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IoT- Based Automated Hazard Detection in Coal Mine

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ABSTRACT—

Coal mining presents significant occupational hazards, including exposure to toxic gases, high ambient temperatures, and a heightened risk of explosions. Conventional safety monitoring methods often suffer from delays and limited responsiveness, compromising the effectiveness of hazard mitigation. This paper proposes an IoT-based automated monitoring system that utilizes a network of environmental sensors to detect critical parameters such as methane concentration, temperature, and air quality in real time. The system is equipped with the LoRa RA-02 module, enabling long-range, low-power wireless communication suitable for underground environments. Instant alerts are generated when hazardous conditions are detected, allowing timely intervention and evacuation. The integration of IoT and LoRa technologies provides a scalable, energy-efficient, and cost-effective solution that significantly enhances operational safety and reduces risks for mine workers. Field simulations demonstrate the system's reliability, responsiveness, and suitability for deployment in active coal mining operations.

Keywords— IoT, Coal Mine Safety, Hazard Detection, LoRa Communication, Environmental Monitoring, Wireless Sensor Networks, Methane Detection, Real-Time Alert System, Embedded Systems, Industrial Automation

I. INTRODUCTION

Coal mining remains a vital component of energy production worldwide, yet it is also one of the most hazardous industrial sectors. Underground coal mines are particularly susceptible to a range of environmental and operational risks, including the accumulation of toxic gases such as methane (CH_4) and carbon monoxide (CO), elevated temperatures, limited ventilation, and the constant threat of explosions and cave-ins. These hazards not only endanger the lives of workers but also contribute to operational downtime and economic loss. Despite the availability of traditional safety protocols, most existing systems rely heavily on manual inspections and delayed data reporting, limiting their effectiveness in preventing accidents in real time.With the advent of Industry 4.0 and the Internet of Things (IoT), there is a growing opportunity to enhance mine safety through intelligent, automated systems. IoT-based monitoring systems provide the capability to sense, process, and transmit real-time environmental data from remote or hazardous locations without the need for human intervention. In the context of coal mining, this translates to a more proactive approach in identifying unsafe conditions before they escalate into critical events.This paper proposes a smart, IoT-enabled hazard detection system that employs a suite of environmental sensors to monitor key parameters such as methane concentration, temperature, humidity, and air quality within underground mines. The system integrates the LoRa RA-02 module to facilitate long-range, low-power wireless communication, enabling the reliable transmission of data across mine networks. Instantaneous alerts are generated when any measured parameter exceeds predefined safety thresholds, allowing timely evacuation or corrective measures.The proposed solution is designed to be cost-effective, energy-efficient, and scalable, making it suitable for both small-scale and large-scale mining operations. Through this work, we aim to contribute a practical, technology-driven advancement in mining safety by leveraging IoT and wireless communication technologies to reduce occupational risk and enhance overall operational security.

II. LITERATURE SURVEY

The mining industry has long been associated with high-risk environments, particularly in underground coal mines where hazards such as toxic gas accumulation, elevated temperatures, poor ventilation, and the risk of explosions persist. Traditional safety mechanisms have typically relied on manual inspections or standalone gas detection devices, which suffer from delayed responses and limited coverage. To overcome these limitations, researchers have increasingly focused on the deployment of Internet of Things (IoT)-based systems for real-time environmental monitoring in mines.Early works concentrated on wired sensor networks for gas detection and ventilation control, but these systems were often inflexible and difficult to scale in dynamic underground environments [1]. The introduction of wireless sensor networks (WSNs) marked a major advancement, enabling remote hazard detection and data acquisition. However, these systems often employed Zigbee or Wi-Fi for communication, which are limited by range and signal interference in underground conditions [2][3]. To address these issues, recent systems have incorporated LoRa (Long Range) technology, particularly the RA-02 module, for low-power, long-distance wireless data transmission suitable for sub-surface deployments [4][5].Real-time detection of hazardous gases such as methane (CH_4), carbon monoxide (CO), and hydrogen sulfide (H_2S) has been a primary focus in many studies. Shah and Kulkarni [6] implemented a gas leakage detection system using MQ-series gas sensors and GSM-based alerting. However, this approach was constrained by network availability and latency. Joshi et al. [7] enhanced the design by integrating Wi-Fi-enabled microcontrollers like the NodeMCU (ESP8266), but such systems remained vulnerable to signal attenuation in dense underground environments.The role of embedded systems has also evolved, with microcontrollers such as Arduino and ESP32 being used for local data processing and threshold-based alert generation [8]. These systems enable autonomous operation without constant cloud dependency, reducing both latency and bandwidth consumption. Sensors such as MQ-2, MQ-4, and DHT11 have become popular due to their low cost and compatibility with microcontrollers [9]. In systems proposed by Soni et al. [10], these sensors were integrated into mobile mine carts to provide mobile environmental mapping within tunnels, although the designs lacked long-range communication capabilities.Cloud-based platforms like ThingSpeak and Blynk have been adopted in several research efforts for data logging and visualization. However, as noted by Desai et al. [11], these platforms often fall short in reliability and customization for mission-critical environments like mining. Edge computing has been introduced in recent studies to mitigate these limitations by enabling localized data analytics and reducing dependency on continuous internet connectivity [12].Recent works have also focused on system resilience, including solar-powered sensor nodes for surface deployment [13], battery optimization for underground modules [14], and rugged enclosures for harsh conditions [15]. Bandyopadhyay et al. [16] proposed a hybrid model combining cloud computing with local gateway nodes that aggregate sensor data from different mine sections, thereby improving scalability and fault tolerance.Despite these advancements, few studies have implemented a fully integrated system combining gas detection, temperature monitoring, long-range wireless communication (e.g., LoRa), and real-time alerting mechanisms in a cost-effective and scalable manner. Furthermore, most existing systems lack user-friendly interfaces or do not address energy efficiency and modularity required for large-scale deployment. This highlights the need for a comprehensive and reliable IoT-based hazard monitoring solution that leverages robust communication protocols, embedded processing, and intelligent alert systems tailored to underground coal mining environmentsWang et al. (2019) proposed an IoT-based air quality monitoring system for coal mines that integrates real-time detection of gases, temperature, and humidity. The system uses an integrated microcontroller for data processing and Zigbee for wireless communication. While effective in monitoring critical parameters, the system was constrained by network instability in deep mining areas. [17]Zhang et al. (2020) developed a multi-sensor IoT system that tracks both environmental and structural parameters in coal mines. The system uses a combination of gas sensors (e.g., methane) and temperature sensors, with data transmitted via LoRaWAN. It provides both real-time hazard alerts and predictive maintenance notifications, improving mine worker safety and equipment longevity. [18] Sundaram et al. (2021) introduced an autonomous underground hazard detection system for coal mines that uses machine learning algorithms for anomaly detection based on IoT sensor data. By analyzing environmental conditions and historical patterns, the system can predict potential hazard scenarios, such as gas leaks or temperature fluctuations, thereby providing preemptive warnings. [19]Patel and Gupta (2020) discussed the use of wearable IoT sensors for monitoring coal mine workers' health in hazardous environments. These sensors measure vital signs, such as heart rate and body temperature, and transmit data to a central monitoring system for immediate response in case of heatstroke or gas exposure. [20]Kumar et al. (2020) designed a low-cost IoT-based gas detection system for underground mines, integrating MQ-series sensors with a microcontroller unit and providing GSM-based text alerts. Their work highlighted the system's practical deployment in resource-constrained mines, but noted potential reliability issues under extreme conditions. [21]Li et al. (2020) demonstrated a mine safety monitoring system using a hybrid IoT-WSN model that combines Zigbee and LoRa for different levels of communication. The approach improved coverage and minimized power consumption, addressing the challenges of maintaining a stable network in deep mine tunnels. [22]Chen et al. (2019) presented a coal mine safety system that integrates environmental sensors with cloud-based analytics to monitor and predict hazardous events. This system uses machine learning algorithms to classify environmental data and predict safety risks such as gas leakages, temperature spikes, and humidity increases. [23]Gupta et al. (2020) proposed an IoT-based mine ventilation monitoring system using wireless sensors to track airflow rates, gas concentrations, and humidity levels. The system is capable of providing real-time updates and automatic adjustment recommendations for optimal ventilation based on the detected data. [24]Patel et al. (2021) developed a mine monitoring system that integrates IoT, GPS, and sensor networks to detect hazardous gas leaks in real time. By using LoRa-based communication for long-range transmission, the system ensures that hazard data is promptly shared with mine operators, even from the deepest mine shafts. [25]Brahmbhatt and Yadav (2018) presented an IoT-based system for monitoring coal mine ventilation and environmental conditions. The system, powered by energy-efficient sensors, ensures continuous data collection and real-time monitoring of temperature, humidity, and gas levels, sending alerts if hazardous thresholds are exceeded. [26]Ding et al. (2019) explored an IoT-based predictive maintenance system for coal mining equipment. The system uses sensors to monitor machine vibrations, temperature, and operating conditions to predict failures and prevent hazardous incidents related to equipment malfunction. This reduces downtime and minimizes the risk of accidents due to machinery failures. [27]Xie et al. (2020) developed an IoT-based early-warning system that uses environmental monitoring sensors and historical mine data to predict dangerous events, such as rock falls or gas explosions, and send early warnings to workers and management. This early-warning system was shown to significantly improve emergency preparedness. [28]Sharma and Bhattacharya (2021) proposed a coal mine hazard detection system that employs IoT sensors for monitoring both environmental conditions and structural stability. Their system also integrates an advanced machine learning model to identify patterns of potential hazards and predict imminent risks based on real-time data. [29]Rathod et al. (2020) developed a multi-functional IoT system for coal mines that incorporates air quality sensors, smoke detectors, and temperature sensors into a unified monitoring network. Their work highlights the role of IoT in ensuring comprehensive safety monitoring by providing instant alerts and enabling effective emergency management strategies. [30]

III. Methodology/system description

The proposed IoT-based Automated Hazard Detection and Monitoring System for coal mines is designed to ensure continuous, real-time monitoring of environmental conditions and potential hazards. It integrates multiple sensor types, including methane (MQ-4), carbon monoxide (MQ-7), and smoke sensors (MQ-2), as well as temperature and humidity sensors (DHT22), to detect dangerous gases, temperature fluctuations, humidity levels, and fire risks. These sensors are connected to microcontrollers like the NodeMCU or ESP8266, which process and transmit data through LoRa or Wi-Fi to a central gateway. The system utilizes cloud-based analytics for data storage and processing, where machine learning algorithms are applied to detect anomalies, predict potential hazards, and identify patterns in the environment that may indicate emerging threats, such as gas leaks or equipment malfunctions. In case of critical conditions, such as excessive gas concentrations or high temperatures, the system triggers real-time alerts through SMS, email, or a mobile application, allowing mine operators and safety personnel to take immediate action. Additionally, the system is designed to be power-efficient, employing low-energy sensors and microcontrollers to ensure long-term, reliable operation in remote underground environments. Security features such as encrypted communication between sensors and cloud servers protect the integrity of data and prevent unauthorized access. This system offers a scalable and cost-effective solution, capable of expanding to monitor larger mining operations, while improving worker safety, reducing operational risks, and providing predictive maintenance for mining equipment. The system's design also emphasizes ease of deployment and integration with existing infrastructure in coal mines. It supports remote monitoring, eliminating the need for frequent physical inspections and enabling quicker identification of hazardous conditions that could pose significant risks to worker safety and operational efficiency. The combination of LoRa WAN for long-range communication and cloud-based data storage ensures that even in the deepest mine shafts, real-time data transmission remains uninterrupted. Additionally, the system’s predictive analytics capabilities offer mine operators the ability to anticipate potential hazards before they occur, thereby reducing the likelihood of accidents and enabling proactive risk management strategies. The modular nature of the system allows for future upgrades, such as incorporating additional sensors or integrating with other safety technologies, ensuring long-term adaptability as mining operations evolve. By continuously analyzing and responding to environmental changes, this IoT-based system significantly improves both the operational safety and sustainability of coal mining.

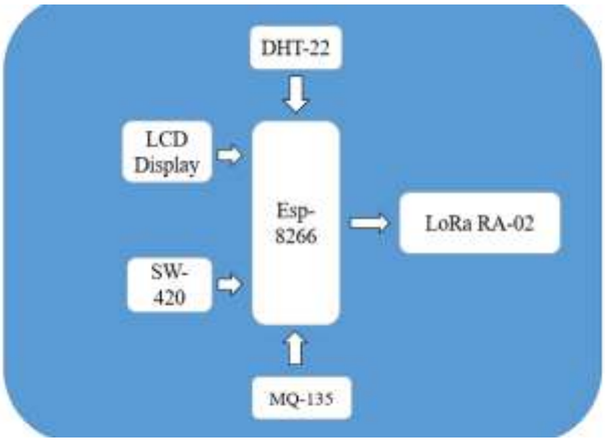

Fig 1 Block diagram -Transmitter

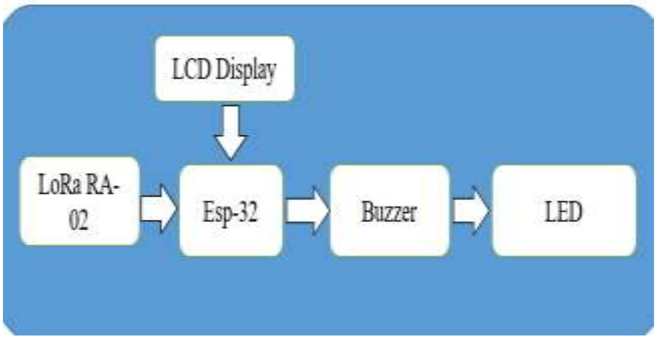

Fig 2 Block diagram-Receiver

IV. PROPOSED SYSTEM

The proposed system for automated hazard detection and monitoring in coal mines is an IoT-based solution designed to provide continuous, real-time monitoring of environmental parameters and potential hazards. The system consists of several key components: environmental sensors, microcontrollers, communication modules, data processing units, and alerting mechanisms. The sensors are deployed throughout the mine to monitor critical parameters such as gas concentrations (e.g., methane and carbon monoxide), temperature, humidity, and air quality. These sensors communicate with microcontrollers (e.g., NodeMCU or ESP8266) that process the collected data and transmit it wirelessly to a central gateway via LoRa or Wi-Fi technologies.Data received by the gateway is sent to a cloud-based platform or edge computing unit for processing and storage. Machine learning algorithms analyze the data to identify anomalies and predict potential hazards such as gas leaks, fire risks, or equipment malfunctions. If hazardous conditions exceed predefined thresholds, the system triggers real-time alerts via SMS, email, or mobile applications, notifying mine operators and safety personnel of the threat. Additionally, the system includes predictive maintenance features, allowing it to forecast equipment failures based on environmental and operational data, further reducing downtime and ensuring operational safety.The system is designed to be scalable and modular, allowing for easy expansion to cover larger mine areas or to integrate additional sensor types as needed. It is also built to be energy-efficient, ensuring long-term, reliable operation in remote mine environments. With its robust security measures, including encrypted communication and secure cloud storage, the system ensures that the collected data is protected from unauthorized access, maintaining the integrity of safety-critical information. By integrating these technologies, the proposed system offers a comprehensive solution for improving safety, reducing operational risks, and optimizing the overall management of coal mines.

V. HARDWARD /SOFTWARE SYSTEM

The hardware system for the IoT-based Automated Hazard Detection and Monitoring System in coal mines is designed to ensure robust, continuous monitoring and immediate hazard detection under harsh conditions. The system is built around a network of various environmental sensors, which are deployed at strategic locations within the mine to capture real-time data on critical parameters such as methane, carbon monoxide, smoke, temperature, and humidity. Gas sensors like MQ-4 and MQ-7 detect the presence of dangerous gases such as methane and carbon monoxide, which are the primary causes of explosions and poisoning in mining environments. Temperature and humidity sensors, such as DHT22, continuously monitor the microclimate of the mine to detect sudden changes that could indicate potential fire risks or other safety hazards. Smoke sensors, like MQ-2, further enhance fire detection capabilities. These sensors are connected to low-power microcontrollers like Node MCU or ESP8266, which process the data and transmit it wirelessly to a central gateway using LoRa (Long Range) for long-distance communication or Wi-Fi in areas with available network coverage. The use of LoRa ensures data can be transmitted over long distances, even in deep and remote parts of the mine where traditional communication methods may fail. The data collected by the microcontrollers is then sent to a cloud-based platform or edge computing unit for further processing, storage, and analysis.

The system is powered by rechargeable lithium-ion batteries paired with solar panels to ensure continuous, energy-efficient operation in remote locations. These power solutions minimize the need for frequent maintenance and allow the system to run autonomously without reliance on external power sources. To further enhance the system's reliability, weatherproof enclosures protect all hardware components from environmental damage such as dust, moisture, and vibration, ensuring their durability in the rough underground conditions typical of coal mines. When the system detects hazardous conditions, such as high concentrations of toxic gases or smoke, it triggers real-time alerts. These alerts are sent to mine operators and safety personnel via SMS, mobile applications, or web-based dashboards, ensuring quick response times. In addition to the immediate alerts, the system is also capable of activating local alarms through buzzers or sirens, providing an instant warning to workers within the mine. The integration of predictive maintenance capabilities further improves the system by using machine learning algorithms to anticipate potential equipment failures, minimizing downtime and ensuring the system's effectiveness over time.

By integrating these hardware components, the system not only enhances worker safety by continuously monitoring critical parameters but also enables proactive risk management and emergency response, ensuring that coal mining operations are both safer and more efficient. The modular nature of the system also makes it scalable, allowing for easy expansion as mining operations grow or as new sensor types are needed for more advanced monitoring.

SOFTWARE SYSTEM

The software system for the IoT-based Automated Hazard Detection and Monitoring System in coal mines is designed to manage the real-time collection, processing, and analysis of environmental data to ensure worker safety and efficient mine operation. It begins by acquiring data from various sensors, such as gas sensors (MQ-4, MQ-7), temperature and humidity sensors (DHT22), smoke sensors (MQ-2), and air quality sensors (MQ-135), which are processed by microcontrollers like NodeMCU or ESP8266. The data is transmitted wirelessly using communication protocols such as LoRa for long-range connectivity or Wi-Fi in areas with coverage. Once received, the data is cleaned and analyzed in real-time, often at the edge or through cloud-based platforms, to detect hazardous conditions like gas leaks, high temperatures, or smoke. The system utilizes machine learning algorithms for predictive analytics, enabling early detection of potential hazards and equipment failures. When dangerous conditions are identified, the software triggers real-time alerts via SMS, emails, mobile apps, or web dashboards, ensuring quick action is taken. It also provides remote monitoring via user-friendly dashboards, offering real-time visualizations of the mine's environmental conditions. The system is designed with robust security features, encrypting data transmission and employing role-based access control to protect sensitive information. This software architecture allows for continuous monitoring, proactive risk management, and improved safety protocols in coal mines. The software provides a **user**-friendly dashboard that displays real-time data visualizations, such as gas levels, temperature, humidity, and overall system health. The dashboard is designed to be intuitive and easily navigable, allowing operators and safety officers to monitor conditions across the mine at a glance. The system is also scalable, capable of accommodating an increasing number of sensors or expanding to cover larger mining operations as needed.

VI. CONCLUSION

In conclusion, the IoT-based Automated Hazard Detection and Monitoring System for coal mines offers a transformative approach to ensuring safety and efficiency in an inherently high-risk environment. By leveraging cutting-edge technologies such as IoT sensors, wireless communication, cloud computing, and machine learning, the system provides real-time, actionable insights that significantly enhance the ability to monitor and manage hazardous conditions, including methane leaks, carbon monoxide buildup, temperature fluctuations, and smoke, which are common risks in coal mining operations. The integration of predictive analytics allows for early detection of potential hazards, facilitating proactive measures to prevent accidents and improve overall safety standards. Furthermore, the system’s design is tailored to the demanding conditions of underground mines, utilizing robust, weatherproof hardware and energy-efficient power solutions to ensure reliability and uninterrupted service. The ability to remotely monitor and access data through web-based platforms and mobile applications provides mine operators, safety personnel, and decision-makers with the flexibility to respond quickly to emerging threats, even from remote locations. The implementation of alerts via SMS, emails, and local alarms guarantees that immediate action can be taken at any given moment, reducing the time between hazard detection and response. Beyond safety, the system optimizes resource management by providing continuous data that can be analyzed for trends, helping to improve operational efficiency and predict maintenance needs. This predictive capability not only minimizes downtime but also reduces the risk of equipment failure, thus lowering operational costs. The scalability of the system ensures that it can grow with the mine's needs, accommodating more sensors and expanding coverage as required. The combination of these features makes the system a highly effective tool in transforming coal mining operations, not only by enhancing worker safety but also by fostering an environment of data-driven decision-making, operational optimization, and long-term sustainability. As technology continues to evolve, further integration of advanced algorithms, edge computing, and deeper analytics will continue to improve the system's capabilities, ensuring that it remains at the forefront of industrial safety solutions. Ultimately, the IoT-based monitoring system is a crucial step toward achieving safer, smarter, and more efficient coal mining operations.

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