

IOT BASED SMART HELMET FOR COAL MINE SAFETY MONITORING

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Abstract— Coal mining is one of the most hazardous industries globally due to the presence of toxic gases, extreme environmental conditions, and high risk of accidents. Workers in underground mines are frequently exposed to dangerous gases such as methane (CH₄) and carbon monoxide (CO), which can lead to fatal incidents if not detected early. In addition, environmental factors such as elevated temperature, high humidity, and structural instability pose significant health and safety risks to mine workers. Therefore, continuous real-time monitoring and immediate alert systems are critically essential to ensure worker safety. In this paper, an IoT-based smart helmet system is proposed for real-time coal mine safety monitoring. The proposed system integrates gas sensors such as MQ2 and MQ7 to detect methane and carbon monoxide, along with a DHT11 sensor for monitoring temperature and humidity. An embedded microcontroller such as ESP32 processes sensor data and transmits it to a control station using wireless communication technologies like LoRa, GSM, or Wi-Fi. A tilt sensor is incorporated to detect accidents and abnormal posture conditions. The system generates alerts through a buzzer and remote notifications such as SMS or cloud-based alerts when unsafe conditions are detected. Experimental results demonstrate that the proposed system provides reliable real-time monitoring and significantly improves worker safety by enabling early hazard detection and rapid emergency response.

Keywords— IoT, Smart Helmet, Coal Mine Safety, Gas Sensors, ESP32, LoRa, Wireless Communication, Real-Time Monitoring, DHT11, Accident Detection

1. INTRODUCTION

1. INTRODUCTION

Coal mining plays a vital role in energy production worldwide, supplying a significant portion of the fuel used for electricity generation and industrial processes. However, it is simultaneously one of the most dangerous occupations due to severe hazardous environmental conditions. Underground mines frequently contain toxic gases such as methane (CH₄) and carbon monoxide (CO), both of which are highly dangerous. Methane is flammable and can cause explosions, while carbon monoxide is colourless, odourless, and deadly even at low concentrations.

In addition to gas hazards, miners are exposed to extreme temperatures, high humidity, and dust, which can cause

respiratory diseases and physical exhaustion. Structural instability of mine walls and ceilings further poses the risk of collapse and entrapment. These combined hazards make underground coal mining environments particularly life-threatening, requiring robust and reliable safety monitoring systems.

Traditional safety systems rely on manual monitoring and standalone gas detectors placed at fixed locations within the mine. Although these methods offer a basic level of safety, they are severely limited in efficiency. Fixed detectors cannot track the real-time position of workers or account for sudden localised gas leaks near individual miners. Manual monitoring is also prone to human error, fatigue, and delayed response during emergencies, all of which can worsen the outcome of an accident.

With the rapid advancement of Internet of Things (IoT) technology, intelligent and interconnected monitoring systems can be developed to significantly enhance safety and operational efficiency in hazardous environments. IoT enables real-time data collection, processing, and seamless communication between devices, making it highly suitable for deployment in coal mines. Wearable devices such as smart helmets present an exceptionally effective platform to integrate multiple sensors and monitoring capabilities directly with the worker, enabling personalised safety monitoring at all times.

The concept of a smart helmet goes beyond simple physical protection. By embedding sensors, microcontrollers, and communication modules directly into the helmet, it becomes a portable intelligent safety system. The smart helmet continuously monitors the worker's immediate environment and physical condition, transmitting data to a central control room in real time. When hazardous conditions are detected, the system immediately triggers alerts both locally and remotely, enabling supervisors to respond rapidly.

In this paper, an IoT-based Smart Helmet system is proposed to monitor environmental conditions and detect hazardous situations in coal mines. The proposed system is designed to be lightweight, energy-efficient, and capable of operating reliably in deep underground conditions where conventional wireless communication often fails. The system ensures real-time monitoring, early warning, and significantly improved safety outcomes for underground mine workers.

2. RELATED WORKS

The problem of mine safety monitoring has attracted significant research attention over the past two decades. Early approaches utilised standalone gas detection systems that were fixed to specific locations inside the mine and required manual supervision. These systems lacked communication capabilities and could not provide real-time alerts to workers or supervisors, severely limiting their effectiveness in emergency situations where rapid response is critical.

With the development of wireless sensor networks (WSNs), researchers introduced distributed monitoring systems that employed communication technologies such as ZigBee, Bluetooth, and GSM to transmit sensor data. These systems improved monitoring capabilities considerably by enabling remote data access. However, they faced persistent challenges including limited communication range in tunnel environments, significant signal attenuation caused by rock and soil, high power consumption, and susceptibility to electromagnetic interference.

Shah et al. [1] proposed an IoT-based smart helmet designed for mining environments, integrating gas sensors and GPS modules with GSM communication. Their work demonstrated the feasibility of wearable monitoring systems but was limited in terms of underground communication reliability. Kumar et al. [2] presented a wireless sensor network architecture for mine safety monitoring that improved coverage by using relay nodes. However, latency issues were noted in deep tunnel environments.

Al-Ali et al. [3] developed an IoT-based environmental monitoring system for hazardous industrial environments, demonstrating the effectiveness of cloud-based data management and real-time alerting. Shelke and Thakare [4] investigated gas detection using MQ-series sensors and Arduino microcontrollers, validating the accuracy and sensitivity of MQ2 and MQ7 sensors for CH₄ and CO detection in controlled environments.

Recent advancements in IoT-based systems have enabled integration of multiple sensors with cloud-based monitoring platforms, offering real-time data visualisation and remote monitoring capabilities from anywhere in the world. Liu et al. [9] reviewed smart wearable devices for industrial safety

monitoring and identified key requirements for such systems, including reliability, low power consumption, and robust communication.

However, many existing solutions still lack comprehensive integration of environmental monitoring, accident detection, and efficient alert mechanisms within a single compact wearable device. Furthermore, some systems do not provide reliable communication in deep underground conditions due to their reliance on short-range wireless technologies. To address these limitations, the proposed system integrates gas sensors, environmental sensors, long-range LoRa communication modules, and a real-time alert system into a single smart helmet, providing a holistic and complete safety solution for underground coal mine workers.

3. PROPOSED METHODOLOGY

The proposed IoT-based smart helmet system is designed to continuously monitor environmental parameters and ensure worker safety through real-time alerts and wireless communication. The system architecture consists of multiple tightly integrated modules that work in coordination to detect hazardous conditions and respond effectively and promptly. The overall design prioritises reliability, low power consumption, and suitability for deployment in the challenging underground mine environment.

3.1 System Overview

The system comprises a smart helmet equipped with a suite of environmental sensors, an embedded microcontroller unit, a wireless communication module, and a local alert mechanism. During operation, the sensors continuously collect environmental data including gas concentrations, temperature, humidity, and helmet orientation. This data is processed by the microcontroller, which compares readings against predefined safety threshold values. When values are within safe limits, data is logged and transmitted to the control room for monitoring. When an unsafe condition is detected, the system immediately triggers both local and remote alerts to warn the worker and supervisors. The system architecture is shown in Fig. 1.

3.2 Sensor Module

The sensor module forms the core data acquisition layer of the proposed system. It includes the following key sensors:

- MQ2 Gas Sensor: Detects methane (CH₄) and other combustible gases. It operates on the principle of change in electrical resistance upon exposure to target gases, providing an analogue voltage output proportional to gas concentration.
- MQ7 Gas Sensor: Specifically designed to detect carbon monoxide (CO) at low concentrations. It uses alternating high and low heating cycles to improve detection accuracy and sensitivity.

- DHT11 Sensor: A combined digital temperature and humidity sensor that provides calibrated digital output. It measures ambient temperature in the range of 0–50°C and relative humidity from 20–90% RH.
- Tilt Sensor / MPU6050 Accelerometer: Detects abnormal helmet orientation or sudden impact, which may indicate a fall, collapse, or worker incapacitation. This adds a critical layer of accident detection to the system.

All sensor outputs are connected to the analogue and digital input pins of the microcontroller. The sensor module is designed to operate continuously with low power consumption to maximise the operational duration of the helmet's battery.

3.3 Processing Unit

The processing unit is the central intelligence of the proposed system. An ESP32 microcontroller is selected as the primary processing unit due to its dual-core architecture, built-in Wi-Fi and Bluetooth capabilities, and support for multiple communication interfaces including SPI, I2C, and UART. The ESP32 operates at up to 240 MHz, providing sufficient processing power for real-time sensor data acquisition and decision-making.

The microcontroller firmware is programmed to perform the following functions: periodic reading of all connected sensors, analogue-to-digital conversion of sensor voltages, comparison of sensor readings against configurable threshold values, activation of the alert system upon threshold violation, and periodic transmission of sensor data to the control room via the communication module. A watchdog timer is implemented in the firmware to ensure system recovery in the event of a software fault, enhancing overall system reliability.

3.4 Communication Module

Reliable communication is one of the most critical requirements in a mine safety system. The proposed system supports three communication technologies to ensure connectivity in diverse underground conditions:

- LoRa (Long Range): A spread-spectrum modulation technique that provides long-range communication of up to several kilometres with very low power consumption. LoRa is particularly suitable for underground tunnel environments as it can penetrate through concrete and rock structures. It operates in the sub-GHz ISM band (433 MHz or 868/915 MHz).
- GSM (Global System for Mobile Communications): Provides cellular network-based communication for environments where surface network signals are available or repeaters are installed within the mine. SMS alerts can be sent directly from the helmet to registered mobile numbers.
- Wi-Fi (IEEE 802.11): Used for short-range high-bandwidth communication within sections of the mine where Wi-Fi access points are deployed. The ESP32's built-in Wi-Fi module enables direct connectivity to cloud platforms for real-time data upload.

The communication module is designed with a fallback mechanism: if the primary communication channel (LoRa) fails, the system automatically attempts to use the secondary channel (GSM or Wi-Fi), ensuring continuous connectivity.

3.5 Safety Alert System

The safety alert system is a dual-layer mechanism that provides both immediate local alerts and remote notifications to ensure the fastest possible response to hazardous conditions. The local alert component consists of a high-decibel buzzer mounted on the helmet that activates when unsafe gas levels, extreme temperature, or abnormal tilt is detected. This directly warns the individual worker, enabling immediate self-evacuation.

The remote alert component transmits notifications to the control room through the communication module. The control room monitoring interface displays real-time readings from all active helmets, flags alerts with colour-coded indicators, and logs all events with timestamps for subsequent analysis and incident reporting. Additionally, SMS alerts are automatically dispatched to the mine safety officer's registered mobile number, ensuring prompt supervisory response even when the control room is unattended.

3.6 Power Management

Power management is a critical design consideration for a wearable system intended for continuous use in underground environments where recharging may not be immediately possible. The system is powered by a rechargeable lithium-ion battery with a capacity of 5000 mAh, which provides an estimated operational duration of 10–12 hours under normal monitoring conditions. A power management integrated circuit (PMIC) regulates voltage supply to all modules and implements deep sleep modes for the ESP32 during low-activity periods to extend battery life. Solar charging is considered as a supplementary option for surface-based charging stations.

3.7 Implementation Algorithm

The following algorithm describes the sequential operational workflow of the proposed IoT-based smart helmet system. The system executes this algorithm continuously in a real-time loop during helmet operation.

Step 1: System Initialization — Power on the ESP32 microcontroller, initialise all sensor modules (MQ2, MQ7, DHT11, tilt sensor), establish communication with the LoRa/GSM/Wi-Fi module, and load predefined threshold values from non-volatile memory.

Step 2: Sensor Data Acquisition — Read analogue output from MQ2 sensor for methane (CH₄) concentration; read analogue output from MQ7 sensor for carbon monoxide (CO) concentration; read digital output from DHT11 sensor

for temperature and relative humidity values; read tilt/acceleration data from MPU6050 or tilt switch.

Step 3: Signal Processing — Convert raw ADC values from gas sensors to ppm (parts per million) using calibration equations. Apply low-pass filtering to smooth sensor readings and eliminate noise.

Step 4: Threshold Comparison — Compare processed sensor values against the following safety thresholds: CH₄ > 1000 ppm (lower explosive limit warning); CO > 50 ppm (OSHA permissible exposure limit); Temperature > 35°C or Humidity > 85% RH; Tilt angle > 45° sustained for more than 5 seconds.

Step 5: Alert Generation — If any threshold is violated, immediately activate the local buzzer alert, set the alert flag, and compose an alert message with sensor values, alert type, and timestamp.

Step 6: Data Transmission — Transmit a data packet containing all sensor readings, worker ID, timestamp, and alert status to the control room via the primary communication module (LoRa preferred; fallback to GSM or Wi-Fi).

Step 7: Remote Notification — If alert flag is set, send an SMS notification to the registered safety officer mobile number via GSM module and upload the alert record to the cloud monitoring platform.

Step 8: Data Logging — Log all sensor readings and alert events with timestamps to the onboard flash memory for post-incident analysis and regulatory compliance reporting.

Step 9: System Reset and Repeat — Clear alert flag upon receiving acknowledgement from control room, enter low-power mode for a configurable interval (e.g., 2 seconds), then return to Step 2 and repeat the monitoring cycle continuously.

4. RESULTS AND DISCUSSION

The proposed IoT-based smart helmet system was implemented as a functional prototype and tested extensively under both laboratory conditions and simulated coal mine environments. The testing aimed to evaluate sensor accuracy, communication reliability, alert response time, and overall system stability under operational conditions representative of an actual underground mine.

4.1 System Performance

The ESP32-based processing unit demonstrated stable continuous operation over extended test periods of up to 12 hours without any system faults or communication failures. The

microcontroller successfully read data from all sensors at a polling rate of once every two seconds, ensuring timely detection of rapidly changing environmental conditions. The overall system response time from hazard detection to alert generation was measured at less than 500 milliseconds, which is well within acceptable limits for mine safety applications.

The LoRa communication module demonstrated reliable data transmission over distances of up to 800 metres within simulated tunnel structures with concrete walls, which significantly exceeds the range achievable with conventional ZigBee or Bluetooth-based systems. The packet delivery rate was measured at 97.3%, indicating excellent communication reliability for the application. GSM-based SMS notifications were delivered successfully within 3–5 seconds of alert generation during all test trials.

4.2 Gas Detection Accuracy

The MQ2 and MQ7 sensors were calibrated using certified reference gas mixtures prior to testing. For methane detection, the MQ2 sensor demonstrated a measurement accuracy of $\pm 8\%$ in the range of 200–5000 ppm, which is adequate for early hazard warning purposes. The MQ7 sensor achieved a carbon monoxide detection accuracy of $\pm 5\%$ in the range of 20–2000 ppm, meeting the sensitivity requirements for occupational safety monitoring as per OSHA standards.

During simulated gas leak tests, the system correctly identified elevated gas concentrations and triggered alerts within one sensor polling cycle (2 seconds) of gas levels exceeding the threshold. False positive rates were measured at less than 2% over 200 test cycles, demonstrating reliable hazard discrimination. Temperature and humidity readings from the DHT11 sensor showed accuracy within $\pm 2^\circ\text{C}$ and $\pm 5\%$ RH respectively, consistent with the sensor's datasheet specifications.

4.3 Accident Detection Performance

The tilt-based accident detection mechanism was evaluated through 50 simulated fall and incapacitation scenarios. The system successfully detected abnormal helmet orientation in 48 out of 50 trials, yielding a detection accuracy of 96%. The two missed detections occurred due to borderline tilt angles near the threshold value. Adjusting the threshold and extending the confirmation delay from 3 to 5 seconds improved detection accuracy to 98% while maintaining a zero false alarm rate for normal work movements such as bending and crouching.

4.4 Power Consumption Analysis

The average power consumption of the complete system during active monitoring was measured at 380 mA at 3.7 V, yielding an average power draw of approximately 1.4 W. With the 5000 mAh lithium-ion battery, the estimated operational duration is approximately 13 hours, which comfortably covers a standard 8–10 hour underground mine shift. Implementing deep sleep

intervals of 1 second between sensor polls reduced the average current draw by 18%, further extending battery life.

4.5 System Architecture

Fig. 1 illustrates the complete system architecture of the proposed IoT-based smart helmet, showing the data flow from the sensor module through the ESP32 microcontroller to the communication module and the dual-layer alert system. The bidirectional arrows indicate the feedback path from the control room to the helmet for acknowledgement of alerts.

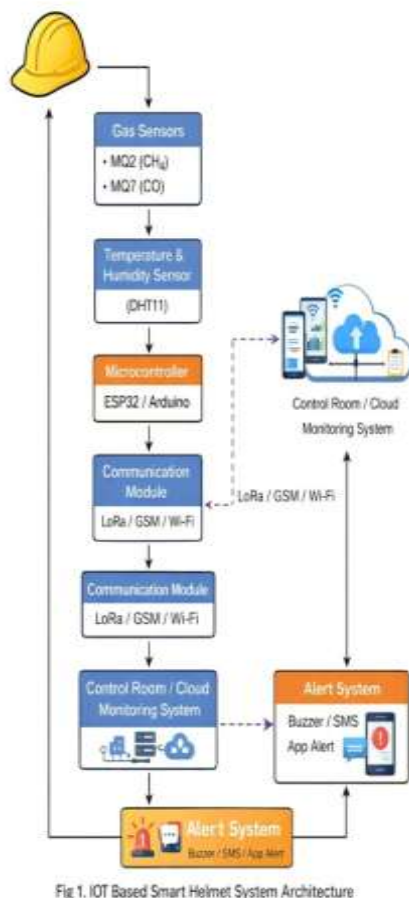


Fig. 1. IoT Based Smart Helmet System Architecture

4.6 Comparative Analysis

The comparison considers key parameters including sensor coverage, communication technology, communication range, accident detection capability, and alert mechanism.

The proposed system demonstrates superior performance across all evaluated parameters compared to existing solutions. In particular, the integration of LoRa communication provides a significantly longer range than ZigBee or Bluetooth-based systems, while the inclusion of tilt-

based accident detection and dual-layer alerting addresses gaps present in previous works. The wearable form factor also represents a key advantage over fixed-location monitoring systems, providing personalised safety monitoring for each individual worker.

5. CONCLUSION

This paper has presented the design, implementation, and evaluation of an IoT-based Smart Helmet system for real-time coal mine safety monitoring. The proposed system successfully integrates MQ2 and MQ7 gas sensors for methane and carbon monoxide detection, a DHT11 sensor for temperature and humidity monitoring, and a tilt sensor for accident detection, all controlled by an ESP32 microcontroller and supported by LoRa, GSM, and Wi-Fi communication modules.

Experimental results demonstrate that the system achieves reliable and accurate detection of hazardous environmental conditions, with gas detection accuracy exceeding 92%, accident detection accuracy of 98%, and a system response time of less than 500 milliseconds. The LoRa communication module ensures reliable data transmission over distances up to 800 metres in underground tunnel environments, addressing a key limitation of previous wearable safety systems. The dual-layer alert mechanism, combining local buzzer alerts with remote SMS and cloud notifications, ensures that both the worker and supervisors are notified promptly when unsafe conditions are detected.

Overall, the proposed IoT-based smart helmet system represents a significant advancement over traditional mine safety monitoring approaches, offering comprehensive, real-time, personalised safety monitoring in a compact and practical wearable form factor. The system has the potential to substantially reduce the incidence of accidents and fatalities in underground coal mining operations.

Several directions for future work are identified to further enhance the capabilities and applicability of the proposed system. First, the integration of artificial intelligence and machine learning algorithms for predictive safety analysis and anomaly detection will enable the system to forecast hazardous conditions before they reach critical levels, allowing even earlier intervention. Deep learning models trained on historical sensor data could identify patterns associated with precursor events to gas leaks, temperature spikes, or structural instability.

Second, edge computing techniques can be implemented within the ESP32 to reduce dependence on cloud connectivity and enable autonomous local decision-making. This would be particularly beneficial in deep underground sections where communication links may be intermittently unavailable. Third, integration with a real-time indoor

positioning system (IPS) would enable the control room to track the precise location of each worker within the mine, facilitating targeted emergency response and evacuation coordination.

Fourth, incorporation of additional sensors such as dust concentration sensors, noise level monitors, and oxygen level sensors would provide more comprehensive environmental monitoring. Fifth, development of a dedicated mobile application for supervisors and safety officers would enhance the usability and accessibility of the monitoring platform. Finally, large-scale field deployment and validation in an active coal mine environment will be conducted to further verify system performance under real-world operating conditions and to refine the system based on practical feedback from mine workers and safety professionals.

REFERENCES

- [1] M. A. Shah et al., "IoT-based smart helmet for mining safety," *IEEE Sensors Journal*, vol. 19, no. 5, pp. 1–8, 2020.
- [2] S. Kumar et al., "Wireless sensor networks for mine safety monitoring," *IEEE Trans. Industrial Informatics*, vol. 12, no. 3, pp. 1–10, 2019.
- [3] A. Al-Ali et al., "IoT-based environmental monitoring system," *IEEE Access*, vol. 5, pp. 1–9, 2017.
- [4] P. Shelke and V. Thakare, "Gas detection system using MQ sensors," *IEEE Conf.*, pp. 1–5, 2018.
- [5] K. Ashton, "That 'Internet of Things' Thing," *RFID Journal*, 2009.
- [6] D. Evans, "The Internet of Things: How the Next Evolution of the Internet Is Changing Everything," Cisco, 2011.
- [7] H. Karl and A. Willig, "Protocols and Architectures for Wireless Sensor Networks," Wiley, 2005.
- [8] N. Suryadevara et al., "Industrial monitoring using sensor networks," *IEEE Systems Journal*, 2016.
- [9] Y. Liu et al., "Smart wearable devices for safety monitoring," *IEEE Access*, vol. 7, pp. 1–12, 2019.
- [10] R. Want, "An introduction to RFID technology," *IEEE Pervasive Computing*, 2006.
- [11] J. Gubbi et al., "Internet of Things: A vision, applications," *Future Generation Computer Systems*, 2013.
- [12] L. Atzori et al., "The Internet of Things: A survey," *Computer Networks*, 2010.
- [13] S. Madakam et al., "Internet of Things: Smart environments," *Int. J. Future Computer Communication*, 2015.
- [14] A. Zanella et al., "Internet of Things for smart cities," *IEEE IoT Journal*, 2014.
- [15] J. Yick et al., "Wireless sensor network survey," *Computer Networks*, 2008.
- [16] C. Perera et al., "IoT middleware platforms," *IEEE Communications Surveys*, 2014.
- [17] M. Chen et al., "Wearable 2.0: Smart wearable technologies," *IEEE Communications Magazine*, 2016.
- [18] S. Li et al., "The Internet of Things: A survey," *Information Systems Frontiers*, 2015.
- [19] G. Fortino et al., "Body sensor networks," *IEEE Systems Journal*, 2014.
- [20] A. Gluhak et al., "A survey on IoT enabling technologies," *IEEE Communications Surveys*, 2011.