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MineGuard-Net: A Context-Driven Embedded Intelligence Framework for Real-Time Subsurface Hazard Cognition

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Abstract

Coal mining is one of the most hazardous industrial activities, where workers are constantly exposed to risks such as toxic gas leaks and unexpected seismic vibrations. Historically, mine safety relied on manual inspection methods and basic mechanical detectors, which were often slow, inaccurate, and unable to provide real-time alerts. With increasing mining depth and complexity, these traditional systems have become insufficient to ensure worker safety. The major problem lies in the lack of continuous monitoring and immediate warning mechanisms, which can lead to severe accidents, environmental damage, and loss of human lives. Conventional safety systems typically operate in isolation, lack remote monitoring capabilities, and require significant human intervention. Their limitations include delayed response, limited coverage, and inability to store or analyse data for preventive measures. Hence, there is a growing need for an intelligent, automated, and reliable monitoring system that can detect hazards in real time and communicate effectively. This research proposes a Zigbee-based IoT embedded system for earthquake and hazardous gas detection in coal mines. The system integrates sensors for gas and vibration detection with a microcontroller, enabling continuous monitoring of environmental conditions. Zigbee technology is used for efficient wireless communication between transmitter and receiver units, while IoT connectivity allows data to be uploaded to a remote server for real-time access and analysis. Additionally, alerts are provided through buzzers and display units to ensure immediate response. The proposed system enhances safety by providing early warning, reducing human dependency, and enabling remote monitoring. It offers a cost-effective, reliable, and scalable solution, significantly improving coal mine safety and helping prevent potential disasters.

Keywords: Coal Mine Safety, ZigBee Communication, Earthquake Detection, Vibration Sensor, Hazardous Environment, Real-Time Monitoring, Emergency Alert System.

1. Introduction

Coal continues to play a vital role in meeting global energy demands, serving as a primary source for electricity generation and industrial applications in many regions of the world. However, despite advancements in mining technologies, underground coal mining remains one of the most hazardous professions. Reports indicate that although the mining sector employs a relatively small portion of the global workforce, it accounts for a disproportionately high number of occupational fatalities. Countries with extensive coal mining activities, including India, China, the United States, and Australia, continue to experience significant incidents each year, many of which are linked to gas leaks, explosions, and ground instability.

The underground mining environment presents several inherent challenges that make safety management difficult. Limited ventilation, restricted working spaces, high temperature, and moisture

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create conditions where harmful gases can accumulate rapidly. Methane gas, commonly found in coal seams, is highly combustible and can lead to explosions when mixed with air in certain proportions. In addition, gases such as carbon monoxide and hydrogen sulfide pose serious health risks due to their toxic nature, even at low concentrations. Apart from gaseous hazards, structural instability caused by geological stress, blasting operations, or natural seismic disturbances can lead to sudden collapses or tremors, endangering both workers and infrastructure. Existing safety measures in mines typically involve manual inspections, wired monitoring systems, and centralized control units. While these methods offer basic protection, they are often limited by delayed detection, high maintenance requirements, and lack of flexibility in dynamic mining conditions. Damage to wired networks and gaps between inspection intervals can prevent timely identification of hazardous situations. Moreover, traditional alert systems may not provide efficient or immediate communication during emergencies, increasing the risk of delayed response and severe consequences.

2. Literature Survey

Zhang et al. [1] presented a wireless monitoring framework based on ZigBee technology specifically designed for underground coal mine safety. Their system focused on detecting methane gas leakage and temperature fluctuations using distributed sensor nodes. A star topology was adopted, where a central coordinator collected data from multiple sensing units deployed across the mine. The design emphasized low power consumption, making it suitable for long-term underground operation. Their implementation demonstrated reliable communication even in challenging conditions with obstacles and signal attenuation. The system maintained a high packet delivery rate within a moderate communication range, ensuring consistent data transfer. The authors highlighted that ZigBee is well-suited for underground environments due to its robustness and energy efficiency. Their approach showed how wireless sensor networks can replace traditional wired systems. It also improved monitoring coverage without complex infrastructure. This work laid a strong foundation for ZigBee-based mine safety systems. Li and Wang [2] designed an IoT-enabled gas monitoring solution using ESP8266 and MQ-series sensors to detect methane levels in underground mines. Their system continuously collected gas concentration data and transmitted it to a cloud platform for remote access. The integration of internet connectivity allowed real-time alerts to be generated whenever gas levels exceeded safe limits. Their design focused on simplicity and ease of deployment using widely available components. Although Wi-Fi provided direct cloud communication, it consumed more power compared to low-power protocols. The authors discussed the trade-off between connectivity and energy efficiency in underground applications. Their system demonstrated the practicality of combining sensing and cloud technologies. It enabled supervisors to monitor conditions without being physically present. The work emphasized the growing importance of IoT in industrial safety. It also showed how remote monitoring can enhance response time during emergencies. Kumar et al. [3] introduced an earthquake detection mechanism using MEMS sensors integrated with a microcontroller-based system. Their design incorporated accelerometers and piezoelectric elements to capture vibration signals in real time. A dynamic threshold algorithm was implemented to differentiate between actual seismic activity and background noise. This approach significantly improved detection accuracy in environments with constant mechanical disturbances. The system was capable of identifying early signs of structural instability. Their model provided fast response times, which are critical in underground safety applications. The authors focused on reducing false alarms through intelligent signal processing. Their implementation proved effective in identifying both minor and significant vibrations. It also demonstrated reliability under varying environmental conditions. This work contributed to improving seismic monitoring in mining operations.

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Chen and Liu [4] developed a ZigBee-based mesh network aimed at improving communication coverage in underground mines. Unlike star topology, their system used multi-hop communication to extend network reach across large areas. Each node acted as both a sensor and a relay, ensuring data could travel even if direct communication was not possible. This design improved network reliability and fault tolerance. In case of node failure, alternative paths were automatically established. Their approach addressed the limitations of single-hop communication systems. The system performed well in complex underground layouts with obstacles. It also supported scalability for expanding mining operations. Their work demonstrated the advantages of self-healing networks. It provided a flexible solution for large-scale deployment in hazardous environments. Rao et al. [5] implemented an ESP32-based monitoring system to track environmental conditions such as temperature and humidity in mines. Their design used DHT sensors to continuously measure atmospheric parameters. A threshold-based alert mechanism was incorporated to detect unsafe conditions. The system was capable of triggering warnings when values exceeded predefined limits. Their approach helped in maintaining a safe working environment for miners. The use of ESP32 enabled both sensing and wireless communication in a single platform. The authors focused on reducing false alarms by combining multiple parameters. Their system performed reliably even in extreme environmental conditions. It demonstrated improved accuracy in detecting abnormal changes. This work highlighted the importance of environmental monitoring alongside gas detection. Singh and Sharma et al. [6] conducted a comparative evaluation of ZigBee and LoRa communication technologies in underground tunnel environments. Their analysis focused on parameters such as range, latency, and energy consumption. ZigBee was found to provide faster data transmission with lower delay for short distances. On the other hand, LoRa offered extended range but with higher latency. The authors emphasized that application requirements play a key role in selecting the communication protocol. For real-time safety systems, low latency is more critical than long-distance coverage. Their findings supported the use of ZigBee for localized monitoring systems. The study also highlighted energy efficiency as a major advantage of ZigBee. Their comparison provided useful insights for system designers. It helped in choosing appropriate communication technology for mine safety applications. Park et al. [7] proposed a multi-sensor integration approach combining gas detection and vibration sensing. Their system used advanced filtering techniques to process data from multiple sensors simultaneously. By applying Kalman filtering, they were able to reduce noise and improve measurement accuracy. This method helped in minimizing false alarms caused by environmental disturbances. The integration of multiple sensor inputs provided a more reliable assessment of hazardous conditions. Their system considered the relationship between gas levels and vibration events. This allowed better interpretation of complex situations in mines. The authors demonstrated improved detection performance compared to single-sensor systems. Their approach enhanced decision-making in safety monitoring. It showed the benefits of sensor fusion in critical applications. Gupta and Mishra et al. [8] developed an IoT gateway system using ESP32 to collect and transmit data from multiple sensor nodes. Their design utilized MQTT protocol for efficient communication with cloud platforms. The system enabled real-time data aggregation and remote monitoring through web interfaces. It was designed to handle large volumes of sensor data with minimal delay. The authors focused on creating a scalable architecture for industrial applications. Their system supported multiple devices connected to a central gateway. It provided reliable communication even under varying network conditions. The use of lightweight protocols improved data transmission efficiency. Their implementation demonstrated practical deployment of IoT in mining environments. It emphasized the importance of centralized data management. Xu et al. [9] introduced a predictive model for methane detection using machine learning techniques. Their approach utilized historical

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sensor data to train an LSTM-based model. This enabled the system to forecast potential hazardous conditions before they occur. The model analyzed patterns in gas concentration over time. It provided early warnings based on predicted trends rather than real-time values alone. The authors achieved high prediction accuracy through continuous learning. Their system reduced the risk of sudden gas-related incidents. It also improved preventive safety measures in mines. The integration of data analytics enhanced decision-making capabilities. Their work highlighted the role of artificial intelligence in modern safety systems.

Fernandez and Ortega [10] examined the performance of different wireless communication technologies in underground environments. Their analysis included ZigBee, Wi-Fi, and Bluetooth under non-line-of-sight conditions. ZigBee demonstrated better reliability in maintaining stable connections. The authors noted that underground tunnels cause significant signal attenuation. ZigBee's low-frequency operation helped in overcoming these challenges. Their findings showed fewer communication failures compared to other technologies. The system maintained consistent data transfer even in obstructed paths. Their work validated ZigBee as a suitable choice for mining applications. It also emphasized the importance of selecting appropriate communication methods. This study supported the adoption of ZigBee in safety systems. Zhao et al. [11] designed a wearable safety device for miners equipped with ZigBee communication and sensing capabilities. The device included gas sensors and motion detection features. It continuously monitored the health and safety status of individual workers. In case of abnormal conditions, alerts were transmitted instantly. Their system ensured real-time personal safety monitoring. Field tests demonstrated reliable performance in detecting emergency situations. The wearable design improved mobility and convenience for miners. It allowed continuous monitoring without restricting movement. Their approach enhanced individual safety in hazardous environments. It also complemented centralized monitoring systems. Mohan and Verma [12] proposed an automated ventilation control system based on IoT technology. Their system adjusted airflow in response to detected gas levels. Sensors continuously monitored methane concentration in the mine. When unsafe levels were detected, ventilation systems were activated automatically. This reduced the dependence on manual intervention. Their system improved response time significantly during hazardous conditions. It helped in maintaining safe air quality for workers. The authors demonstrated effective reduction in gas accumulation. Their approach enhanced overall mine safety management. It showed the benefits of automation in industrial environments. Kim et al. [13] evaluated different vibration sensors for detecting seismic activity in mining conditions. Their comparison included commonly used modules with varying sensitivity levels. The study focused on identifying reliable detection methods. Combining threshold-based detection with frequency analysis improved accuracy. This helped in distinguishing real seismic events from noise. Their findings provided guidance for selecting appropriate sensors. The system performed well in dynamic environments with constant vibrations. It reduced the chances of false triggering. Their work contributed to improving earthquake detection reliability. It supported the design of better monitoring systems.

3. Proposed System

The system represents a dual-node architecture consisting of a transmitter and receiver unit interconnected through Zigbee communication, designed for continuous environmental monitoring in underground conditions. The transmitter node collects real-time data from sensors such as temperature, humidity, gas, and vibration, processes it using an ESP32 microcontroller, and encodes it into a structured data frame. This encoded information is transmitted wirelessly to the receiver node

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via Zigbee. The receiver node decodes the incoming data, displays it on an LCD, triggers alerts when abnormal conditions are detected, and further uploads the data to an IoT server through WiFi. The workflow ensures both local and remote monitoring, enabling immediate response and long-term data analysis. The integration of sensing, processing, communication, and cloud storage forms a complete safety monitoring framework.

Sensor Module (Data Acquisition Unit)

- The system utilizes multiple sensors to capture environmental parameters from underground conditions.
- A gas sensor is used to detect the presence of hazardous gases such as methane and other combustible gases.
- A vibration sensor is employed to identify seismic activity or structural instability within the mining area.
- A temperature and humidity sensor is used to monitor atmospheric conditions affecting worker safety.
- These sensors continuously collect real-time data and send it to the embedded controller for processing.

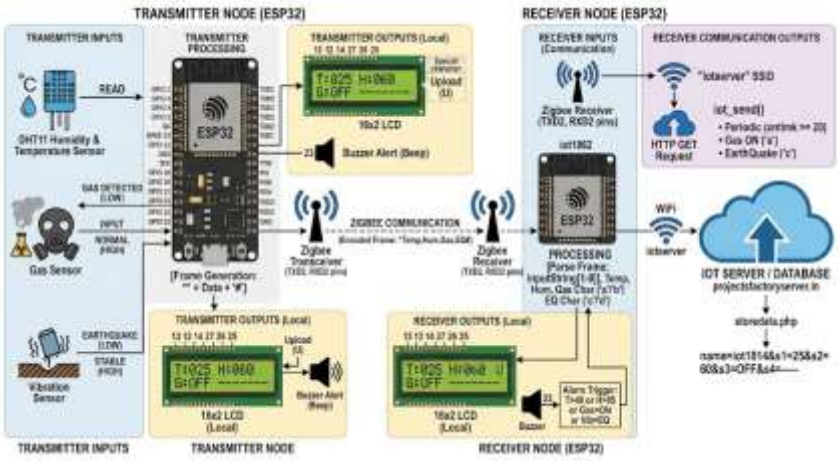


Figure. 1: System architecture.

Embedded Processing Unit (Microcontroller System)

- The core processing unit is based on a microcontroller platform responsible for handling sensor data.
- It reads analog and digital inputs from all connected sensors.
- The collected data is processed and converted into a structured format suitable for transmission.
- The system encodes the sensor values into a serial data packet for efficient communication.
- It also controls display units and local alert mechanisms such as buzzers.

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Zigbee Communication Module

- Zigbee technology is used for wireless communication between sensing and monitoring units.
- The transmitter module sends encoded sensor data to the receiver through serial communication.
- The receiver module captures incoming data and reconstructs the original information.
- Zigbee ensures low power consumption and reliable communication in underground environments.
- The communication protocol uses start and end indicators to maintain data integrity.

Receiver and Monitoring Unit

- The receiver unit processes incoming data from the Zigbee module.
- It extracts temperature, humidity, gas status, and vibration information from the received packet.
- The decoded data is displayed on an LCD for real-time monitoring.
- The system continuously updates the display to reflect current environmental conditions.
- It acts as the central monitoring station for underground safety.

Alert and Safety Mechanism

- The system includes a buzzer-based alert mechanism to warn about hazardous conditions.
- If gas leakage is detected, the buzzer is activated immediately.
- In the case of seismic activity, the system triggers alerts to indicate possible danger.
- Temperature and humidity thresholds are also monitored to ensure safe working conditions.
- This mechanism ensures quick response and enhances worker safety.

IoT Cloud Integration Module

- The system integrates IoT functionality for remote monitoring and data logging.
- The receiver unit connects to a WiFi network and sends data to a remote server.
- Sensor readings are transmitted using HTTP protocols.
- The cloud platform stores the data for future analysis and monitoring.
- Remote users can access real-time data from anywhere.

Data Transmission and Encoding Mechanism

- Sensor data is encoded into a structured serial format before transmission.

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- A start character indicates the beginning of the data packet.
- Temperature and humidity values are converted into digit form and transmitted sequentially.
- Gas and vibration statuses are represented using specific character codes.
- An end character marks the completion of the data packet.

Display and Output Interface

- The system uses an LCD module to display real-time sensor values.
- Temperature and humidity readings are shown on the first line.
- Gas status and vibration alerts are displayed on the second line.
- The interface provides clear and continuous updates for monitoring.
- It enhances usability by presenting data in an easily readable format.

Remote Monitoring Workflow

- The system supports remote monitoring through IoT integration.
- Data from the receiver unit is uploaded to a server at regular intervals.
- Users can access this data remotely for analysis and decision-making.
- The workflow ensures continuous monitoring without physical presence.
- It improves response time during emergency situations.

System Evaluation and Reliability

- The system ensures reliable detection of hazardous conditions through continuous monitoring.
- Wireless communication reduces dependency on wired infrastructure.
- Real-time alerts improve safety response efficiency.
- The design supports scalability for larger deployment areas.
- The integration of multiple technologies enhances overall system performance.

Sensor Data Acquisition: In the first stage, multiple sensors continuously monitor environmental parameters such as temperature, humidity, gas levels, and vibration. The DHT11 sensor captures temperature and humidity values, while the gas sensor (MQ series) detects hazardous gases and the vibration sensor identifies seismic activity. These sensors provide real-time analog or digital signals to the microcontroller. The data collected reflects the current underground conditions, ensuring no critical change goes unnoticed.

Data Processing and Frame Generation: The ESP32 in the transmitter node processes the incoming sensor data and converts it into a usable format. Each parameter is encoded into a structured data

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frame consisting of temperature, humidity, gas status, and vibration status. Special characters are used to indicate the start and end of the data packet, ensuring proper synchronization between transmitter and receiver. This step prepares the data for reliable wireless transmission and includes a local display on an LCD.

Zigbee Wireless Communication: The encoded data frame is transmitted from the transmitter to the receiver using Zigbee modules. Zigbee ensures low power consumption and stable communication in complex underground environments. The transmitter sends the data serially, and the receiver captures it through its communication interface. This wireless link eliminates the need for complex wired connections and enables flexible deployment in dynamic mining conditions.

Data Reception and Decoding: At the receiver node, the ESP32 reads the incoming serial data and reconstructs the original sensor values. The system identifies the start and end of the data frame to extract specific environmental information. Each parameter is decoded and converted back into numerical values for display on the LCD. This acts as the central monitoring stage, ensuring accurate interpretation of the transmitted information.

Alert Generation and Local Response: The system continuously checks the received data against predefined threshold values. If gas leakage or seismic activity is detected, or if temperature and humidity exceed safe limits, a buzzer is activated immediately. Visual alerts are also displayed on the LCD to indicate the type of hazard, enabling quick decision-making and preventing potential accidents.

IoT Data Upload and Remote Monitoring: The receiver node connects to a Wi-Fi network and sends the processed data to an IoT server using HTTP requests. This uploaded data includes all environmental parameters along with their status conditions, allowing remote users to monitor mine conditions in real time from any location. The server stores the data for future analysis and persistent record-keeping.

Continuous Monitoring and System Feedback: The entire process runs in a continuous loop, providing real-time monitoring of underground conditions. Data is repeatedly collected, processed, transmitted, and analysed without interruption. This proactive workflow enhances reliability and safety, allowing the system to adapt quickly to the changing environmental conditions of the mine.

4. Result and Discussion

Figure 2 illustrates the experimental hardware setup developed for real-time monitoring and hazard detection in underground environments using embedded and wireless communication technologies. The arrangement depicts both transmitter and receiver units integrated with ESP32 microcontrollers, sensor modules, display interfaces, and communication components. The sensing section captures environmental parameters such as temperature, humidity, gas presence, and vibration levels, which are processed and transmitted through a Zigbee-based communication link. The received data is further analysed and displayed locally while simultaneously enabling alert generation through a buzzer mechanism under abnormal conditions. The configuration also demonstrates the integration of IoT capabilities for remote data transmission and monitoring.

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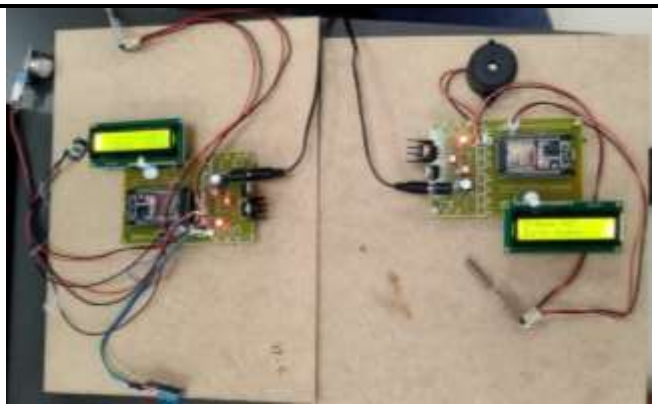


Figure. 2: Hardware implementation of Zigbee-Based IoT mine safety monitoring system

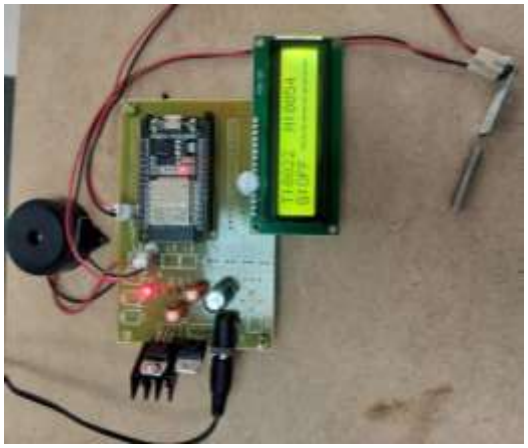


Figure. 3: Receiver Node Hardware Implementation with Real-Time monitoring and alert system

Figure 3 depicts the receiver unit of the developed safety monitoring framework, showcasing the integration of embedded processing, data reception, and alert generation mechanisms. The figure highlights the microcontroller-based system responsible for decoding incoming wireless data and converting it into meaningful environmental parameters. It illustrates the real-time visualization of sensed data through a display interface, enabling continuous monitoring of temperature, humidity, and hazard conditions. The setup also demonstrates the inclusion of an alert system that activates during abnormal situations, ensuring immediate response. Furthermore, the configuration represents the interaction between communication modules and processing units, forming a centralized monitoring station.

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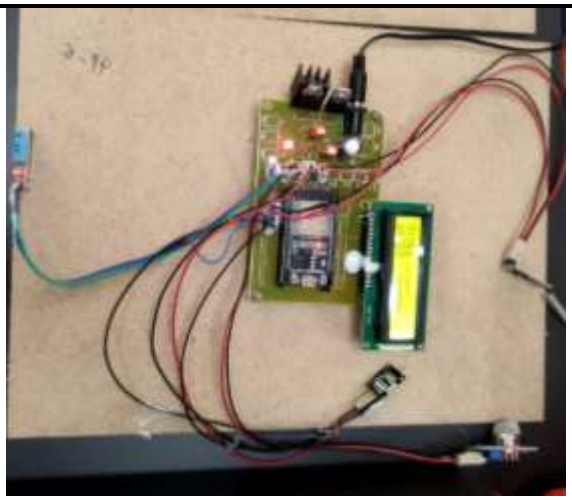


Figure. 4: Transmitter node hardware setup with sensor integration and data processing

Figure 4 illustrates the transmitter unit of the developed monitoring framework, highlighting the integration of sensing elements with the embedded processing system. The figure depicts the acquisition of environmental parameters through connected sensors, which are interfaced with a microcontroller for continuous data collection and processing. It represents the conversion of raw sensor inputs into structured data suitable for wireless transmission. The setup demonstrates real-time parameter visualization through a display module, supporting local monitoring capabilities. Additionally, the arrangement reflects the role of the transmitter in initiating communication by encoding and sending environmental data to the remote unit.

5. Conclusion

The research successfully demonstrates an efficient and reliable safety monitoring system for underground mining environments using embedded, Zigbee, and IoT technologies. The developed system is capable of continuously monitoring critical parameters such as temperature, humidity, gas concentration, and seismic activity in real time. The integration of wireless communication ensures stable and low-power data transmission between sensing and monitoring units. The system effectively identifies hazardous conditions such as gas leakage and abnormal vibrations, triggering immediate alerts through buzzer and display mechanisms. IoT integration further enhances the system by enabling remote monitoring and data logging, improving accessibility and response time. Compared to traditional systems, the proposed approach reduces dependency on manual inspection and wired infrastructure, thereby improving flexibility and scalability. The performance evaluation indicates reliable communication, quick response to threshold violations, and consistent operation under simulated conditions. The structured data transmission and decoding mechanism ensures accuracy in monitoring and minimizes data loss. The system contributes significantly to improving safety standards and reducing risks in the underground environment.

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