Advanced Coal Mine Monitoring Techniques with Land Slide Detection- A Review

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Abstract: Coal mines and landslide-prone regions are some of the most dangerous places for workers and nearby communities. Unpredictable hazards like toxic gas build-up in mines or sudden slope failures demand reliable, real-time monitoring systems that can detect early signs of danger. In coal mines, gases like methane and carbon monoxide, along with high temperatures and structural weaknesses, pose serious risks to miners' lives. Likewise, landslides are triggered by factors such as soil saturation, unstable slopes, earthquakes, or heavy rainfall, often striking without warning.

Traditional safety checks and basic sensors often fail to provide enough timely information. However, advances in wireless sensor networks, IoT devices, embedded controllers, and AI now offer better solutions. This review outlines various modern techniques for building safety systems for coal mines and landslide detection. It discusses suitable hardware, communication methods like LoRa, ZigBee, or GSM, and cloud-based monitoring dashboards. The focus is on hybrid setups that combine sensors for gases, temperature, humidity, vibration, soil moisture, tilt, and rainfall with intelligent data processing.

Key challenges such as underground signal loss, sensor calibration, and power supply are also examined. By highlighting recent progress and comparing available systems, this paper shows how AI and modern sensor networks can greatly improve hazard detection and worker safety in these high-risk areas.

Keywords: Coal mine safety, landslide detection, wireless sensor networks, IoT, real-time monitoring, gas leakage detection, MEMS sensors, embedded systems, edge computing, disaster risk management.

1. Introduction:

Coal mine and landslide safety systems are important for ensuring the safety of workers and minimizing accidents in mining operations. Various systems have been developed to address the different challenges associated with coal mining safety. The most common approach involves the integration of monitoring devices and alarm systems to detect environmental hazards such as gas concentrations, temperature, and humidity, which can monitor the state and are critical for preventing accidents like firedamp explosions and mine fires (Sulin et al., 2015) (Xianglin & Houcheng, 2016). We have also seen that advanced safety systems incorporate fixed-point base stations connected to industrial ethernet networks, enabling real-time data transmission and control from a central monitoring hub, which enhances the system's stability and functionality (Liulu et al., 2017). Security and protection systems are designed and implemented additionally to detect and respond to potential disasters, such as floods and fires, by providing early warnings and facilitating remote monitoring and control, thereby allowing for timely evacuation and disaster management (Bo et al., 2019). The use of wireless communication units and positioning systems further helps in tracking worker locations and environmental parameters, ensuring that personnel can be quickly alerted and evacuated in case of emergencies (Fengchao et al., 2019. The logging capabilities of IoT modules allows for continuous monitoring and data analysis, which is crucial for identifying and mitigating potential hazards (Nagrale et al., n.d.). Safety systems also include but not limited to emergency prevention and control mechanisms which need to be designed , such as double-tier roadway structures with emergency exits, to facilitate rapid evacuation in case of unpredicted or unforeseen incidents (Jianfeng et al., 2014). The development of these systems is very much essential for the effective implementation and operation of safety measures in coal mines (Jian-zheng, n.d.). Overall, these systems collectively enhance the safety and operational efficiency of coal mining activities by providing a reliable and safe monitoring, early warning, and emergency response capabilities.

2. Relevance:

It has been observed that the frequency and severity of accidents in coal mines and landslide-prone regions call for the the critical need for intelligent and real-time monitoring solutions. In existing conventional systems, the dependency is on the manual inspection or single-parameter sensors and such system often lack the predictive capability required to ensure early warning and effective risk minimization. Various technological advancements in Wireless Sensor Networks (WSNs), Internet of Things (IoT), embedded systems, and artificial intelligence (AI) have created new opportunities for proactive hazard detection. The deployment of these technologies can significantly enhance safety, reduce human casualties, and minimize environmental and economic losses. This review is especially relevant in the current era of digital transformation, where leveraging sensor fusion, edge computing, and cloud-based analytics is vital for the development of adaptive, scalable, and energy-efficient systems for coal mine and landslide hazard prevention.

3. Problem Statement:

Despite the evolution of safety technologies, coal mines and landslide-prone areas continue to face high risks due to unpredictable environmental dynamics and delayed hazard detection. Existing safety systems either rely on wired infrastructure that is impractical for harsh environments or fail to address multi-parameter monitoring effectively. These systems are typically non-adaptive, energy-intensive, and lack intelligence in decision-making. Furthermore, challenges such as underground signal attenuation, inaccurate data fusion, limited coverage, and uncalibrated sensors further degrade system performance. There is an urgent need for a robust, low-power, and intelligent safety framework that combines environmental sensing (e.g., gas, temperature, vibration, rainfall, moisture, tilt) with real-time wireless communication (e.g., LoRa, ZigBee, GSM) and AI-driven analytics. The proposed review addresses this gap by evaluating and comparing current solutions, proposing a hybrid, intelligent architecture for real-time hazard detection and early warning in both coal mines and landslide-vulnerable zones.

4. Literature Review:

With respect to proposed work an extensive literature survey is conducted accordingly which is present below. Recent advancements in safety monitoring technologies have significantly improved the early detection and prevention of accidents in hazardous zones such as coal mines and landslide-prone areas. Yang et al. (2021) conducted a in their review hilighted the causes of safety issues in coal mining, with the importance on the influence of human factors such as perceptual errors, skill deficiencies, and inadequate emergency planning. Their study concluded that with the use of intelligent mining technologies and IoT systems there can be lesser safety issues and is necessary to improve both human safety and environmental monitoring in coal mines.

Wang et al. (2013) proposed a coal mine safety monitoring system which was based on wireless sensor networks (WSNs), using different components such as MSP430 microcontrollers, gas sensors, and ARM9-based sink nodes. The system utilized nRF2401 for short-range communication and GPRS for remote communication. In their architecture they have enabled real-time environmental data acquisition and alerting via GIS-enabled platforms, proving effective in monitoring hazardous gases, temperature, and humidity within underground tunnels.

Similarly, Rehak et al. (2020) discussed critical infrastructure protection frameworks, which inclided geological disaster prediction using real-time sensor data. Their study emphasized the importance of resilient design and inter-organizational cooperation in monitoring risk-prone zones such as mines and unstable hillsides. The researchers suggested incorporating predictive analytics into existing safety systems to enable dynamic response strategies.

A study by Hassard et al. (2015) explored the use of robotic in-line inspection sensors in hazardous environments. Their evaluation was primarily based on the sensing modalities suitable for such structures and provided insights into how such robotic systems can support real-time hazard detection in coal mines and landslide tunnels.

In the another research on landslide detection, Mahajan et al. (2020) developed a microcontroller-based landslide early warning system using tilt and moisture sensors. In this system, which was installed in hilly terrains, researchers aimed to provide timely alerts using GSM modules. Their work illustrated the viability of low-power embedded systems in geotechnical monitoring applications.

In another design-focused contribution is seen in Dongre et al. (2017), who proposed a LoRa-based environmental monitoring system which was designed specifically for mountainous regions. Their design featured a multi-node configuration which was capable of detecting slope movement, changes in humidity, and seismic vibrations. The use of LoRa enhanced long-range communication capabilities in terrain where traditional wireless signals degrade rapidly.

According to Jiskani et al. (2021), research focused on the miner issues mining such as back and joint pains from improper posture and high physical demand which are frequently ignored in automated safety system design. Their findings give an idea for a holistic integration of biomechanical data in future mine safety systems to protect workers from chronic physical injuries.

In another study, Bhise et al. (2017) described a comprehensive underground coal mine monitoring system based on embedded microcontrollers and alerting techniques that included local displays and web dashboards. Their focus was on cost-effective design for real-time monitoring and gas leak detection

A review of research by Rana et al. (2025) compared different WSN topologies for landslide and coal mine safety, concluding that LoRa-based systems offered the best balance of range, power efficiency, and reliability in rugged terrains

Overall, literature suggests a convergence of WSNs, IoT, and AI/ML in modern safety systems. However, challenges such as sensor calibration, data fusion accuracy, underground communication reliability, and the integration of human behavioral factors still need substantial attention.

4.1 Wireless Sensor Networks:

Wireless sensor networks (WSNs) and Internet of Things (IoT) technologies have emerged as most important technologies in enhancing safety measures in coal mines and landslide-prone areas. In the case of the coal mines, these technologies facilitate real-time monitoring of environmental parameters such as temperature, humidity, and gas concentrations, which are critical for detecting potential hazards like toxic gas leaks, fires, and structural instabilities. The deployment of multi sensor nodes which are connected wirelessly will allow for cost-effective and efficient surveillance, providing workers working in coal mines with timely alerts to reduce the risks associated with such hazards (V., 2023) (Kumari et al., 2020). The implementation of WSNs in coal mines involves addressing different challenges related to wireless communication, transmission routing protocols, and positioning algorithms, which are very important for the effective operation of these systems in the complex underground environment (Chen & Wang, 2021). The recent effective protocols like ESP-NOW enhances real-time data acquisition and analysis, enabling early warning systems that can alert mine operators to potential safety hazards (Lenin et al., 2024). Additionally, the application of WSNs in coal mines includes the development of intelligent monitoring systems that utilize event-driven service coordination patterns to detect and respond to complex alarming events, thereby improving the overall safety management (Bo et al., 2012). The feasibility of these systems is supported by theoretical models that evaluate the propagation characteristics of electromagnetic waves in coal, ensuring reliable communication even in challenging conditions (Akkaş, 2018). Moreover, the integration of IoT with WSNs allows for the automation of safety control processes, further enhancing the ability to early detection and addressal of hazardous situations (Kirubakaran et al., 2024). These advancements underscore the potential of WSN and IoT technologies to significantly improve safety standards in coal mining operations, providing a robust framework for early warning and risk mitigation (Chen et al., 2009)

4.2 Machine Learning And Deep Learning Techniques:

Machine learning and deep learning techniques have emerged as very important tools in enhancing coal mine safety and early detection of the landslide hazards. In the coal mining industry, these technologies can be utilized to address various safety challenges, such as unexpected roof falls, rock bursts, and general safety risk predictions. Considering the example machine learning algorithms implemented have been effectively applied to predict roof fall events in underground coal mines by analyzing control problems which assures miner safety and reducing equipment damage (Dürrschmidt, 2023). Similarly the unsupervised learning methods, such as those based on long short-term memory and autoencoders, have also been employed to provide early warnings for rock burst hazards, achieving high accuracy in hazard recognition fused with sensor data , which are crucial for proactive risk management (Song et al., 2024). Additionally, named entity recognition models using deep learning architectures like BERT-CNN-BiGRUs-CRF have been developed to extract critical information from unstructured text data related to coal mine safety hazards, significantly improving the precision and recall of hazard detection (Ma et al., 2023). Recently incremental extreme learning machines have been used to predict coal mine safety risks by dynamically selecting features from big data, demonstrating superior accuracy compared to traditional methods (Sang et al., 2022). In the case of the landslide hazards, machine learning and deep learning have been instrumental in landslide detection and early mapping and risk assessment. These methods have improved the accuracy and efficiency of landslide mapping by quantifying complex nonlinear relationships between soil structures and predisposing factors, with convolutional and recurrent neural networks being particularly effective (Liu et al., 2023) (He et al., 2024). In Challenging situations like data scarcity, transfer learning approaches have been applied to enhance the applicability and accuracy of landslide detection models (Liu et al., 2023). Overall, we can come to the opinion that the integration of machine learning and deep learning in these domains not only enhances safety measures but also contributes to the economic efficiency of mining operations by reducing the risk of catastrophic events.

5. Proposed Methodology:

The proposed system is developed in a systematic sequence of phases to ensure reliability, and accuracy throughout the implementation. Each phase has a specific objective, contributing to the overall for overall detection of risks in landslide detection and coal mine alerts.

1. Sensor Networks:

The system can use a variety of sensors suited for coal mine and landslide hazard detection. For coal mine safety, sensors like the MQ-135 are utilized to detect hazardous gases such as methane and carbon monoxide. A DHT11 sensor monitors temperature and humidity levels, which are essential for understanding environmental conditions underground. Flame sensors are deployed to detect the presence of fire in mines. For landslide-prone areas, the system uses MEMS accelerometers (ADXL335) to detect vibrations or ground shifts. Soil moisture sensors assess water content in the soil to predict potential landslides, while vibration sensors monitor seismic disturbances. These sensors work together to provide continuous, real-time data about environmental safety parameters.

2. Microcontroller Interface:

The central processing unit of the system is based on the ESP32 microcontroller, chosen for its dual-core performance, integrated Wi-Fi and Bluetooth, and compatibility with various sensor inputs. The ESP32 collects data from the attached sensors, performs preliminary processing, and checks whether any of the collected values cross their respective danger thresholds. It is programmed to handle multiple sensor readings simultaneously, offering low-latency decision-making and real-time response. Additionally, the ESP32 enables modular design, supporting future expansion of sensor nodes or communication peripherals.

3. Communication System:

The system employs a dual-communication strategy combining LoRa and GSM technologies to ensure robust and redundant data transmission. LoRa modules are used to transmit data over long distances with minimal power consumption, which is crucial for deployment in remote areas where internet connectivity is limited. In parallel, a GSM module sends SMS alerts directly to emergency contacts and safety officers when hazardous conditions are detected. This dual-layer communication ensures that alert messages are delivered promptly, even if one communication channel fails.

4. Alert Generation:

Whenever a sensor reading exceeds its predefined threshold, the ESP32 triggers an alert mechanism. Locally, a buzzer and siren are activated to immediately notify workers or personnel in the vicinity. Simultaneously, an SMS alert is sent to registered phone numbers via the GSM module. This multi-level alert system ensures that both on-site personnel and remote monitoring centers are informed of the threat, enabling rapid evacuation or countermeasures.

5. Data Display and Visualization:

The system is equipped with a 0.96-inch OLED display module that shows real-time sensor values on-site. This visual feedback allows operators to manually verify system status and identify ongoing risks without needing to interface with cloud services. The display refreshes continuously and shows values like temperature, gas concentration, soil moisture level, and vibration intensity, giving users a comprehensive snapshot of current conditions.

6. Cloud Monitoring:

For extended monitoring and analytics, the system optionally integrates with an IoT dashboard through Wi-Fi connectivity. Sensor readings are uploaded to the cloud at regular intervals, where data can be visualized in graphical format. This supports remote diagnostics, historical trend analysis, and proactive maintenance planning. Cloud storage also facilitates long-term data archiving and can help identify recurring patterns or conditions leading to hazardous events.

7. Power Management:

The power supply for the system is optimized for low-energy operation. A rechargeable battery pack is used along with a voltage regulator to provide a consistent 5V power output to the ESP32 and sensors. Additionally, power-saving modes are implemented in the microcontroller, where it enters sleep mode when the environment is stable and awakens upon receiving new sensor inputs or interrupts. This improves battery life, making the system viable for continuous operation in remote or inaccessible locations.

The proposed architecture Diagram of the system is given below:

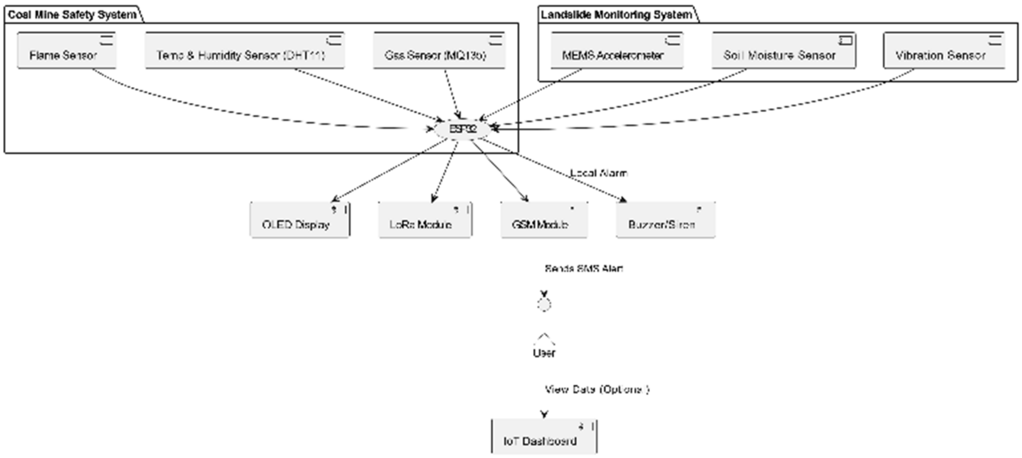

Figure 1: Proposed System Architecture

6. Conclusion:

Coal mines and landslide-prone regions are considered among the most hazardous environments, where the safety of workers and infrastructure depends heavily on early detection of environmental risks. This review discussed in detail the evolution of safety monitoring systems, particularly focusing on wireless sensor networks, IoT integration, and embedded technologies. Various studies have demonstrated that sensor-based, real-time monitoring can significantly reduce life hazards and operational losses by enabling early warning systems for gas leaks, temperature anomalies, structural instability, and ground vibrations.

In this review we have also focused on modern communication protocols like LoRa, ZigBee, and ESP-NOW, along with cloud platforms and edge computing units, which enables seamless data acquisition, processing, and alert mechanisms. These systems which have evolved from traditional reactive approaches to proactive and intelligent solutions capable of autonomous decision-making.

Despite technological advancements, challenges persist in terms of sensor calibration, network reliability in underground or remote areas, power management, and false alarm mitigation. Future work must focus on hybrid sensor fusion, low-power AI inference at the edge, and interoperability between mine safety systems and disaster management platforms. With the future adoption of such architectures there is a huge potential to revolutionize coal mine and landslide safety standards globally, ultimately contributing to the goal of zero-fatality operations and sustainable environmental management.

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