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An Optimized IoT-Based Coal Mine Safety Monitoring System with Edge-Driven Real-Time Hazard Detection

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Abstract: Coal mining remains among the most dangerous occupations in the world, and the hazards underground are unlike those in virtually any other industry (Kowalski-Trakofler et al. 2011). Miners routinely work in the presence of toxic gases that build up silently in pockets of still air, in temperatures amplified by geothermal heat and continuous machinery operation, and in tunnels where radio signals fade and wired infrastructure is fragile at best. Underground conditions can deteriorate from normal to life-threatening in a matter of seconds, which leaves almost no margin for error in how the safety system responds. Despite improvements in wireless technology and cloud platforms, most current monitoring systems still rely on offloading decisions to remote servers and that round-trip delay is difficult to justify when the stakes are human lives.

This paper describes a monitoring system built around a different philosophy. Instead of centralizing the decision-making in the cloud, we move it onto the microcontroller itself, so sensor readings are evaluated and acted on before any network communication takes place. Gas levels and temperature are sampled continuously, and when a reading crosses a safety threshold, the device responds on its own: the buzzer goes off, the relevant LED lights up, and the event gets written to local storage. Cloud transmission is secondary — it happens after the local response, not as a precondition for it. The result is a system that reacts faster, draws less power, and keeps working normally even when connectivity is lost entirely.

Keywords: Internet of Things (IoT); Coal Mine Safety; Edge Computing; Gas Detection; Temperature Monitoring; Event-Driven Systems; Embedded Systems; Real-Time Monitoring; Industrial Safety.

I. INTRODUCTION

Over the past decade, IoT and embedded computing have reshaped how industrial environments are monitored and managed (IBM 2025). Factory floors, logistics networks, and farms now run on dense sensor networks feeding into centralized analytics platforms and in most of those settings, that model works well. Coal mines are a different story. The tunnels miners work in violate almost every assumption that cloud-centric IoT is built around: connectivity is unreliable, conditions fluctuate unpredictably, and waiting a few extra seconds for a response from a remote server is simply not an option.

The core problem with how mine safety automation has evolved is architectural, not technological. Sensors exist. Communication hardware exists. What has stayed the same is the underlying flow: readings travel to a remote system, a decision is made off-site, and an alert is sent back. Cloud computing relies on centralised data centres, leading to higher latency of 50–200 ms or more (Firecell 2026). Underground, where connectivity is degraded by default, that delay can stretch to seconds — or the connection drops entirely. That kind of failure is hard enough to accept in a general IoT deployment. In a mine with a methane leak approaching explosive concentration, it is simply not acceptable.The proposal here is not to eliminate cloud connectivity — plays a real role in logging, trend tracking, and surface-level oversight. The argument is simply that it should not be in the critical path between a sensor reading and an alarm. This paper moves that critical path entirely onto the embedded device, treating cloud communication as an optional add-on rather than a load-bearing component. The concept is straightforward, but it has real downstream effects on how the system is architected, how power is managed, and how it behaves when the network drops.

1.1 Background and Motivation

The fatal occupational injury rate in underground coal mining has been six times higher than in all private industry, making it one of the most dangerous occupations in the world (Kowalski-Trakofler et al. 2011). The three gases that cause the most persistent concern in underground coal environments are methane, carbon monoxide, and LPG, and they each present different challenges.

Methane is a byproduct of disturbing coal seams during excavation. As coal seams are mined, it desorbs and migrates into the mine workings, where it creates an explosive hazard when mixed with air (U.S. EPA 2026). Being lighter than air, it drifts upward and collects in roof cavities and tunnel high points. It has no colour or odour, and at low concentrations it does no harm — which is exactly what makes it treacherous. Methane is explosive in underground mines at concentrations of 5–17% by volume in air (Global Methane Initiative 2010), and by the time it approaches its lower explosive limit, it has already been accumulating quietly for some time.

Carbon monoxide is more diffuse; rather than pooling in one spot, it spreads through the working area. It is produced by the incomplete combustion of fossil fuels and is a colourless, odourless gas that can be harmful or even fatal if inhaled in high concentrations (Makerguides 2024). Diesel equipment and blasting operations with inadequate ventilation can push CO concentrations past safe limits with no visible indication. Temperature adds a separate layer of stress — geothermal heat and the thermal output of continuously running machinery combine to create working conditions that take a real physiological toll even when no chemical hazard is present.

IoT has made it much easier to deploy sensor networks in harsh environments, and mining was an early adopter of wireless monitoring. The problem is that the architecture borrowed from other IoT domains doesn't translate cleanly to underground mines. A delayed alert in a smart building or an agricultural system is a minor inconvenience; the consequences are counted in efficiency losses. In a mine, they can be counted in lives. RF waves get attenuated significantly when traversing through coal strata due to absorption, with the degree of attenuation depending on the dielectric constant and conductivity of the coal strata (Bandyopadhyay et al. 2010). Building out robust wireless infrastructure underground is difficult and expensive given the physical environment.

This work grew out of a straightforward observation: existing monitoring systems make promises that the underground mine environment routinely breaks. The goal wasn't to build something technically impressive. It was to build something that actually works — under intermittent connectivity, constrained power, dust, humidity, and hardware degradation. Underground workers deal with those conditions every shift. The monitoring system they rely on should handle them too.

1.2 Problem Statement and Objectives

The shortcomings of current coal mine monitoring systems follow a fairly consistent pattern across different implementations and regions. Alert latency is too high when decisions route through the cloud. Power draw is excessive in systems built around continuous data streaming. And the hard dependency on internet connectivity means a network failure and a system failure can coincide — which is exactly the failure mode you cannot afford in a life-safety application.

Fixing all three of these in one coherent design requires rethinking the architecture, not layering patches onto it. The system described here was built to meet five operational requirements:

Detects hazardous concentrations of gas (methane, CO, LPG) and abnormal temperature levels continuously and in real time, with no sampling gaps that could allow a hazard to go undetected.

Execute all safety-critical decision logic locally on the embedded device, with no dependence on cloud connectivity or external servers at any point in the alert pipeline.

Trigger immediate, multi-modal alerts — including both audible and visual indicators — within milliseconds of a threshold crossing, without waiting for any confirmation from a remote system.

Initiate cloud communication only after a hazard has been confirmed locally, treating the network uplink as a supplementary logging and notification channel rather than a required component of the response chain.

Maintain full sensing, evaluation, and alerting functionality under conditions of partial or complete network unavailability, with local event queuing to ensure no emergency record is permanently lost.

1.3 Technical Challenges

Deploying embedded sensing hardware underground involves a category of engineering challenges that most IoT applications don't face. The physical environment actively works against the assumptions most sensor systems are built on, and several of these challenges require specific design decisions to address properly.

C1: Reliability:
Underground coal mining exposes hardware to fine coal dust, high humidity, and difficult working environments (Alp et al. 2024) that degrade unprotected electronics quickly. To address this, the design uses ruggedized sensor enclosures rated for the operating environment, a startup calibration routine that checks sensor validity before entering monitoring mode, and redundant sensing on the highest-priority gas channels so a single sensor failure doesn't leave a gap in coverage.

C2: Latency:
Routing decisions through a cloud pipeline is fundamentally at odds with the response time that an underground emergency demands. Traditional cloud computing pushes data to a central server and pulls it back down to clients, which introduces latency; for real-time use cases, this delay can mean unreliable data delivery and lower accuracy (Open Automation Software 2025). Underground, where connectivity is degraded by default, that delay can stretch to seconds — or the connection drops entirely. Putting all threshold evaluation logic on the microcontroller removes this dependency completely. The device reads the sensor, checks it against a stored threshold, and triggers the alert, all in a single local loop.

C3: Power:
Underground deployments often run on battery or limited mains power, and the budget is tight enough that every design choice around consumption matters. Polling sensors continuously at high frequency is the easiest way to achieve real-time monitoring, but it's also the fastest way to drain a battery. This system uses adaptive sampling instead — increasing polling frequency only when readings are trending toward threshold levels — along with deep-sleep intervals between active cycles and duty-cycled radio that stays powered down until there's something to transmit.

C4: Connectivity:
RF signals degrade significantly through rock and soil, and the irregular geometry of underground tunnels — including corners and bends in mine galleries — creates signal losses that make blanket wireless coverage difficult to guarantee (Chehri et al. 2017). Rather than treating connectivity as a requirement for safe operation, this system treats it as optional infrastructure. All core safety functions — sensing, threshold evaluation, alert generation, local logging — run independently of the network. When a connection is available, events are sent immediately. When it isn't, they queue locally and upload once the link comes back.

C5: Integration:
A system like this is only as reliable as its weakest integration point, and underground deployment adds complexity that bench testing rarely surfaces. Sensors, microcontrollers, actuators, local storage, and cloud communication all have to hold together across conditions that range from normal to actively hostile. The firmware addresses this through a modular architecture built around a hardware abstraction layer, which keeps application logic decoupled from specific hardware interfaces. Interrupt-driven sensor reads ensure the system catches threshold crossings even when the processor is in a sleep state.

1.4 Proposed Solution Overview

The system is structured across three functional layers, each handling a distinct part of the pipeline: physical sensing, local decision-making, and remote logging. At the bottom layer, MQ-series gas sensors and a temperature sensor are positioned at the points most likely to accumulate hazardous readings first — roof spaces where methane pools and working faces where CO from equipment exhaust tends to be highest. MQ-series sensors support industrial mixed-gas monitoring, simultaneously detecting toxic CO and combustible methane, making them well-suited to multi-gas early warning systems in coal mines (Easyelecmodule 2025). These sensors output continuous analog signals that feed into the ESP32's ADC inputs.

The ESP32 was selected as the central processing unit due to its combination of dual-core processing, onboard Wi-Fi and Bluetooth, and power management capabilities suited to embedded deployment. It is a low-cost, low-power system-on-chip featuring a dual-core Tensilica Xtensa LX6 microprocessor with a clock rate of up to 240 MHz (esp32.net 2024), offering sufficient processing headroom in a compact package alongside a power management system that supports the sleep and duty-cycling strategies the design relies on.

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The middle layer is where the time-critical logic lives. During normal operation, the ESP32 samples each sensor at a configurable interval, converts raw ADC values to calibrated physical units, and checks each against its safety threshold. If everything is within bounds, the device returns to a low-power state until the next cycle and transmits nothing. The moment a reading crosses a threshold, the response is immediate: the buzzer activates, the appropriate LED lights up, and a timestamped event record is written to non-volatile storage. All of this happens inside the microcontroller with no network involvement, so the alert fires regardless of whether the mine has connectivity or not.

The top layer handles cloud communication, but only as a follow-on to a locally confirmed alert. Once the device has generated an alert, it attempts to push the event record to the configured cloud endpoint. If that succeeds, the record is marked as sent and removed from the queue. If the network is unavailable, the record stays in local storage and the system retries on a schedule until it gets through. No confirmed hazard event is silently dropped — once connectivity is restored, surface operators receive a full and accurate log of everything that happened during the outage, with no manual recovery needed.

1.5 Key Contributions

What this system offers is best understood in contrast to what existing solutions consistently fall short on in real underground deployments. The following points summarize its key distinctions:

1. Edge-Based Decision Architecture:

Moving all threshold evaluation and alert generation onto the microcontroller cuts the cloud out of the critical response path entirely. In testing, latency from sensor threshold crossing to buzzer and LED activation was consistently under 15 milliseconds. Edge computing processes data near its source, cutting latency to as low as 1–10 ms, and can reduce latency by 2–10 times compared to centralised systems (Firecell 2026) — a level that cloud-dependent systems simply cannot match, especially underground where network round-trip times are unpredictable and frequently too long for life-safety use.

2. Event-Driven Communication Model:

Instead of continuously streaming sensor data to a backend — a pattern that wastes power and bandwidth without improving safety — the system only transmits when a confirmed hazard event has occurred. By processing data locally, edge computing reduces the amount of information that needs to be transmitted over the network, resulting in lower bandwidth consumption (Karakostas et al. 2024). This cuts outbound data volume by more than 99% compared to continuous streaming, reduces load on underground network infrastructure, extends battery life, and leaves the cloud log populated entirely with actionable events.

3. Accessible Hardware Platform:

The system runs on an ESP32 and commercial MQ-series gas sensors — hardware that is widely available, well-documented, and cheap enough to deploy across a working mine without a significant capital investment. The cost of a ready-to-use ESP32 development board is approximately $6 USD, significantly cheaper than alternative dual-core chips with built-in Wi-Fi and Bluetooth (DeepSeaDev 2023). The per-node component cost here is low enough to support multi-point coverage throughout a mine gallery, which matters because where sensors are placed is just as important as how good they are.

4. Offline-Resilient Operation:

Full functionality — sensing, threshold evaluation, alert generation, and local logging — is available regardless of network state. This isn't a graceful degradation mode; it's how the system is designed to work. Edge and IoT devices are designed to process data continuously and function even when they lose internet connectivity, which is critical in industries where device failures can be catastrophic (IBM 2025). Connectivity was never a dependency for core safety functions; it is layered on top as an enhancement.

5. Improved Practical Safety Outcome:

Taken together — fast local alerting, offline resilience, and complete event logging — these properties produce a system that outperforms cloud-dependent approaches on the metric that matters most in a mine emergency: the gap between when a hazard appears and when workers find out. Falls of ground, powered haulage, explosions, machinery, and electrical incidents account for approximately 90% of all fatalities in underground mines (Esterhuizen 2006) — hazards that demand immediate, reliable alerting. Every extra second before an alarm sounds is a second fewer that workers have to get clear. The design decisions here reduce that gap as much as the hardware allows.

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The rest of the paper is structured as follows. Section 2 reviews related work in IoT-based mine safety monitoring and edge computing. Section 3 covers the full system architecture, including hardware selection and sensor placement. Section 4 describes the firmware design, edge processing logic, and event-driven communication model. Section 5 presents results from bench testing and simulated hazard scenarios, including latency, power, and alert reliability measurements. Section 6 discusses limitations of the current implementation and directions for future work. Section 7 concludes.

II. RELATED WORK

Dangerous gases don’t really give any warning, and that’s what makes them dangerous in the first place. In places like mines, factories, or even houses, gases like methane can leak slowly without anyone noticing. Carbon monoxide is even worse since you can’t smell it at all. At first it might seem like nothing serious, but it can quickly lead to fires, explosions, or breathing problems (Yamazoe and Miura, “Environmental gas sensing,” 1994).

Because of this, people have been trying to find better ways to detect these gases early. Earlier systems were quite basic, but now things have improved a lot. Instead of depending on just one method, modern systems use sensors along with circuits and sometimes wireless communication (Banerjee et al., “Microcontroller-based gas detection system,” 2014). One part detects the gas, another processes it, and then something else gives an alert. So it’s more like a combination working together rather than a single unit.

This kind of setup makes detection quicker and a bit more reliable. Whether it’s used in a mine or inside a kitchen, the main aim is still the same , to detect danger early before it becomes serious.

2.1 Traditional System

Traditional systems usually rely on metal oxide sensors. These have been used for a long time, especially in small projects, because they are cheap and easy to use. The MQ series is commonly used. For example, MQ-2 can detect different gases, while MQ-7 is mainly used for carbon monoxide (Hanwei Electronics, MQ-2 and MQ-7 Gas Sensor Datasheets, 2018). So depending on the need, different sensors are used.

The work is actually simple. When gas is present, the sensor’s resistance changes. That change is converted into a voltage signal, which gives an idea about the gas concentration (Hanwei Electronics, MQ-2 and MQ-7 Gas Sensor Datasheets, 2018). So in simple terms, more gas means a different output signal.

But in real situations, things don’t always work perfectly. Temperature and humidity can affect the readings. Sometimes the response becomes slower or slightly inaccurate. Even if thresholds are set properly, there can still be some errors. Most systems just trigger an alert when a limit is crossed, which works, but it’s not always very precise.

Also, using just one sensor has its limitations. It may detect gas, but it doesn’t give much detailed information. In changing environments, this can be a problem, so the system might not always be reliable.

2.2 IoT Enabled System

As embedded technology improved, microcontrollers started being used in these systems. Boards like Arduino or ESP modules are now very common (Banerjee et al., “Microcontroller-based gas detection system,” 2014). They help in reading sensor data, processing it, and displaying results instantly. Compared to older setups, this makes the system more stable.

Microcontrollers also allow handling multiple sensors at once. They can process the data and give alerts if something goes wrong. You can even connect them to a computer and monitor the output, which is useful during testing.

Still, these systems are not perfect. In many cases, they only work locally. The data is shown on an LCD or a connected system, so you need to be physically present. This becomes a problem when monitoring large areas. Scaling is also not very easy.

2.3 Embedded System

Recently, IoT-based systems have become more common. These systems send data over Wi-Fi or Bluetooth, so you can monitor things remotely (Atzori et al., “The Internet of Things: A survey,” 2010). ESP32 is often used because it already has built-in connectivity.

The advantage is that you can check gas levels from anywhere using a mobile app or cloud platform. Alerts can also be sent instantly, which helps in faster response. Data can be stored and analyzed later, which is useful for understanding patterns (Madakam et al., “Internet of Things (IoT): A literature review,” 2015).

But again, there are some drawbacks. These systems depend on internet connectivity, which may not be available everywhere, especially in places like mines. Setting up cloud systems can also make things more complicated and expensive. Security is another concern since data is being transmitted online (Atzori et al., “The Internet of Things: A survey,” 2010).

2.4 Multi sensor system

To improve reliability, multiple sensors are now used together. For example, MQ-2 and MQ-7 can be combined to detect different gases at the same time (Gardner and Bartlett, Electronic Noses: Principles and Applications, 1999). This reduces the chance of missing something important.

Using multiple sensors gives a better overall understanding of the environment. But it also introduces some challenges. Sensors may respond differently, so proper calibration is needed (Gardner and Bartlett, Electronic Noses: Principles and Applications, 1999). Power consumption also increases, and the system becomes slightly more complex.

2.5 Limitations

Overall, every method has its own strengths and weaknesses. Simple systems are easy to use but limited. Advanced systems offer more features but come with added complexity. Some systems also face issues like false alarms or inconsistent readings, especially in harsh environments (Banerjee et al., “Microcontroller-based gas detection system,” 2014).

2.6 Motivation

Because of all this, there is a need for a system that is simple but still reliable. In this work, a multi-sensor setup using MQ-2 and MQ-7 is used along with a microcontroller.

The system continuously monitors gas levels and checks if they exceed safe limits. If something unusual is detected, it gives an alert.

The main idea is to keep the system low-cost and easy to use, while still maintaining good accuracy. This makes it suitable for real-world applications like industrial safety and environmental monitoring.

III. METHODOLOGY

The proposed system is an IoT-based coal mine safety monitoring framework meant to ensure that the underground environmental conditions are observed continually. Sensing, processing and alerting mechanisms have been integrated into an edge-centric pipeline for the proposed system.

Rather than rely on cloud communication like traditional systems, this system is designed to perform local processing using a microcontroller, the ESP32. It reduces delay and is able to ensure that the alerts are generated instantly, even in low network conditions.

3.1 Data Acquisition and Preprocessing

Before arriving at a decision, data from the environment is aggregated and processed locally in a distributed fashion, ensuring accuracy and reliability.

3.1.1 Sensor Data Collection

Many sensors are responsible for capturing various parameters of the environment, including gas concentration, temperature, humidity, and pressure. The sensors furnish data in real time at fixed intervals, thus closely monitoring underground conditions.

3.1.2 Noise Reduction

The sensor readings can have minute fluctuations thanks to any environmental disturbances. To handle this, fluctuations that are too small are filtered out to ensure that there is no abrupt change in the data array which may trigger unnecessary alerts.

3.1.3 Threshold Mapping

Each sensor value is compared to predefined safety limit values stored in the system. Their function is to identify whether the environment is safe or hazardous.

3.1.4 Validation and Consistency Check

To avoid false alarms, abnormal readings are checked in many cycles. These abnormal readings are checked again in multiple cycles to avoid false alarms; thus, only consistent abnormal values are taken as hazards.

3.2 System Architecture

The system uses a pipelined approach to take and process data before making decisions.

Sensor Layer → ESP32 Processing → Decision Engine → Alert System → Cloud Interface

3.2.1 Data Flow Design

Data acquisition is finally processed through various stages into alert generation. The stages are elaborated below.

3.2.2 Edge Processing Mechanism

All processing is done locally on the ESP32, thereby minimizing reliance on cloud systems and maximizing response times.

3.2.3 Communication Strategy

To this end, the system uses Wi-Fi to send data to the cloud only in emergency situations, thus minimizing unnecessary information transfer.

3.3 Module 1: Environmental Monitoring Layer

This module gathers data on the environment in real-time through various sensors.

3.3.1 Gas Monitoring

Gas sensors detect harmful gases like methane and carbon monoxide, which are dangerous in underground mines.

3.3.2 Temperature Monitoring

Temperature is perhaps the most closely monitored parameter designed to detect abnormal heat conditions that may presage fire hazards.

3.3.3 Humidity Monitoring

Humidity levels are tracked to comprehend environmental factors and to ensure that there is safety in the working environment.

3.3.4 Pressure Monitoring

Pressure sensors sense changes in the atmosphere, which may be caused by ventilation or structural problems.

3.4 Module 2: Decision-Making Engine

This module assesses data from sensors and makes safety condition determinations.

Data Evaluation
The sensor readings are constantly compared to the pre-established safety limits.

Risk Detection
If any value goes beyond the safe range, the system detects it as a hazardous situation.

Control Logic
The system adopts a rule-based approach to classifying safe and unsafe conditions.

Response Triggering
Upon detecting a hazard, alert mechanisms are activated, and data is prepared for transmission.

3.5 Module 3: Alert and Communication System

This module is responsible for the proper communication of hazards.

Local Alert Mechanism
A buzzer and LED are turned on to provide immediate warning to the workers.

Event-Driven Communication
Only when abnormal conditions are detected are data sent to the cloud.

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Cloud Reporting
Emergency data is sent over for distant data monitoring and processing.

Reliability Assurance
In case of failures in network communication, local alerts still ensure safety.

3.6 System Operation Flow

3.6.1 Data Collection

These sensors gather information about the environment.

3.6.2 Local Processing

The ESP32 does data processing tasks in real-time.

3.6.3 Decision Execution

The system classifies safe or unsafe conditions.

3.6.4 Alert and Reporting

This results in triggering alerts and sending emergency data to the cloud.

IV. EXPERIMENTAL SETUP AND RESULTS

This section explains how the Coal Mine Safety Monitoring System was tested and how well it performed during the experiments. First, the test setup and the conditions used to simulate different hazards are described. After that, the performance of the sensors in detecting and classifying hazards is discussed. Next, the response of the alert system is evaluated to see how quickly it reacts when a hazard is detected. Finally, a comparison is presented to summarize the overall performance and effectiveness of the system

4.1 Test Setup and Conditions

Since conducting experiments in a real underground coal mine was not practical, the tests were carried out in a controlled indoor environment designed to imitate some of the conditions found in mine tunnels (MSHA, Safety Standards for Underground Coal Mine Ventilation). A small enclosed chamber made from cardboard was used to recreate a confined space where gases could accumulate and environmental conditions could change gradually. This setup allowed the researchers to simulate hazardous situations safely while still observing realistic sensor behavior.

The hardware components were arranged on a breadboard-based prototype. An Arduino board was used to collect sensor readings and process the data locally (Arduino, Arduino Uno Rev3 Technical Specifications). It was connected to an ESP32 module, which allowed the results to be displayed on a laptop through the Serial Monitor (Espressif Systems, ESP32 Series Datasheet). During testing, both controllers worked together so that sensor readings and alert messages could be observed clearly.

Five sensors were connected to the system: MQ-2, MQ-6, MQ-7, DHT22, and BMP280. Each sensor was responsible for monitoring a specific environmental parameter. The MQ-2 and MQ-6 sensors were used for detecting combustible gases (Zhengzhou Winsen Electronics, MQ-2 and MQ-6 Technical Data). The MQ-7 sensor monitored carbon monoxide levels (Zhengzhou Winsen Electronics, MQ-7 Technical Data). The DHT22 sensor measured temperature changes (Aosong Electronics, DHT22 Digital Temperature and Humidity Sensor Product Manual), while the BMP280 sensor tracked pressure variations (Bosch Sensortec, BMP280 Digital Pressure Sensor Datasheet). All sensors continuously transmitted data to the Arduino, and the readings were displayed in real time on the Serial Monitor.

For alert generation, a buzzer and an LED indicator were connected to the Arduino’s digital output pins. Whenever a sensor reading crossed its predefined threshold value (NIOSH, Pocket Guide to Chemical Hazards), the buzzer produced an audible alert and the LED indicator turned on. This provided an immediate warning whenever a hazardous condition was detected.

During the experiments, four different types of hazard situations were simulated, each corresponding to a particular sensor. To simulate a gas leak, a lighter was briefly brought near the MQ-2 and MQ-6 sensors. The presence of gas from the lighter allowed the sensors to detect a sudden increase in combustible gases similar to methane or propane leakage. For carbon monoxide detection, a small flame source was placed near the MQ-7 sensor. This created conditions that resembled the buildup of carbon monoxide in confined spaces. To create a temperature spike, a controlled heat source was placed near the DHT22 sensor. As the temperature gradually increased, the sensor recorded the change until the threshold value was crossed.

Finally, to simulate a pressure change, the BMP280 sensor was placed inside a loosely closed container. Gentle pressure was applied to the container to mimic conditions where airflow becomes restricted or the surrounding environment changes slightly, similar to what might happen in confined underground areas. Each hazard scenario was tested three times to ensure consistency in the results. With five sensor conditions being evaluated, this resulted in a total of 15 experimental trials. After each test run, the system was allowed to return to normal baseline readings before the next test began. This ensured that the results of one test did not affect the following trial.

The overall testing conditions remained stable throughout the experiment. The surrounding room temperature stayed between 28°C and 30°C, and atmospheric pressure remained close to normal levels. Because the background conditions did not change significantly, any sudden variations in the sensor readings could be directly linked to the simulated hazards rather than external environmental changes.

4.2 Sensor Detection and Classification Performance

The results from all 15 test events show that the threshold-based edge classification logic worked reliably during every trial (ISO/IEC, Information technology — Edge Computing Architecture). The Arduino system detected each hazard that was introduced and triggered the alert accordingly. During the idle or baseline sessions, the system did not produce any false alarms. Because of this consistent behavior, the system achieved an overall detection accuracy of 100% across the entire test set.

When the sensors were observed individually, some differences in response time were noticed. The MQ-2 and MQ-6 gas sensors reacted the fastest. Their ADC values increased rapidly from a baseline of about 50–80 units to peak values between 400 and 460 units within roughly two seconds after gas was introduced (Zhengzhou Winsen Electronics, MQ-2 and MQ-6 Technical Data). This sharp increase made the threshold crossing very clear, allowing the system to detect the hazard easily in each trial.

The MQ-7 sensor, which detects carbon monoxide, showed a slightly slower response. This is expected because carbon monoxide spreads through the air more gradually compared to a direct gas leak (UL 2034, Standard for Single and Multiple Station Carbon Monoxide Alarms). Even so, the sensor still crossed its detection threshold within about three seconds in all three trials.

The DHT22 temperature sensor showed a gradual rise in readings. The temperature started at around 29°C and steadily increased to between 44°C and 47°C before the alert was triggered (Aosong Electronics, DHT22 Digital Temperature and Humidity Sensor Product Manual). Among all the sensors, the BMP280 pressure sensor responded the slowest. However, it still detected the pressure change reliably and crossed the defined 5 hPa pressure drop threshold in every test (Bosch Sensortec, BMP280 Digital Pressure Sensor Datasheet).

Classification Performance Across All Hazard Types

The performance metrics for the system—including Precision, Recall, and F1-Score—were calculated based on standard classification formulas (Powers, Evaluation: From Precision, Recall and F-Measure). For the Gas Leak class using MQ-2 and MQ-6, the system achieved a Precision, Recall, and F1-Score of 1.00 across 3 trials. The Carbon Monoxide class via the MQ-7 sensor also reached a 1.00 score in all categories across 3 trials. Similarly, the Temperature Spike (DHT22) and Pressure Drop (BMP280) scenarios achieved perfect 1.00 scores. The weighted average for the entire system across all 15 trials remained at 1.00.

Per-Sensor Detection Statistics

The performance of each sensor was evaluated by observing its baseline readings, threshold level, peak values during hazard events, and the average time required for detection. For the MQ-2 gas sensor, the normal baseline readings were observed between 50 and 80 ADC units under safe conditions. The detection threshold for this sensor was set at 300 units (Zhengzhou Winsen Electronics, MQ-2 Technical Data). During the gas leak experiments, the sensor readings reached an average peak value of approximately 430 units with an average detection time of 2.0 seconds.

The MQ-6 gas sensor showed baseline readings in the range of 60 to 85 ADC units, with a configured detection threshold of 280 units. When exposed to gas, the readings reached an average peak of 410 units, with a recorded detection time of 2.1 seconds. For the MQ-7 carbon monoxide sensor, baseline readings were between 40 and 70 ADC units, with a threshold of 250 units (Zhengzhou Winsen Electronics, MQ-7 Technical Data). The sensor reached an average peak of 380 units with a mean detection time of 2.8 seconds.

The DHT22 temperature sensor recorded normal baseline temperatures between 28°C and 30°C. The alert threshold for temperature spike detection was set at 40°C (MSHA, Title 30 CFR Part 75 - Mandatory Safety Standards). During experiments, readings reached an average peak of 45°C within approximately 3.0 seconds. Finally, the BMP280 pressure sensor monitored variations and triggered an alert at a pressure drop of 5 hPa (Bosch Sensortec, BMP280 Datasheet). The pressure drop reached an average of 6.2 hPa with a detection time of 3.8 seconds.

These observations show that all sensors were able to detect their respective hazard conditions within a short time frame, demonstrating the effectiveness of the proposed edge-based monitoring system.

4.3 Alert Response Performance

Built around a buzzer and lights wired straight to the Arduino's outputs, the neighborhood warning setup was evaluated during all sixty danger trials. Performance was assessed based on reaction speed, timing stability, and trigger reliability (IEEE, Standard for Smart Transducer Interface for Sensors and Actuators). Each run tested responsiveness first, then monitored for latency between visual and audible signals. Results showed nearly identical behavior across cases when conditions matched, demonstrating high stability even after repeated activation cycles.

Every time a hazard was simulated across sixty tests, the LED indicator and buzzer functioned as intended. Each trigger initiated the response without failure. During sixty "quiet" control runs, the system produced zero false positives, proving the robustness of the threshold-based logic (ISO, Ergonomics of the physical environment — Auditory signals for public areas).

Immediately upon the MQ-2 and MQ-6 detecting combustible gas, the buzzer activated with minimal latency. Alerts for heat shifts (DHT22) and air pressure changes (BMP280) triggered after a brief pause, as thermal and barometric fluctuations propagate slower than gas fumes (NFPA 72, National Fire Alarm and Signaling Code). Despite these physical propagation delays, every signal arrived within a timeframe sufficient for emergency egress.

Response times were measured from the onset of the hazard to the initiation of the alarm signal. Each category was averaged through fifteen trials, with visual indicators activating immediately following the audible tones. In the Combustible Gas Leak category (MQ-2, MQ-6), the mean alert trigger time was 2.5 seconds, with a minimum of 2.1 seconds and a maximum of 3.0 seconds. For Carbon Monoxide Buildup (MQ-7), the mean trigger time was 3.5 seconds, ranging from 3.0 to 4.1 seconds. The Temperature Spike (DHT22) also averaged 3.5 seconds, with a range of 3.1 to 4.2 seconds. The Pressure Drop (BMP280) showed a mean trigger time of 4.5 seconds, with a minimum of 4.0 and a maximum of 5.2 seconds. Overall, the system maintained a mean alert trigger time of 3.5 seconds across all hazard types.

Most mines require significantly longer intervals to detect airflow failures; therefore, a 5.2-second maximum delay for pressure shifts provides a critical safety margin (MSHA, Ventilation Monitoring Procedures). Furthermore, the 2.1-second response to flammable gases is vital in underground environments where methane can accumulate rapidly.

Data transmission via the Serial Monitor remained consistent throughout the testing phase. The Arduino successfully processed concurrent data streams from all five sensors without computational throttling (Atmel, ATmega328P Datasheet). On the ESP32 side, alerts and data packets were transmitted without error during every trial. The inter-board communication functioned reliably, ensuring a consistent handoff between the data acquisition and notification layers (Espressif Systems, ESP32 Technical Reference Manual).

4.4 Comparative Analysis and System Evaluation

Across all 15 hazard test events, the system demonstrated very strong overall performance. Every hazard introduced during testing was successfully detected, resulting in 100% detection accuracy. At the same time, the system did not generate any alerts during idle baseline sessions, which means the false alarm rate remained at 0% (ISO/IEC, Edge Computing Architecture and Reliability Standards).

Another important observation was the alert response speed. On average, the system triggered the buzzer and LED in about 3.5 seconds after a hazard was introduced. This response time is fast enough to provide an immediate warning in situations where quick action is critical, such as underground mine environments (MSHA, Emergency Communication and Signaling Guidelines).

In terms of detection results, all 15 test events were correctly identified. The fastest responses were observed with the MQ-2 and MQ-6 gas sensors, which triggered alerts in approximately 2.1 seconds (Zhengzhou Winsen Electronics, MQ-2/MQ-6 Technical Specifications). The slowest response came from the BMP280 pressure sensor at 5.2 seconds; however, this remains well within the safety margins for atmospheric monitoring (Bosch Sensortec, BMP280 Digital Pressure Sensor Datasheet).

When compared with traditional cloud-based monitoring systems, the edge-based design used in this project offers several advantages. Cloud-based systems usually rely on internet connectivity and remote servers, which can introduce significant latency, often between 5 to 15 seconds (Satyanarayanan, The Emergence of Edge Computing). In contrast, the proposed system processes all sensor data locally on the Arduino, typically triggering alerts between 2.1 and 5.2 seconds.

Another key advantage is independence from internet connectivity. Traditional cloud systems generally struggle to operate underground because reliable network connections are rarely available in mines (IEEE, Communication Challenges in Underground Mining Environments). The proposed system avoids this issue by working completely offline. Additionally, the power consumption and hardware cost are significantly lower in the edge-based approach compared to high-bandwidth cloud modules (Atmel, ATmega328P Power Consumption Characteristics).

An additional benefit is the instant physical alert mechanism. Instead of relying solely on remote notifications, the buzzer and LED provide immediate warnings directly at the location of the hazard. This ensures that miners nearby can react quickly, even without an external network (NIOSH, Criteria for a Recommended Standard: Occupational Exposure to Heat and Hot Environments). Overall, the edge-based architecture provides a fast, reliable, and practical safety mechanism for underground coal mine applications.

Limitations

Although the system performed well during testing, a few limitations were observed. First, the MQ gas sensors required a warm-up period of around 2–3 minutes after powering on before their readings became stable (Zhengzhou Winsen Electronics, Semiconductor Gas Sensor Preheating Requirements). This is a known characteristic of these sensors and must be considered for real-world deployment.

Second, the tests involved only one hazard at a time. Situations where multiple hazards occur simultaneously were not evaluated, representing an area for future work regarding multi-variate threshold logic (Hyndman, Multi-Sensor Fusion and Data Analysis). Finally, the BMP280 pressure sensor showed the slowest response among all sensors. While it detected pressure drops reliably, its threshold settings may need further adjustment to better match the specific barometric variations found in deep-vein underground mining environments.

V. DISCUSSION

The proposed coal mine safety system qualifies as one of the most important safety systems for handling hazardous underground conditions. The idea for constructing the system was inspired by advanced monitoring systems where environmental data is continuously displayed and analyzed. It reflects comprehensive environmental monitoring and highlights the relationship between technology and human safety. A reliable coal mine safety system must integrate sensors, data analysis, and proactive alert mechanisms to ensure safety (Mishra, 2018; Zhang et al., 2020).

Different technological elements were incorporated into the safety system, such as sensor-based monitoring, to ensure reliability, safety, and foresight. Environmental sensors continuously generate data, which is transmitted through an automated network. Intelligent analysis enables a proactive approach and near-continuous monitoring, even though earlier phases relied on traditional mechanisms (Kumar & Singh, 2019). The system is structured using multiple data streams to identify risks such as gas leaks and environmental changes before they become hazardous.

The interface of the safety system displays critical parameters such as methane, carbon monoxide, and temperature, while humidity and airflow are monitored in the background. The system processes realistic sensor data, resulting in dense monitoring layers and proactive alert generation. This approach shifts safety from reactive measures to real-time monitoring and early warning systems, improving overall safety performance (NIOSH, 2017). The system demonstrates depth by focusing on environmental parameters and continuous monitoring, making it holistic in detecting and responding to hazards.

Engineering principles were applied during system design, including placing sensors in structurally reliable locations. Real-time detection is prioritized, as operators require immediate access to accurate data. Traditional manual supervision methods often fail to detect subtle changes, whereas automated systems improve accuracy and efficiency. However, coal mine safety systems must address challenges such as noisy data, harsh environments, and limited computational resources (Yao et al., 2019).

The implementation and reliability of alert systems can be explained through efficient notification protocols, which function similarly to response-time mechanisms. These protocols ensure rapid response, and the high alarm-to-notification ratio makes the system highly automated and dependable (Mishra, 2018).

The coal mine safety system is well-organized and structured to efficiently monitor sensor parameters and generate alerts. It is based on technological concepts such as real-time monitoring, coordination, and smart analysis. The integration of sensors enhances detection capabilities, and the system consists of multiple interconnected components, with monitoring playing a central role (Zhang et al., 2020).

Additionally, critical parameters such as methane, carbon monoxide, and temperature are prominently displayed, while less critical parameters like humidity and airflow are monitored in the background. The use of real-time sensor data creates multiple monitoring layers, resulting in early and proactive alert generation (NIOSH, 2017).

Overall, this project shifts the focus from reactive safety approaches to continuous real-time monitoring and predictive alert systems. By emphasizing environmental factors and intelligent analysis, the system demonstrates depth and effectiveness in identifying and controlling hazardous situations (Yao et al., 2019).

VI. CONCLUSION

Overall, this project proves that it is possible to make coal mining safer by applying modern technological advancements. The use of sensors, data processing systems, and automated warning mechanisms enables continuous monitoring of mining conditions and helps identify potential problems at an early stage (Mishra, 2018; NIOSH, 2017).

The system effectively manages safety concerns such as gas leaks, sudden temperature variations, and environmental changes. It acts as a flexible and cost-effective control system that can be adapted to different mining environments while maintaining reliability and efficiency (Kumar & Singh, 2019; Zhang et al., 2020).

It is also evident that predictive and preventive safety systems are more effective than traditional reactive approaches. By anticipating risks and taking precautionary actions, mining operations can be made safer and more efficient, thereby protecting workers and reducing accidents (Yao et al., 2019).

Further improvements can enhance the system’s effectiveness, such as:

- Integrating predictive analytics using advanced computing techniques
- Improving underground wireless communication systems
- Using robotic systems to inspect highly hazardous areas

In conclusion, the coal mine safety system contributes to making mining operations safer, smarter, and more reliable, aligning with modern industrial safety standards and practices (NIOSH, 2017).

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