen sulfide (H_2S), which is a product of sulfate-reducing bacteria, ammonia (NH_3), and volatile organic compounds (VOCs).[8] Such a mixture poses complex risks, including explosion hazards linked to methane accumulation and acute effects from exposure to gases like H_2S. These dangers are especially great in the workplace. The engineering, maintenance, and sanitation employees often perform their duties inside sewer manholes, septic tanks, and pumping stations, which are regulated by OSHA 29 CFR 1910.146 on permit-required confined spaces (PRCS) due to the risk of unsafe atmospheres. According to reports on occupational safety around the world, sanitation workers continue to die as a result of asphyxiation, greater amounts of hydrogen sulfide, and ignition of methane.[9,10]

Traditional safety interventions, such as personal protective gear (PPE) and pre-entry gas testing, are only point-in-time measures with a great deficiency in preventing the build-up of the gaseous material during active operation, which is crucial, as there is no follow-up. [11]

The current protectors against sewer gas risks to people in residential and workplace settings are mainly passive. These are plumbing provisions required by codified policies, such as ventilation pipes and water traps on residential properties, and administrative controls, such as routine inspections and procedure checklists used in occupational environments.[4,12] These measures are by their nature prone to failure because of blockages, loss of hydraulic seals, poor maintenance, or environmental degradation. More to the point, passive systems lack real-time sensitivity and automated response, which reduces their usefulness in curbing dangerous gas buildup. The Internet of Things (IoT) has shown considerable promise in environmental and safety factor usage. The development of IoT systems that incorporate sensor nodes, microcontrollers, wireless communication units, and cloud-based systems has enabled continuous monitoring of city air quality and gas leakage detection in industries.[5,13] Metal-oxide semiconductor (MOS) gas sensors, in particular, are known to be low-cost and highly sensitive, and their operating characteristics are well documented in the literature.[14]

Such systems are used to provide a background for real-time data capture and remote monitoring across a variety of settings. These developments notwithstanding, there remains a significant gap in the development and use of IoT technologies for sewage gas hazard management. Although previous research has delved into general air quality monitoring and the detection of isolated fuel gas leaks, little has been done on the sequential sensing of complex sewage gas mixtures in closed sanitation settings. The literature is silent on closed-loop cyber-physical systems that can, at the same time, detect various sewage gases and automatically trigger physical mitigation processes in real-time. Moreover, the problem of maintaining sensor reliability in circumstances of chronic background contamination, where other techniques of sensor calibration are not feasible, has not been adequately tackled. The current paper aims to fill this gap by suggesting and experimentally proving an IoT-based multi-sensor system tailored explicitly to real-time sewage gas detection and automated mitigation of the sewage gas in any sanitation setup.

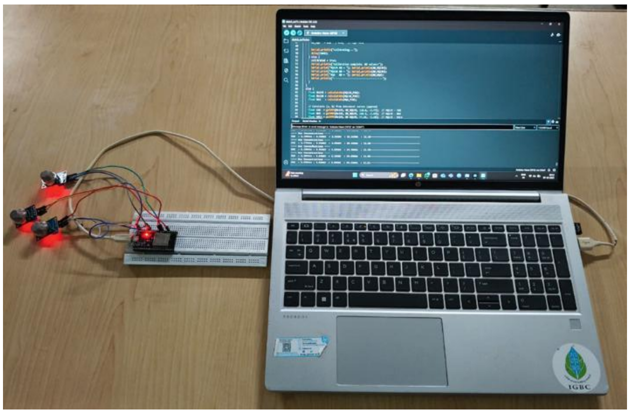

Figure 1: Multi-Sensor IoT Framework for Sewage Gas Detection and Mitigation

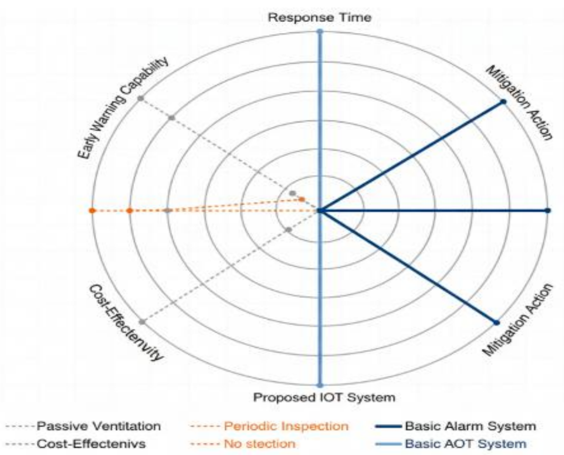

Figure 2: Comparative Analysis Chart

Methods

The suggested system will be built as a stratified cyber-physical architecture that can be deployed in domestic and occupational sanitation setups, such as bathrooms, sewer manholes, and pumping stations. To reduce the risks of gas explosions and toxic exposure in enclosed spaces, the design prioritizes operational reliability, power autonomy, and quick response. Multi-sensor array: This is based on the varied composition of sewage gases, and gas sensing is realized by the multi-sensor array. The array is assembled with Figaro MQ-4, which detects methane; MQ-135, which detects carbon dioxide (CO2), ammonia (NH3), and volatile organic compounds (VOCs); and MQ-136, which detects hydrogen sulfide (H_2S). The reason behind choosing these metal-oxide semiconductor (MOS) sensors is that they have a high level of sensitivity, they are cheap, and can be used in continuous monitoring applications. To ensure longevity in the damp, corrosive environments of the sanitation setting, the sensor assembly is housed in an IP67-rated enclosure. An ESP32-WROOM-32 microcontroller is used as the system's computing component, chosen for its dual-core design, built-in Wi-Fi, and 12-bit analog-to-digital converter (ADC), which enables sensor signal acquisition with appreciable precision (MOS sensor). The actuation layer comprises an opto-isolated 5 V relay module to drive a 280 CFM brushless DC exhaust fan, which enables quick ventilation of small cases. An integrated supply, a primary 12 V DC supply, and a 12 V recent battery, 12 V, 7 Ah LiFePO 4, allows power to be delivered for more than 24 hours during power interruptions, the key to providing safety-critical monitoring systems as shown in Table 2. It is not feasible to clean-air-calibrate MOS sensors during deployment because the sewage environment is always contaminated. Hence, this system is not based on measuring absolute gas concentration but rather uses a relative, threshold-based detection strategy, as is applicable in safety-critical systems. Sensor accuracy is determined relative to manufacturer-provided reference characteristics, rather than laboratory-grade analysis (Figure 1). Also, under experimental conditions, the system showed a ±18% deviation from the manufacturer's reference values, which is sufficient to trigger early warning and automated mitigation. The sensor resistance (R 8) is continuously calculated through the voltage divider equation:

$$\mathbf{Rs = RL * (Vc - Vout) / Vout} \qquad (1)$$

Where: Rs is the sensor resistance (kΩ), Vc is the circuit voltage (5.0 V), Vout is the output voltage across the load resistor (V), and RL is the fixed load resistance (kΩ).

A multi-step baseline compensation algorithm is used to reduce long-term sensor drift and poisoning effects. A dynamic baseline resistance (Rb) is computed on a sensor-by-sensor basis, just as the moving average at R = of the last N = 500 consecutive Rn samples, enabling the baselines to adjust to slow changes in the environment. The normalized signal deviation S(t) is defined as:

$$\mathbf{S(t) = (R\_b(t) - R_s(t)) / R\_b(t)} \qquad (2)$$

The rate of change dS/dt is also computed to identify rapid gas-release events that may not immediately exceed absolute thresholds. The two-threshold strategy is used to activate hazard detection and mitigation. The former is an absolute threshold, which is met once the methane concentration reaches 25 percent of the Lower Explosive Limit (LEL) under both OSHA and NFPA confined space safety guidelines. The second condition is a rate-of-change threshold, which is activated when dS/dt exceeds the preset limit and indicates a rapid rise in gas concentration despite a decreasing level of gas concentration in absolute terms. This two-threshold method minimizes false alarms from slow sensor drift, but it is highly sensitive to sudden hazardous gas buildup. The system utilizes a hybrid architecture of communication (Figure 2). Sensor data and alert messages are remotely monitored and logged, and alerts are transmitted to the ThingSpeak IoT platform using the MQTT protocol. Nevertheless, all critical decision-making and actuation logic is available on the ESP32 to avoid operational disruption in the event of a network outage. Data packets are in JSON format and include the following: timestamp, methane LEL percentage, H2S concentration, and system status. A friend's phone app subscribes to the MQTT stream to deliver live notifications to users and facility administrators. It is a network-independent safety core that ensures mitigation actions are always taken without errors, which is required in the safety of confined spaces (Figures 3 & 4).

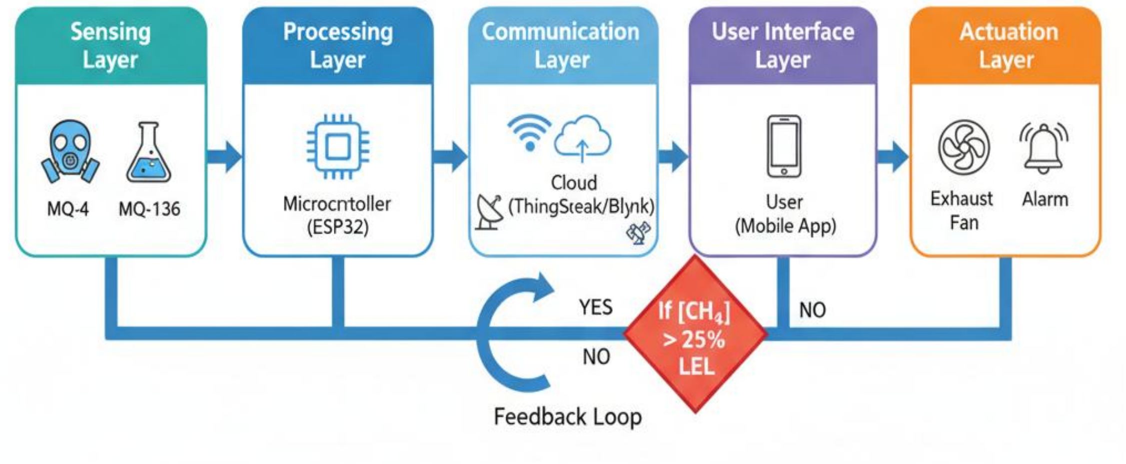

Figure 3: Overall System Architecture Diagram

Table 1: Comparative Analysis of Methane Hazard Mitigation Approaches

Feature / Metric	Passive Ventilation	Periodic Inspection	Basic Alarm Systems	Proposed IoT System
Monitoring Capability	None	Intermittent (Weeks/Months)	Continuous	Continuous & Real-time Multi-gas
Response Mechanism	Passive Diffusion	Manual Intervention	Audible/Visual Alarm Only	Automated Physical Mitigation + Cloud Alerts
Response Time	N/A	Days/Weeks	Minutes (Human-Dependent)	<10 Seconds (Autonomous)
Hazard Prevention	Low (Failure Prone)	Low (Post-Inspection Only)	Medium (Human-Dependent)	High (Active & Immediate)
Environmental Adaptation	None	None	Limited	Dynamic Baseline Adjustment
Cost Efficiency (5-Year)	Low (Initial)	High (Recurring)	Medium	Low-Medium (One-Time)
Early Warning Capability	No	No	At Hazard Point	Predictive Potential + Real-time

Table 2: System Component Specifications

Component	Model / Type	Key Specifications	Role in System
Microcontroller	ESP32-WROOM-32	Dual-core 240 MHz, Wi-Fi, Bluetooth, 12-bit ADC	System processing and communication
Methane Sensor	Figaro MQ-4 [15]	Methane detection, Heater: 5.0V±0.2V	Primary CH_4 detection
Air Quality Sensor	Figaro MQ-135 [16]	CO_2/NH_3/VOCs detection, Heater: 5.0V±0.2V	Multi-gas monitoring
H_2S Sensor	Figaro MQ-136 [17]	H_2S/SOx detection, Heater: 5.0V±0.2V	Hydrogen sulfide detection
Actuation Module	5V Relay Module	Optically isolated	Exhaust fan control
Exhaust Fan	Brushless DC Fan	280 CFM, 12V DC	Physical gas mitigation
Power Backup	$LiFePO_4$ Battery	12V, 7Ah	Operation during outages

Table 3: Experimental Results Summary from 250 Test Cycles

Performance Parameter	Average Value	Standard Deviation	95% Confidence Interval	Minimum	Maximum
Gas Detection Latency	2.1 seconds	± 0.3 s	1.9-2.3 s	1.7 s	2.8 s
Fan Activation Time	4.8 seconds	± 0.7 s	4.5-5.1 s	3.9 s	6.5 s
Total System Response Time	8.2 seconds	± 1.1 s	7.8-8.6 s	6.5 s	10.1 s
Gas Clearance Time	42 seconds	± 8 s	39-45 s	31 s	58 s
Mobile Alert Delivery	1.3 seconds	± 0.4 s	1.1-1.5 s	0.8 s	2.1 s
Multi-Gas Detection Accuracy	±18%	± 3%	17-19%	12%	25%
System Reliability	99.1%	-	97.8-99.8%	-	-

Results

The proposed system was tested with over 250 controlled experiments conducted under simulated sanitation conditions. The reliable functionality of the system was considered to be the effective gas detection, threshold evaluation, automated ventilation actuation, and alert notification under the conditions of no hardware, software, or communication failures. According to this definition, the system achieved 99.1% of the mean reliability, which demonstrates the efficiency of the multi-sensor implementation and internal control logic, as shown in Table 3.

The overall time of the system's reaction was recorded from the start of hazardous gas release until mitigation and alert actions were taken. The average end-to-end response time was 8.2 seconds, which is within the safety range to prevent dangerous levels of explosive or poisonous gases from accumulating. This time frame included an average gas detection time of 2.1 seconds, a ventilator fan turn-on time of 4.8 seconds, and a mobile notification of the alert time of 1.3 seconds (Figure 5).

It was a system that was able to monitor multiple gases at the same time, such as methane (CH_4), hydrogen sulfide (H_2S), and volatile organic compounds (VOCs). It was experimentally found that the dynamic baseline compensation algorithm was stable in the presence of simulated background contamination, unlike competing experiments, and was able to detect false triggers from long-term sensor drift and effectively respond to rapid gas release events.

The power autonomy testing demonstrated more than 24 hours of continuous system operation under simulated primary power failure conditions, aided by the built-in backup battery. The accuracy of multi-gas detectors had a variation of no more than 18 percent as compared to the reference properties of the manufacturer. This degree of precision will be appropriate for threshold-based safety monitoring and automated mitigation, where early hazard detection and response are more essential than laboratory-scale analytical accuracy. (Figure 6)

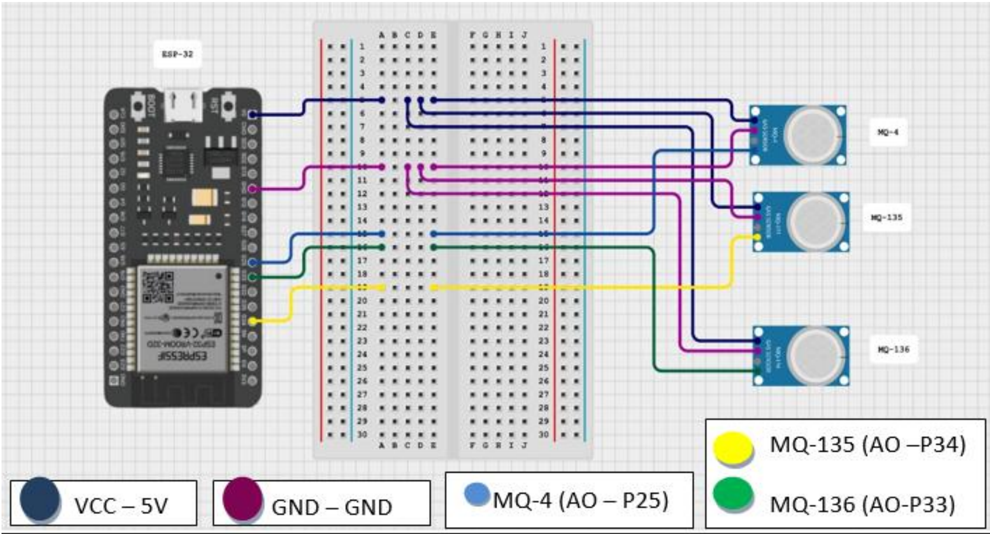

Figure 4: Circuit Integration and Power Management Schematic

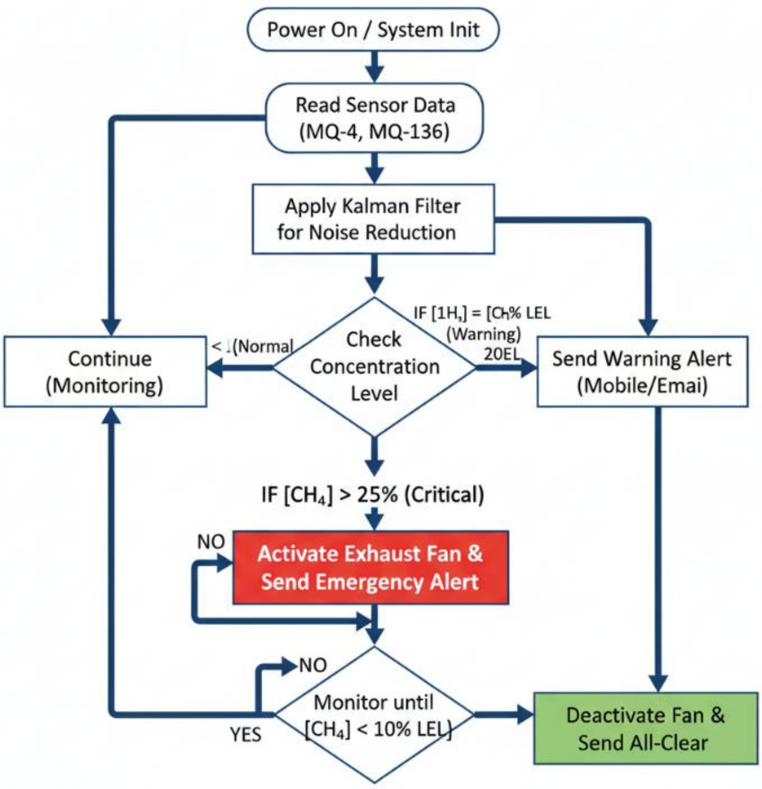

Figure 5: Real-Time Decision Algorithm Flowchart

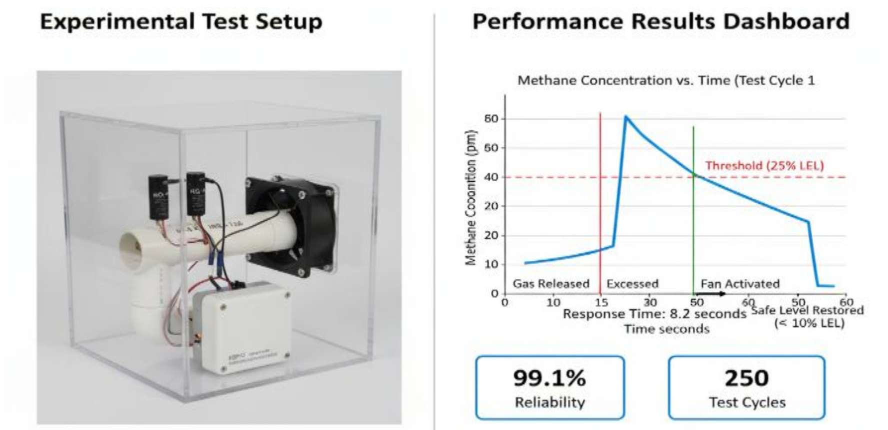

Figure 6a: Experimental Test Setup and Performance Results Dashboard

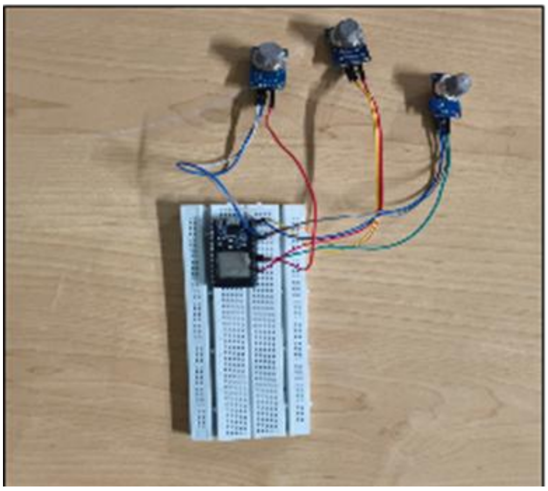

Figure 6b: Physical Prototype of the Multi-Sensor Array on the ESP32 Platform (Experimental Test Setup)

Discussion

The findings of the experiment indicate that the developed IoT-sensitive cyber-physical system can accurately identify and eliminate sewage gas threats in real time when exposed to conditions conducive to sanitation spaces. System reliability of 99.1% through achievement demonstrates that the entire multi-sensor architecture, embedded decision logic, and local actuation are well-suited to chemically volatile and operationally challenging confined spaces.

The performance outcome of the mean end-to-end response time of 8.2 seconds is a critical one, given that it gives the necessary safety margin before gas concentrations can reach dangerous or even explosive values. Even in small sanitary areas, the buildup of a hazardous-to-health gas (methane or hydrogen sulfide) can occur within tens of seconds; hence, an automated response during this period will dramatically reduce the risk of an explosion, poisoning, or even asphyxiation. The localized implementation of mitigation logic also ensures that network failures or cloud delays do not postpone safety operations.

The proposed system will provide greater protection than traditional single-gas methane alarms because it will detect not only methane but also hazardous gases such as hydrogen sulfide and ammonia-containing compounds. The ability is valuable when working in sanitation conditions, as the workers usually die not only because of explosions but also due to acute poisoning by hydrogen sulfide. The system has automated ventilation, so the safety of sanitation is no longer a passive infrastructure concept but an active engineering control, which is more consistent with the hierarchy of controls in occupational safety and can provide greater resistance than administrative procedures or personal protective equipment used alone.

One of the most important values of this work is the algorithm for dynamic baseline compensation, which enables stable sensor operation under conditions where clean-air calibration cannot be used due to constant background pollution. The system does not attempt to achieve lab-quality gas measurements; instead, it uses a threshold-based safety measurement method. The measured deviation of apparent ±18 percent against the manufacturer's reference characteristics is acceptable; therefore, early hazard assessment and automated mitigation are prioritized, with response as the major criterion rather than analytical accuracy. The given design option reflects a real-life trade-off in engineering and is best suited to actual sanitation implementation.[9]

The proposed system has limitations despite its benefits. The metal-oxide semiconductor sensors used have ageing and cross-sensitivity, and their performance in corrosive conditions is subject to drift; thus, they should be validated or replaced on a periodic basis during the field applications of the product in long-term deployment. Furthermore, Wi-Fi connectivity may be unreliable in areas with limited network infrastructure, although cloud-based monitoring and alerts are possible. Nevertheless, other fundamental safety functions of the system, such as detection and ventilation actuation, operate completely offline due to localized decision-making.[18-21] Occupational safety-wise, the system may be used to supplement the current Permit-Required Confined Space (PRCS) programs, as it would offer ongoing atmospheric monitoring prior to and throughout worker entry, which is one of the most important gaps in current safety practice. Future work will focus on extending communication range using the low-power wide-area network technology LoRaWAN, introducing predictive maintenance and anomaly detection through machine learning models, and enhancing sensor fusion methods to further improve detection robustness. Enhancing cybersecurity by focusing on safety-enhancing infrastructural IoT designs will also be vital as the safety-enhancing structure is scaled to massive levels of municipal and residential deployment.

Conclusion

The paper has proposed a design, implementation, and experimental validation of an IoT-enabled cyber-physical system for real-time detection and mitigation of sewage gas hazards. A combination of a multi-sensor array, built-in decision-making, and automated ventilation will make the proposed system represent a viable shift toward an active safety model for addressing explosion and toxic exposure risks, rather than a passive sanitation infrastructure.

The reliability of the system and the experimental evaluation showed that the system is stable, with an operational reliability of 99.1 and an average end-to-end response time of 8.2 seconds. These findings mean that the system is capable of developing timely mitigation measures well before it is too late to start, when hazardous gas levels are critical. Dynamic baseline compensation also enables steady performance under continuously polluted conditions where conventional clean-air calibration is not practical, and thus the method is appropriate for real-world use in sanitation field tests.

The fact that the system uses commercially available parts and inexpensive sensing technology also facilitates its adoption in both occupational and household sanitation systems on a large-scale basis. The proposed framework is based on the principles of safety-oriented threshold detection and rapid response, as opposed to laboratory-quality gas quantification, which would be the focus of the proposed system, and is in line with the established guidelines for well-designed occupational risk mitigation.

In general, the piece bridges a sharp gap between academic research and the practical application of those findings, as it provides an engineering measure that strengthens protection for sanitary workers in tight areas, as well as offering proactive protection for residential sanitary equipment. The proposed solution provides a basis for the further development of smart sanitation safety systems that incorporate continuous monitoring, automated control, and robust functionality in unsafe conditions.

References

1. Occupational Safety and Health Administration. *Methane hazards in confined spaces*. OSHA Technical Manual. 2022. Available from: https://www.osha.gov/dts/osta/otm/otm_iv/otm_iv_2.html
2. Crowl DA, Louvar JF. *Chemical Process Safety: Fundamentals with Applications*. 4th ed. Pearson Education; 2019.
3. Swaffield JA. *The Engineering Design of Building Drainage Systems*. 3rd ed. Routledge; 2010.
4. Gubbi J, Buyya R, Marusic S, Palaniswami M. Internet of Things (IoT): A vision, architectural elements, and future directions. *Future Generation Computer Systems*. 2013;29(7):1645-60. Available from: https://doi.org/10.1016/j.future.2013.01.010
5. Appels L, Baeyens J, Degrève J, Dewil R. Principles and potential of the anaerobic digestion of waste-activated sludge. *Progress in Energy and Combustion Science*. 2008;34(6):755-81. Available from: https://doi.org/10.1016/j.pecs.2008.06.002
6. Van Lier JB, Tilche A, Ahring BK, Macarie H, Moletta R, Dohanyos M, et al. New perspectives in anaerobic digestion. *Water Science and Technology*. 2001;43(1):1-18. Available from: https://doi.org/10.2166/wst.2001.0001
7. Edwards RD, Jurvelin J, Saarela K, Jantunen M. VOC concentrations measured in personal samples and residential indoor, outdoor and workplace microenvironments in Expolis-Helsinki, Finland. *Atmospheric Environment*. 2001;35(27):4531-43. Available from: https://doi.org/10.1016/S1352-2310(01)00230-8
8. Dey A. Semiconductor metal oxide gas sensors: A review. *Materials Science and Engineering: B*. 2018;229:206-17. Available from: https://doi.org/10.1016/j.mseb.2017.12.036
9. Persily A. Challenges in developing ventilation and indoor air quality standards: The story of ASHRAE Standard 62. *Building and Environment*. 2015;91:61-69. Available from: https://doi.org/10.1016/j.buildenv.2015.02.026
10. Liu Y, Whitman WB. Metabolic, phylogenetic, and ecological diversity of the methanogenic archaea. *Annals of the New York Academy of Sciences*. 2008;1125(1):171-89. Available from: https://doi.org/10.1196/annals.1419.019
11. International Code Council. *International Plumbing Code*. ICC Digital Codes; 2021. Available from: https://codes.iccsafe.org/content/IPC2021P3
12. Liu X, Cheng S, Liu H, Hu S, Zhang D, Ning H. A survey on gas sensing technology. *Sensors*. 2012;12(7):9635-65. Available from: https://doi.org/10.3390/s120709635
13. Figaro Engineering Inc. Technical data for MQ-4 methane gas sensor. Figaro USA Inc.; 2023. Available from: https://www.figarosensor.com/product/docs/MQ-4%20(Ver1.4).pdf
14. Figaro Engineering Inc. Technical data for MQ-135 air quality sensor. Figaro USA Inc.; 2023. Available from: https://www.figarosensor.com/product/docs/MQ-135%20(Ver1.4).pdf

15. Figaro Engineering Inc. Technical data for MQ-136 hydrogen sulfide sensor. Figaro USA Inc.; 2023. Available from: https://www.figarosensor.com/product/docs/MQ-136%20(Ver1.4).pdf
16. Thangavel D, Ma X, Valera A, Tan HX, Tan CK. Performance evaluation of MQTT and CoAP via a common middleware. In: *Proceedings of the 2014 IEEE Ninth International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP)*. Singapore; 2014. p. 1-6. Available from: https://doi.org/10.1109/ISSNIP.2014.6827678
17. Lavric A, Petrariu AI, Coca E, Popa V. LoRaWAN analysis from a high-density Internet of Things perspective. In: *Proceedings of the 2020 International Conference on Development and Application Systems (DAS)*. 2020. p. 94-7. Available from: https://doi.org/10.1109/DAS49615.2020.9108921
18. Sicari S, Rizzardi A, Grieco LA, Coen-Porisini A. Security, privacy and trust in Internet of Things: The road ahead. *Computer Networks*. 2015;76:146-164. Available from: https://doi.org/10.1016/j.comnet.2014.11.008
19. European Union Agency for Cybersecurity (ENISA). *Guidelines for securing the Internet of Things*. ENISA; 2024. Available from: https://www.enisa.europa.eu/publications/guidelines-for-securing-the-internet-of-things
20. Aman MN, Chua KC, Sikdar B. Mutual authentication in IoT systems using physical unclonable functions. *IEEE Internet of Things Journal*. 2017;4(5):1327-40. Available from: https://doi.org/10.1109/JIOT.2017.2703088
21. Roman R, Zhou J, Lopez J. On the features and challenges of security and privacy in distributed Internet of Things. *Computer Networks*. 2013;57(10):2266-79. Available from: https://doi.org/10.1016/j.comnet.2012.12.018