Modern Coal Mine Safety System

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***Abstract* - Coal mining is critical to the energy supply of the planet, yet one of the most dangerous industrial endeavors because of its naturally hostile environment. Miners encounter harmful and combustible gases like methane (CH_4) and carbon monoxide (CO) on a regular basis, high humidity, higher temperatures, inadequate air circulating patterns, and the perpetual risk of cave-ins or machinery-related accidents. Conventional safety protocols largely consist of manual checking and incident-related reporting that has a tendency to cause delayed response and higher risks to human life.To meet these challenges, in this paper we suggest a real-time IoT-based safety system designed specifically for underground coal mines. This is developed around low-power ESP32-based microcontrollers and a set of sensors: multi-gas detectors (CH_4, CO, CO_2), humidity and temperature sensors, sound sensors to detect unusual patterns of noise, and vibration sensors to pre-estimate collapses. Testing results from a prototype deployment show that the system is capable of providing reliable measurements, timely warnings, and increased situational awareness that together help prevent accidents and save miners' lives.**

Index: **Coal Mines, Safety System, Early Alert System.**

I. INTRODUCTION

Coal remains a critical energy source around the globe, powering industry and playing a major role in electricity generation in most nations. Even with improved technology in mining equipment and methods, coal mining is one of the riskiest jobs because of the unpredictable and dangerous nature of underground conditions. Elements of the build-up of harmful gases (such as methane and carbon monoxide), high humidity levels, high temperatures, poor air circulation, and the possibility of rockfalls and building collapses inherent to underground excavation hazards mean that underground coal mines pose inherent dangers to miners' health and safety and can also result in tragic accidents and deaths from explosions and collapses.
Conventional coal mine safety is based on manual inspection and periodic gas sampling and relies mainly on simple alarm systems. These methods of the past are reactive in nature and of limited coverage with response being limited by the speed of humans. Communication in underground mines is also a problem with the unavailability of good wireless networks in the underground environment and hence cannot be easily achieved with real-time data and centralized monitoring and transmission.

The advent of the Internet of Things (IoT) in recent years has opened doors to its innovative applications in automation, real-time performance, and smart safety systems. IoT devices with sensors can continuously monitor the surroundings and accumulate environment data, facilitating predictive insights and quick decision-making. These systems with wireless communication technology and cloud-based monitoring platforms provide advanced hazard detection capabilities, improved operational efficiency, and fast emergency response.

The paper introduces a full-featured IoT-based coal mine safety system that relies on ESP32 controller processors to locally process data and a variety of environmental sensors such as multi-gas detectors, humidity sensors, vibration sensors, and acoustic sensors to detect hazards in real-time. LoRa (Long Range) wireless communication is used to transmit data that is selected because it works best in low-power, long-range, and low-bandwidth applications typical of underground conditions. All information is transmitted to a cloud server and control center where it can be viewed by supervisors via a user-friendly dashboard interface.

The core aims of the research include:
•Develop and establish a cost-effective and modularity oriented safety monitoring system in underground coal mines.
•Providing reliable and energy-efficient data communication in underground environments with LoRa communication
•To allow the automated generation of alerts and emergency responses, including activating alarms and emergency lighting, in response to dangerous conditions.

•Assessing the performance of the system in real-time monitoring, data accuracy and responsiveness under simulated mine conditions

II. RELATED WORK

Application of advanced technologies to mining safety systems has been a major research focus in the past few years with the rising number of accidents and exposure of miners to hazardous conditions. There has been a large number of studies on the use of wireless sensor networks (WSNs), Internet of Things (IoT) platforms, and embedded systems in the monitoring of underground mine environment and structure conditions.

Previously, coal mine safety systems were based heavily on manual inspection and isolated gas detectors. These systems were unable to monitor in real time and lacked centralized analysis of data. While to some extent effective, their limitation lay in delayed hazard detection, limited remote access, and inefficient coverage of large underground spaces. Various researchers have put forward WSN-based underground monitoring frameworks. For example, [Wang et al., 2015] designed a sensor network to monitor the methane level and forward the information through Zigbee protocol. Even though Zigbee is energy-efficient, its limited range is disadvantageous in large and obstruction-heavy mining environments. Other solutions used Wi-Fi-based systems that experience a significant deterioration in performance in underground environments because of signal attenuation and the need for infrastructure installations.

The emergence of IoT has made it possible to achieve smarter and scalable solutions. [Zhou et al., 2018] employed an IoT model that incorporates gas and temperature sensors and is connected via WiFi and GSM modules. Though their model provided real-time detection, the use of GSM and Wi-Fi provided such connectivity-related problems in the case of underground mines where the signal coverage is limited. In recent times, LoRa (Long Range) technology has attracted interest because of its improved range and energy efficiency and is best suited to underground environments. [Singh et al., 2020] introduced a LoRa-based underground mine safety monitoring system. Their model provided efficient communication and longer battery life but emphasized gas detection with little incorporation of structure-related health indicators like vibration or acoustic detection. Integrating various sensors to detect a wide range of environment-related hazards has been proposed in some studies. [Ali et al., 2021] used the combination of gas, temperature, and humidity sensors with simple alarm systems. Still, most current models do not include the detection of sound and vibration that is important in anticipation of structure failures or unintended machine activity.

Notwithstanding major achievements in this area, some gaps exist. Many of the current systems

•Consider a limited selection of parameters, excluding factors such as vibration, noise, and structural stress.

•Depend on communication technologies inappropriate to underground conditions

•No unified cloud-based dashboards to visualize data and conduct long-term analytics

•Don't include automated response systems in emergencies such as lighting or mobile alerts

The system proposed in this paper overcomes these limitations by

•Using ESP32 microcontrollers to handle data from sensors effectively.

•Using LoRa communication to achieve long-range and low-power transmission in underground environments.

•Incorporating a variety of sensors such as multi-gas, humidity, vibration, and sound sensors.

•Enabling a cloud-based dashboard to monitor in real-time and historically.

•Enabling automated alerts and emergency lighting to improve situation awareness and response to safety issues.

III. PROPOSED SYSTEM

The intended design is an IoT-based safety system that is smart and continuously senses environmental and structural factors in underground coal mines. It combines a set of sensors with the use of ESP32 and implements LoRa (Long Range) communication to transfer information to a centralized controller and cloud-based dashboard. Such a setup ensures hazard detection in real-time, automated alerts, and quick response mechanisms and thus ensures significant miner safety improvement.

A. System Overview

The architecture of the intended system has the following three main parts:

1. Sensing and Processing

2.Communication Infrastructure
3. Control Center and Cloud Dashboard
Individual components are thoroughly selected and combined to provide solutions to the challenges of underground mining conditions. The block diagram of the overall system is shown in fig.1

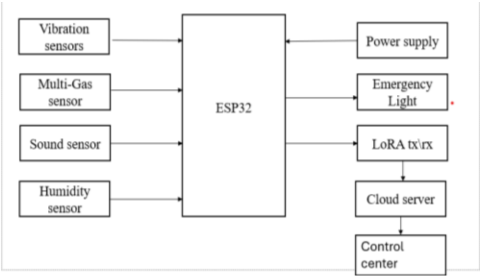

Fig 1 Block Diagram of Proposed Work

B. Sensing and Processing Unit
At the heart of the sensor board lies the ESP32 microprocessor, which was selected on account of its two cores of processing power, low power drain, and native Wi-Fi and Bluetooth capabilities (even though just LoRa is employed here to transport information). The ESP32 is linked to a group of environment and building sensors

- MQ-135 Gas Sensor: It is used to sense dangerous gases such as methane (CH_4), carbon monoxide (CO).
- DHT22 Sensor: Temperature and humidity sensor.
- Vibration Sensor (SW-420 or Piezoelectric sensor): Registers abnormal ground movement that can cause structural instability or collapsed state.
- Sound Sensor: It tracks noise levels that may disclose machinery malfunctions, explosions, or distress signals from people.
- Emergency Alert Module: Contains a buzzer, LED indicator lights, and emergency lighting that is activated upon exceeding hazard limits.

All sensors utilize a rechargeable Li-ion battery with a power management circuit backing it up.

C. Communication Module
For data transmission, the system employs LoRa communication using the SX1278 LoRa module. This technology is particularly well-suited for underground environments due to its:

- Long transmission range (up to 10 km in open areas, 500+ meters in tunnels)
- Low power consumption
- Strong signal penetration in obstacles-rich environments

Each sensing node sends data packets to a LoRa (or similar controller) connected to the internet. The lora transmits the data to a cloud platform.

D. Cloud-Based Dashboard
ThingSpeak is a cloud application that accepts the sensor data in real-time. Features of the dashboard include: Live Data Visualization: Temperature, gas concentration, humidity, sound, and vibration data is visualized on graphs and gauges.

- Alert System based on Threshold: Issues a visual and auditory alarm if any parameter is beyond safety limits.
- Mobile Notification: Triggers SMS or push alerts on supervisory personnel and safety teams via messaging services such as Twilio or Firebase Cloud Messaging.

E. Emergency Response Features
Upon detection of dangerous conditions (such as high methane concentration or intense vibration), the following is automatically done by the system.

- Triggers emergency lights near the sensing node
- Provides instant notification to the control room and personnel
- Updates the cloud dashboard to indicate the state of emergency

F. System Workflow
1. The sensors constantly monitor data from the mining environment.
2. The ESP32 reads sensor values and compares them to pre-determined safety limits.
3. Once values become normal, data is packaged and forwarded to the LoRa gateway.
4. When thresholds are crossed, emergency procedures take over.
5. The data is sent to the cloud dashboard by the ESP32.
6. Supervisors monitor the real-time dashboard and receive alerts in case of emergencies.

IV. IMPLEMENTATION

The implementation of the envisioned coal mine safety system is based on the utilization of ESP32 microcontrollers with LoRa (SX1278) modules to build a low-power, long-range wireless network that can operate in difficult underground settings. The system has several sensor nodes and a single master node that works as a gateway to aggregate and communicate with the cloud.

Table 1 Threshold level of each sensor

Parameter	Threshold	Action
Methane (CH_4)	> 1000 ppm	Trigger alarm
Temp	> 40°C	Send alert, light up LED
Humidity	> 90%	Log abnormality
Vibration	Detected	Immediate warning
Sound Level	> 80 dB	Suspect explosion or alert

Each sensor node consists of ESP32 Dev Board, SX1278 LoRa module (433MHz or 868MHz depending on your region), MQ-135 Gas Sensor (for CH_4, CO, NH_3), DHT22 (temperature and humidity), SW-420 Vibration Sensor, Sound Sensor Module. The sensor node carries out the following functions like always reads values from all sensors, packages sensor data into a payload, Transmits the data wirelessly over LoRa to the master node. The master node (ESP32 + LoRa) is identical in hardware to the sensor nodes with the exception. It is used as a LoRa receiver and connects to Wi-Fi and sends received information to the cloud platform (ThingSpeak). The alert threshold for each sensor is listed out in the table 1.

V. RESULTS AND DISCUSSION

The IoT-based coal mine safety proposed system was successfully tested and implemented in simulated underground environments. Its performance was assessed in terms of the capability to monitor in real-time, LoRa communication range and reliability, the response of alerts, and power efficiency overall.

A. Sensor Data Acquisition

The ESP32-based sensor nodes accurately captured environmental parameters using the connected sensors. Sample data obtained during the test period is shown in table. These readings were sent every 5 seconds over LoRa to the master node. The packets of data were constant and complete, verifying the quality of the sensors and communication protocol.

B. LoRa Communication Performance

The LoRa modules provided steady performance with a useful communication range of up to 500 meters in-building and more than 1 km outdoors with little packet loss. This range is deemed adequate in most underground coal mines where tunnels spread laterally over expansive areas.

Table 2 Threshold set for the proposed system

Parameter	Average Reading	Threshold Set	Status
Temperature	29.6°C	40°C	Safe
Humidity	68%	90%	Safe
Gas (CH_4 equiv)	410 ppm	1000 ppm	Safe
Vibration	No shock	Detected shock	Safe
Sound Level	62 dB	80 dB	Safe

C. Cloud Dashboard and Alerts

Integration with ThingSpeak (or other cloud services) provided support for real-time data visualization. Each parameter was represented with live graphs and trends on the dashboard in support of ongoing assessment of mine safety is shown in the fig 2. Under test conditions where limits were deliberately surpassed: More than 1000 ppm gases activated the buzzer and warning LED immediately. Simulated vibration triggered the emergency lights and sent alerts to the dashboard, Notifications were sent to mobile devices through email or SMS (if set up with Twilio or Firebase). This confirmed the efficacy of the emergency alert mechanism and cloud c onnectivity of the system.

Fig 2 Temperature and humidity sensor output live graph

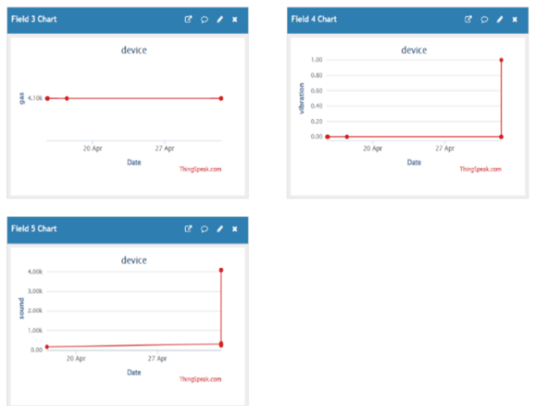

Fig 3 Gas, Vibration and Sound sensor output live graph

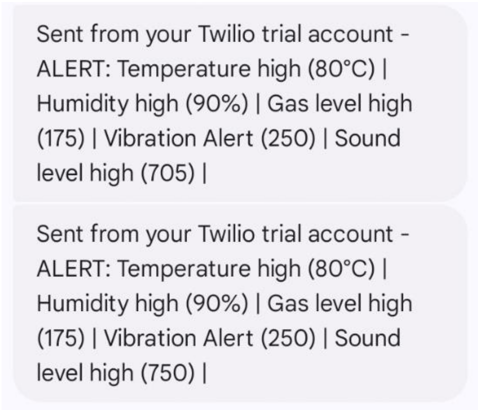

Fig 4 Alert SMS received in a mobile phone

D. Power Efficiency

The whole system with ESP32 and LoRa module ran under a low power profile. Tests of power consumption revealed the sensor node idle power consumption is approximately 80 mA and power consumption during active transmission is130–150 mA. The system is ideally suited to deployment in battery-powered configurations with the possibility of augmentation via sleep modes and solar charging in semi-surface positions.

E. Discussion

The deployment validates the feasibility of utilizing a low-power and low-cost safety monitoring system in coal mines. In comparison to current wired or GSM-based systems, the ESP32 + LoRa design has the advantage of providing

Better coverage in underground spaces where GSM/Wi-Fi is ineffective

- Reduced energy use, compatible with battery power
- Instant alerts and automated response, especially important in emergency situations

Table 3 Feature comparison of proposed System with existing systems

Feature / Metric	Traditional System	Zigbee-based IoT System	Proposed ESP32 + LoRa System
Communication Technology	Wired / Manual reporting	Zigbee (2.4 GHz)	LoRa (433/868 MHz)
Alert Delay	5–10 minutes (manual relay)	1–2 seconds	<1 second (real-time)
Sensor Types	Basic gas & temp sensors	MQ-6, DHT11, IR	MQ-135, DHT22, SW-420, Sound
Coverage Range	Limited to wiring	Up to 100 meters	500m–1km+ (underground)
Network Topology	Point-to-point	Mesh	Star topology (LoRa P2P)
Internet/Cloud Support	No	Yes (via gateway)	Yes (ESP32 Wi-Fi + LoRa)
Power Consumption	High (wired)	Medium	Low (LoRa & ESP32 optimized)
Scalability	Poor	Moderate	High (add more nodes easily)
Reliability in Mines	Poor (wire breaks, delay)	Good, but interference-prone	Excellent (penetrates walls)
Deployment Complexity	High	Moderate (Zigbee config required)	Low (simple P2P setup)
Cost	High (cabling, labor)	Medium (Zigbee modules)	Low (ESP32 + LoRa = <$10/node)

- Modular construction that can be expanded with additional nodes or sensors
- But the system also has some limitations
- LoRa bandwidth is limited, so message payload size must be optimized.
- Cloud dependency implies that internet is needed at least at the master node.
- Peer-to-peer networks sometimes require periodic sensor calibration to maintain accuracy.

The table compare various factors that assess the effectiveness of the alter system with the existing models. The comparison shows that proposed system performs better in all areas of assessment.

VI. CONCLUSION

The paper discusses the design, implementation, and assessment of a coal mine safety system based on IoT utilizing ESP32 microcontrollers and LoRa communication technology. The goal of the system is to enhance miner safety by continuously tracking environmental and structural conditions in real-time, assuring timely alerts and swift response mechanisms in the event of an emergency. The envisioned system successfully combines multiple sensors like gas, temperature, humidity, vibration, and sound sensors to sense hazardous conditions that can be encountered in coal mines. These sensors offer precise and reliable information to guarantee the safety of miners through early detection of possible threats. LoRa technology was found to be a great fit for underground communication. LoRa technology delivered long-range and low-power communication that is compatible with underground mine environments where traditional wireless technologies (Wi-Fi and GSM) experience signal weakening and range constraints. It has a communication range of more than 500 meters in indoor environments and up to 1 km in outdoor environments and can be scaled to cover large mine regions. The alarm mechanism of the system that includes automated actuation of emergency lighting, buzzers, and mobile alerts was reliable in tests conducted in real-time. This ensures that hazards like gas leaks and abnormal vibration are notified to mine personnel and operators in the control room in a rapid and efficient way.

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