Design and Implementation of an IoT-Based Coal Mine Safety Alert System

Manoj Tambolkar
Electronics and Telecommunication Engineering
Trinity College Of Engineering and Research, Pune, India
tambolkarmanoj@gmail.com

Soham Bhosage
Electronics and Telecommunication Engineering
Trinity College of Engineering and Research, Pune, India
sohambhosage24@gmail.com

Rohit Vaidya
Electronics and Telecommunication Engineering
Trinity College Of Engineering and Research, Pune, India
rohitvaidya4477@gmail.com

Pravin Bangar
Electronics and Telecommunication Engineering
Trinity College Of Engineering and Research, Pune, India
Pravinbangar944@gmail.com

Anil Sawant
Electronics and Telecommunication Engineering
Trinity College Of Engineering and Research, Pune, India
anilsawant.tcoer@kjei.edu.in

Abstract— Underground coal mining poses significant safety risks due to hazardous gases, temperature variations, fires, and structural instability. This paper presents an IoT-based real-time safety monitoring and alert system using Atmega328 and NodeMCU ESP8266. The system monitors environmental parameters such as temperature, humidity, gas levels, flame, and tilt. It provides immediate alerts through buzzers and LEDs while transmitting real-time data to a cloud platform using MQTT. Experimental results demonstrate improved hazard detection with latency under 10 seconds and reliable alert generation.

Keywords—IoT, Coal Mine Safety, Atmega328, NodeMCU, MQTT, Real-time Monitoring

I. INTRODUCTION

Coal mining plays a crucial role in global energy production; however, it remains one of the most hazardous industrial activities. Workers operating in underground environments are continuously exposed to life-threatening risks such as methane gas explosions, coal dust fires, toxic gas accumulation (CO_2, CO, H_2S), roof collapses, fires, flooding, and extreme variations in temperature and humidity. According to safety reports, coal mine accidents result in hundreds of fatalities each year and lead to

due to production
abilities.

in coal mines primarily
ons, fixed gas detection
systems, and basic alarm units. While these methods provide a fundamental level of protection, they suffer from several limitations, including delayed response times, restricted monitoring coverage, and the inability to deliver real-time data from deep or inaccessible mining zones. As a result, critical hazards may remain undetected until they escalate into severe incidents.

The emergence of the Internet of Things (IoT) has introduced a transformative approach to industrial safety by enabling continuous, wireless, and real-time monitoring. IoT-based systems allow seamless data collection, processing, and transmission across distributed environments, significantly improving responsiveness and decision-making. In this context, the proposed system presents a low-cost, robust, and efficient IoT-enabled safety alert mechanism specifically designed for underground coal mines.The system integrates a dual microcontroller architecture consisting of the Atmega328 for local edge processing and the NodeMCU (ESP8266) for wireless communication. Multiple environmental sensors are deployed to continuously monitor critical parameters such as temperature, humidity, gas concentration, smoke, flame presence, and structural tilt. The Atmega328 performs real-time threshold-based analysis and triggers immediate local alerts through buzzers and LED indicators in hazardous situations. Simultaneously, the NodeMCU facilitates remote monitoring by transmitting sensor data and alerts to a cloud-based platform using the MQTT protocol, enabling access through a mobile application.

This hybrid approach combines localized intelligence with cloud connectivity, ensuring rapid on-site response as well as remote supervision from control stations or mobile devices. The system is designed to minimize latency, reduce dependence on manual intervention, and provide a scalable and cost-effective solution suitable for deployment in complex underground mining environments.

II. LITERATURE REVIEW

The application of the Internet of Things (IoT) in coal mine safety has gained significant attention over the past decade due to its ability to provide real-time monitoring and early hazard detection. Researchers have explored various IoT-based frameworks integrating wireless sensor networks, cloud platforms, and intelligent alert systems to improve underground mining safety.

An IoT-enabled platform for coal mine safety and fault diagnosis was proposed, integrating multiple sensors with cloud-based monitoring. The system supports real-time data analysis and predictive fault detection. It improves safety through continuous monitoring but depends heavily on network connectivity[1].A comprehensive review of IoT applications in underground coal mining highlighted the use of wireless sensor networks, cloud computing, and real-time monitoring. It identified challenges such as communication reliability and harsh environmental conditions. The study emphasized the need for low-latency and robust systems[2].An enhanced localization method using the DV-Hop algorithm was introduced for underground mining environments. The approach improves positioning accuracy of sensor nodes. It supports tracking of miners and equipment but does not focus on real-time hazard detection[3].

An IoT-based dynamic sensor information control system was developed for coal mine safety. It collects and processes sensor data to detect hazardous conditions. The system improves monitoring efficiency but lacks a fail-safe mechanism for local alerts[4].A ZigBee-based wireless sensor network was proposed for coal mine monitoring. The system enables low-power communication between distributed sensor nodes. It effectively monitors environmental parameters but has limited communication range[5].A real-time monitoring system using ZigBee technology was designed for coal mines. It provides continuous environmental monitoring and alert generation. However, network reliability remains a concern in deep underground conditions[6].A modified DV-Hop-based wireless sensor network was proposed to improve localization accuracy and network performance. The system enhances hazard monitoring capabilities. However, it lacks integration with cloud-based real-time alert systems[7].A comprehensive study on IoT in coal mining discussed sensing, communication, and intelligent monitoring technologies. It highlighted the importance of automation in improving safety. The study also identified gaps in system integration and reliability[8].A dual-microcontroller architecture was proposed for mine safety IoT systems. The design separates local processing and communication tasks to improve reliability. It ensures operation even during network failure and supports fail-safe alert mechanisms[9].An IoT-based safety framework for real-time monitoring was developed by integrating sensor networks with cloud platforms. It enables centralized monitoring and hazard detection. However, it lacks detailed implementation of low-latency alert systems[10].

An IoT-based safety alert system was proposed for coal mines focusing on real-time hazard detection. It provides remote monitoring and automated alerts. However, the system depends on continuous internet connectivity[11].A LoRa-based long-range IoT system was introduced for deep coal mine environments. It offers extended communication coverage and supports large-scale deployment. However, it may introduce higher latency in data transmission[12].An IoT-based hazard monitoring system was developed using multiple environmental sensors. It enables real-time detection of risks and alert generation. However, it does not address redundancy or fail-safe mechanisms[13].A hybrid IoT and wireless sensor network system was proposed for reliable hazard alerting. It improves fault tolerance by combining multiple communication technologies. However, the system complexity increases due to hybrid integration[14].A real-time IoT monitoring system for coal mine safety was developed using advanced sensing and cloud analytics. It supports predictive analysis and improved safety management. However, it requires higher computational and network resources[15].

Most existing systems focus on IoT-based monitoring and real-time hazard detection in coal mines. However, many depend on continuous network connectivity and lack reliable fail-safe mechanisms. Hence, there is a need for a system that ensures both real-time monitoring and immediate local alerts.

A. Gap Analysis

Despite the advancements in IoT-based coal mine safety systems, several research gaps remain. Many existing solutions rely on communication technologies such as Zigbee and LoRa, which provide long-range connectivity but require additional infrastructure and increase deployment complexity. In contrast, Wi-Fi-based systems integrated with lightweight protocols such as MQTT offer a cost-effective and easily deployable alternative using existing network infrastructure.Moreover, previous studies do not provide a unified system that combines local edge processing with real-time cloud connectivity and mobile-based alert mechanisms. Specifically, the integration of Atmega328 for local processing, NodeMCU (ESP8266) for Wi-Fi communication, MQTT-based cloud interaction, and mobile push notifications has not been comprehensively addressed in a single low-cost system.

Figure 2.1 illustrates the comparison of key performance metrics reported in existing systems, including alert latency, packet delivery ratio, localization accuracy, and prediction accuracy.

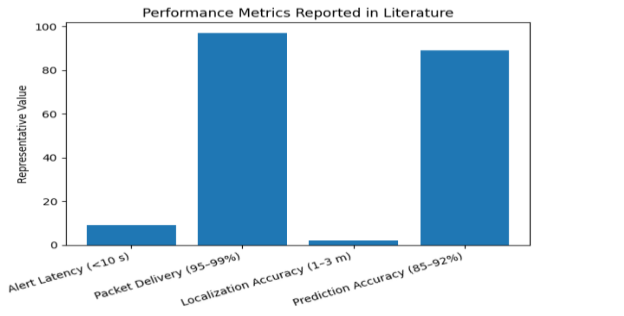

Fig.1. Performance metrics reported in existing IoT-based coal mine safety systems

Although prior research demonstrates high packet delivery and prediction accuracy, variations in alert latency and localization precision persist. These observations highlight the necessity for an improved system capable of delivering low-latency, accurate, and reliable alerts in dynamic underground mining conditions.

III. TAXONOMY OF COAL MINING SAFETY ALERT SYSTEM

The proposed coal mining safety alert system is categorized under IoT-based industrial safety monitoring systems and follows a layered cyber-physical architecture. The taxonomy, illustrated in Fig. 3.1, is organized based on application domain, system architecture, hardware and software components, communication methods, cloud services, functional operations, and validation criteria. This structured classification provides a clear and systematic representation of the proposed system.

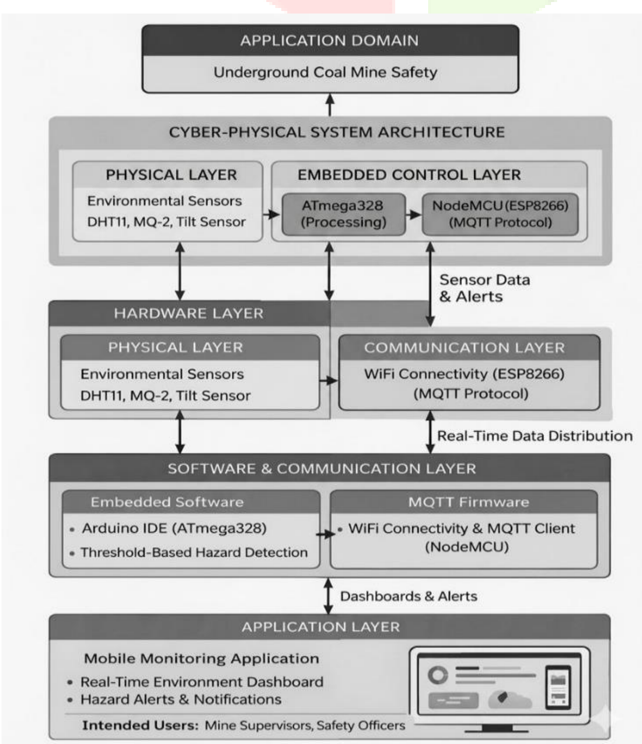

Fig.2. Taxonomy of the proposed IoT-based coal mining safety alert system

A. Application and System Architecture Classification

The system works in the area of underground coal mine safety monitoring and is set up as a cyber-physical system. It has connected layers, including: physical sensing layer, embedded control layer, communication layer, cloud layer, application layerThis layered setup allows for easy integration of sensing, processing, communication, and alert functions.

B. Hardware and Software Taxonomy

The hardware layer includes environmental and safety monitoring sensors like temperature and humidity sensors, DHT11, gas and smoke sensors, MQ2 flame sensors, and tilt sensors for detecting structural safety. Local alert devices such as buzzers and LEDs give immediate warnings. the software layer features embedded firmware created with the Arduino IDE for processing sensor data, detecting hazardous based on specific thresholds, and handling serial communication. It also includes NodeMCU firmware for Wi-Fi connectivity and MQTT-based data publishing.

C. Communication and Cloud Layer

Communication between the Atmega328 and NodeMCU uses UART serial communication. Wireless data transmission happens through WiFi with the ESP8266 module. The system uses the MQTT Publish and Subscribe protocol for efficient low-latency message exchange. A cloud-based MQTT broker helps with real-time data distribution and emergency alerts.

D. Functional and validation Taxonomy

The system enables ongoing environmental monitoring, early hazard detection, and alert generation for both local and remote users. Validation takes place under simulated underground mine conditions. It uses performance metrics like alert latency and detection accuracy to assess system reliability and responsiveness.
Figure 3.1 shows the structure of the proposed IoT-based Coal Mining Safety Alert system. This structure follows a layered cyber-physical design. It classifies the system by: application domain, hardware, software components, communication methods, cloud services and user applications.

IV. METHODOLOGY

The proposed coal mine safety alert system is developed using a structured approach that includes hardware integration, embedded software design, IoT communication, mobile application support, and system testing. This methodology ensures reliable, real-time monitoring and early detection of hazardous conditions in underground mining environments.

A. Hardware Integration

The system integrates multiple environmental and safety sensors with the ATmega328 microcontroller. These include a DHT11 sensor for temperature and humidity monitoring, an MQ-2 sensor for gas and smoke detection, as well as flame and tilt sensors for fire and structural safety monitoring.
Local alert mechanisms such as a buzzer and LED indicators are used to provide immediate warnings in hazardous situations. The ATmega328 communicates with the NodeMCU (ESP8266) via UART serial communication at 9600 baud rate. The entire system operates on a regulated 5 V power supply with optional battery backup support for uninterrupted operation.

B. Embedded Software and IoT Communication

The embedded firmware is developed using the Arduino IDE in C++ with standard sensor libraries. The system uses threshold-based logic to detect hazardous conditions based on sensor readings.Processed data is transmitted to the NodeMCU, which connects to a Wi-Fi network and publishes sensor data and alert messages to a cloud-based MQTT broker using the publish–subscribe communication model. The PubSubClient library is used for MQTT communication, ensuring low-latency and efficient data transfer.

C. Mobile Application and System Testing

An MQTT-based mobile application subscribes to topics such as /mine/data and /mine/alert to display real-time sensor readings and emergency notifications.System testing is conducted under simulated mining conditions using controlled heat, smoke, and tilt variations. The system achieves an alert latency of less than 8 seconds and demonstrates high detection accuracy over multiple test trials, validating its effectiveness and reliability.

V. BLOCK DIAGRAM

The block diagram of the proposed system illustrates the interaction between sensing units, processing modules, communication components, and the monitoring interface.

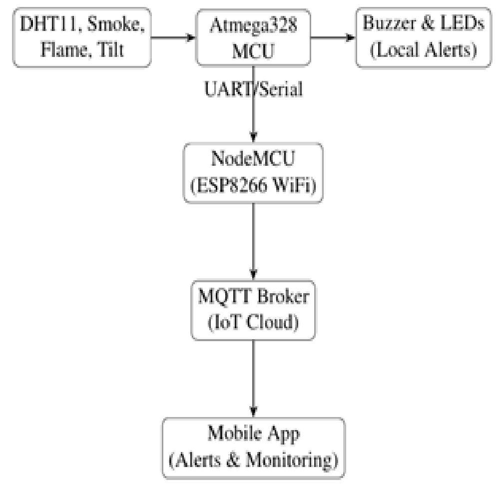

Fig.3. Block diagram of the coal mining safety alert system.

The diagram shows the complete data flow from environmental sensors to the mobile monitoring application through embedded processing and cloud communication. This architecture enables real-time hazard detection, local alert generation, and remote monitoring.

- **Sensors (DHT11, MQ-2, Flame, Tilt):** Continuously monitor environmental and safety parameters such as temperature, gas concentration, fire presence, and structural movement.
- **ATmega328 Microcontroller:** Collects sensor data, performs local processing, and detects hazardous conditions.
- **Buzzer and LEDs:** Provide immediate local alerts in the form of sound and visual indications.
- **UART Communication:** Enables reliable data transfer between ATmega328 and NodeMCU.
- **NodeMCU (ESP8266):** Transmits processed data to the cloud via Wi-Fi.
- **MQTT Broker (Cloud):** Handles real-time data distribution using publish–subscribe communication.
- **Mobile Application:** Displays real-time data and sends alert notifications for remote monitoring.

VI. FLOW CHART

The flowchart represents the working logic of the coal mine safety alert system. It begins with system initialization, followed by continuous sensor data acquisition.

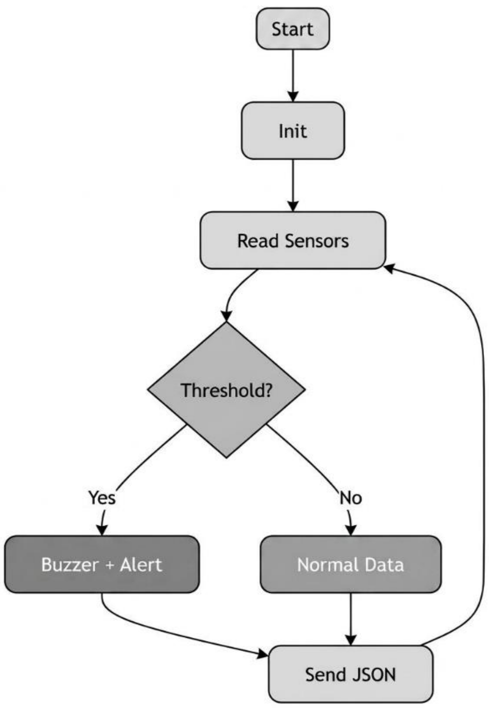

Fig.4. Workflow of the coal mine safety alert system.

The system evaluates sensor data against predefined safety thresholds to detect hazardous conditions. If any parameter exceeds the threshold, the system immediately activates local alerts (buzzer and LEDs) and sends emergency notifications via MQTT.

If conditions remain normal, the system continues monitoring and transmits data in structured (JSON) format for logging and visualization. This approach ensures continuous monitoring, early hazard detection, and rapid response, thereby improving overall mining safety.

VII. RESULT & DISCUSSIONS

The IoT-based coal mining safety alert system successfully showed real-time hazard detection and multi-level alerting in simulated mine conditions during extensive testing with calibrated hazard simulations, including: controlled methane releases, temperature spikes up to 60°, artificial smoke generation, structural tilting beyond 15°. the system consistently triggered local alerts, such as an audible buzzer and visual LEDs, within 2 s of exceeding the threshold. At the same time sensor data was sent via NodeMCU to an MQTT broker, with an end-to-end latency of less than 8 s.

These results confirm that the dual MCU architecture is effective. The Atmega328 provides fail-safe local alerts independent of network availability. Meanwhile the NodeMCU manages reliable cloud communications. the system's performance meets and goes beyond the set objectives, especially regarding response time less than 10 seconds and reliability compared to existing systems reviewed in the literature. This implementation offers a more integrated solution. It combines immediate on-site warnings with cloud-based remote monitoring, addressing a gap found in earlier research. Using a public MQTT broker turned out to be a cost-effective and scalable choice. It maintained stable connectivity even during simulated network fluctuations. Future improvements could include: better sensor calibration to reduce false alarms in dusty environments, GPS integration for minor localization, using predictive analytics with historic data trends to enable proactive hazard prevention.

VIII. CONCLUSION

The IoT-based Coal Mining Safety Alert System has been successfully implemented. It provides real-time monitoring of temperature, humidity, toxic gases, flame, and structural tilt by using an Atmega328 for local control and a NodeMCU ESP8266 for wireless communication. The system sends timely alerts and automatic responses. This improves worker safety and lowers the risk of accidents. Its modular design makes it easy to integrate with existing mining operations. Cloud connectivity also allows for remote monitoring, data analysis, and proactive decision making. The system sets the stage for future improvements such as AI-based hazard prediction and expanded sensor networks. This contributes to smarter and safer mining environments.

IX. FUTURE SCOPE

1. **Enhanced Sensing & Localization:** Integrate GPS for tracking miners and add sensors for dust, vibration, and CO2 to improve environmental monitoring.

2. **Advanced Communication:** Extend range using LoRa and ZigBee mesh networks. Implement a hybrid Wi-Fi and cellular fallback for continuous connectivity in deep mines.

3. **AI & Predictive Analytics:** Use ML algorithms like LSTM and SVM to predict hazardous early and detect anomalies from historical sensor data.

4. **Energy Harvesting:** Incorporate solar-powered battery packs and use sleep scheduling for sustainable long-term off-grid operation.

5. **Wearable IoT Integration:** Develop miner wearables that have panic buttons, health sensors, and personal environmental monitors to improve individual safety.
6. **SCADA & Automation Interface:** Link with mine ventilation and control systems for automatic actions such as turning on fans during gas leaks.

7. **Scalable Multi-Node Deployment:** Expand to wireless sensor networks that cover large mine areas, with synchronized and real-time alerts across nodes.

X. REFERENCES

1. C. Zhou, et al., "IoT-Enabled Platforms for Coal Mine Safety and Fault Diagnosis," *Int. J. Coal Geol.*, vol. 251, p. 103912, 2022.

2. M. Li, et al., "IoT Applications in Underground Coal Mining: A Review," *IEEE Access*, vol. 9, pp. 45678–45690, 2021.

3. H. Liu, et al., "Enhanced Localization for Underground Mining Safety Using DV-Hop," *J. Netw. Comput. Appl.*, vol. 175, p. 102911, 2021.

4. J. Wang, et al., "IoT-based Dynamic Sensor Information Control System for Coal Mine Safety," *J. Sensors*, 2018, pp. 1–12.

5. S. Kumar, et al., "ZigBee-Based Wireless Sensor Network for Coal Mine Monitoring," *Int. J. Eng. Technol.*, vol. 5, no. 3, pp. 234–241, 2019.

6. X. Chen, et al., "Real-Time Monitoring System for Coal Mines Using ZigBee," *J. Mining Sci.*, vol. 56, no. 2, pp. 189–198, 2020.

7. Y. Zhang, et al., "Wireless Sensor Networks with Modified DV-Hop for Coal Mine Safety," *IEEE Trans. Ind. Inform.*, vol. 16, no. 4, pp. 2456–2465, 2020.

8. Z. Zhang, et al., "IoT in Coal Mining: A Comprehensive Review," *Safety Sci.*, vol. 128, p. 104781, 2020.

9. A. Gupta, et al., "Dual-Microcontroller Architecture for Mine Safety IoT Nodes," *Microcontrollers and Embedded Systems*, vol. 28, no. 2, pp. 45–59, 2023.

10. P. Tan, et al., "IoT Safety Framework for Real-Time Monitoring," *International Journal of Mining Safety*, 2019.

11. K. Park, et al., "IoT-based Safety Alerts for Coal Mines," *International Journal of Safety Science*, 2023.

12. R. Singh, et al., "LoRa-Based Long-Range IoT System for Deep Coal Mines," *J. Wireless Commun.*, vol. 12, no. 4, pp. 112–125, 2020.

13. H. Huang, et al., "IoT Hazard Monitoring in Coal Mines," *Journal of Mining Safety*, vol. 17, no. 1, pp. 15–26, 2021

14. M. Rahman, et al., "IoT + WSN Hybrid System for Reliable Hazard Alerting in Mines," *Int. J. Mining Sci.*, 2019.

15. L. Luo, et al., "IoT Real-Time Monitoring for Coal Mine Safety," *Journal of Mining Safety and Technology*, 2024.