

# MineGuard: An AI-Driven Intelligent Safety Helmet for Underground Mining

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## Abstract:

MineGuard is an intelligent AI safety helmet to improve safety in underground mines. The system combines multi-sensor environmental surveillance with lightweight machine learning-based hazard classification to offer real-time risk identification and responses to crises. MineGuard is a system constructed based on an ESP32 microcontroller, MQ-4 and MQ-7 gas sensors to sense the methane (CH<sub>4</sub>) and carbon monoxide (CO) concentrations, and an MPU6050 accelerator and gyroscopes sensor to measure the movement of the worker and the occurrence of falls. MineGuard uses a Decision Tree-based classification model to interpret combined sensor data and classify conditions as either Safe, Warning or Emergency, in contrast to traditional safety systems, which rely on fixed-threshold detection. Such a clever design allows evaluation of multi-parameters in context, minimizes false alarms, and enhances reliability of hazard detection. When the critical conditions are detected the system sends an onboard buzzer through a GSM communication module, which delivers the emergency alerts to the responsible supervisory staff. Its underlying architecture is scalable, uses low power, and makes real-time embedded decisions that could be applicable in harsh underground scenarios. Combining artificial intelligence with sensing and wireless communication through the IoT, MineGuard offers an affordable and scalable safety solution that enhances preliminary hazard recognition, quick emergency reaction, and the general protection of the mining personnel

**Keywords:** The AI-based safety system, Safety in underground mining, Decision tree classifier, IoT-based hazard detection, Gas sensing technology, Fall detector system, Embedded machine learning, GSM emergency communication.

## 1. Introduction:

Underground mining has been rated as one of the most dangerous jobs in the world owing to toxic and flammable gases, small working areas, lack of light and the ever present attitude of collapse. Workers who work in these conditions are often exposed to methane (CH<sub>4</sub>), a highly flammable gas that is able to cause explosions, and carbon monoxide (CO), a toxic gas that can lead to suffocation and permanent health harm. Besides environmental risks, accidental falls and unexpected impacts dramatically risk the safety of workers. Although safety standards have improved in terms of industry, there is still a poor level of real-time monitoring of hazards at the worker level. The traditional mining helmets are most often aimed at the protection of the head physically, without the introduction of intelligent mechanisms of monitoring and communication. Although there are industrial gas detection systems, most of them are fixed systems and might not be able to offer a wearable, personalised, and safety solutions.

In addition, traditional monitoring mechanisms usually use a fixed threshold-based detection strategy, which might trigger a false alarm or cause the response to be slow, since they cannot simultaneously interpret several risk factors. The latest trends in embedded systems, Internet of Things (IoT), and edge-based artificial intelligence have made it possible to create small, low-energy, and smart wearables. By combining environmental sensing and machine learning, it is possible to perform contextual hazard detection instead of using parameters on the bases of triggering. Microcontrollers can be used to execute real-time multi-parameter classification using lightweight classification algorithms like Decision Trees, without the need to utilize excessive computing power.

Here, the proposed paper is MineGuard: An AI-Driven Intelligent Safety Helmet in Underground Mining, a wearable

embedded system, which includes gas sensing, motion tracking, and GSM-based emergency contacts, along with an embedded machine learning model to distinguish between different hazards intelligently. The system uses MQ-4 and MQ-7 gas sensors to measure the concentration of methane and carbon monoxide, an MPU6050 acceleration and gyroscopes board to detect falls and an ESP32 microcontroller to process the information in real-time. The classifier is a Decision Tree based tool that can be used to examine combined sensor data to classify conditions as Safe, Warning or Emergency to allow adaptive and context sensitive reactions to safety.

MineGuard hopes to deliver a cost-effective, scalable, and reliable safety solution in underground mining situation, through AI based decision making during the future, coupled with IoT enabled communication and embedded sensing. The suggested system will promote timely identification of hazards, minimize false alarms and maximize efficiency in responding to emergencies, thus helping increase occupational safety levels in the dangerous industrial environment.

## 2. Literature Survey:

**IoT Based Smart Helmet for Coal Miner Safety:** Mining is said to be among the most dangerous professions because of the concentration of poisonous gases and high temperatures, as well as undetermined conditions below the surface. This paper presents a smart helmet system through the IoT that is intended to enhance the safety of miners by constantly observing the environmental conditions. The helmet incorporates gas sensors, temperature sensors and wireless communication modules to gather and transmit real-time data into a central monitoring station. In case of dangerous weather conditions like methane leak or high temperature, to alert miners and supervisors, the system automatically precipitates messages. The suggested solution indicates the way in which the IoT technology will contribute to a safer workplace by providing a real-time tracking system, as well as quick response measures in underground mines [1].

**Smart Helmet for Mining Industry Using Wireless Sensor Networks:** The Smart Helmet is a wireless sensor network (WSN) based smart helmet system and the proposed present investigation to ensure better security in underground mining activities. The helmet has environmental sensors, which are able to read the parameters like gas concentration, humidity, and temperature. The obtained data is sent by wire to a control unit where the safety condition is constantly calculated. The system is responsive even in demanding underground conditions and can guarantee the system is reliable due to its energy efficient sensor nodes. It is shown that the experimental results support the opinion that the proposed WSN-based strategy can effectively monitor potentially dangerous conditions and fire warning signals in time, thus mitigating the

risk of mining accidents [2].

**IoT Enabled Safety Monitoring System for Underground Mines:** This paper presents an IoT-enabled monitoring system, which is a wearable gadget that can measure the surrounding conditions and provide information to ensure the safety of miners. The system works with smart helmets which have gas sensors and temperature sensors to continuously display data on a cloud based platform. Powerful analytics are used to identify suspicious trends and raise alarm bells. The cloud network enables the supervisors to track several miners at a time and keep track of past records in terms of safety. The experiment shows that IoT and cloud technologies can profoundly enhance safety management and safer accidents in the mines [3].

**AI-Based Hazard Detection in Underground Mining Environments:** The study investigates how artificial intelligence can be used to identify dangerous situations in underground mines. The suggested system gathers data about sensors on the environment like gas concentration and temperature, interprets it with machine learning algorithms in order to warn about possible hazards. The AI model has the ability to produce early alerts by detecting trends related to dangerous conditions and prevents accidents before they happen. The findings indicate that AI predictive models have the potential to drastically enhance safety precautions during mining activities as they can lead to proactive risk reduction [4].

**Smart Helmet with Gas Detection and Worker Monitoring:** Research paper hypothesizes a smart safety helmet that is able to monitor the environment dangers and workforce in the underground mines. The helmet incorporates gas sensors to check harmful gas level corrupted with methane and carbon monoxide gas, temperature and movement of workers. The system employs wireless communication modules where real-time alert messages to central control room are sent in case abnormal conditions are detected. After joining both environmental sensing and worker monitoring, the system augments the situational awareness, and serves as a means of minimizing the risk of fatal accidents in mining operations [5].

**Accident Detection and Emergency Alert System for Miners:** The paper will examine a smart helmet system that will sense the accident as well as an emergency alert through a mining process. The helmet is equipped with sensors and accelerators to figure unusual motions like falls or collisions. In the event of an accident, the system sends alerts automatically and provides information about the location to the control center. The suggested system will ensure that the time of emergency response increases and the operations of rescue during underground mining are improved [6].

**Cloud-Based Mine Safety Monitoring System Using IoT Devices:** In this paper, the authors of the study suggest the

implementation of cloud-based mine safety monitoring system with the use of the IoT devices that are placed in the mining area. The mine is lined with sensors that record information on the surrounding. The acquired information is sent to a cloud system where analytics code is used to analyze the data to identify safety risks. The cloud system will allow their monitoring to be done remotely, as well as the visualization dashboards to the supervisors. The study shows that cloud computing can increase the extent of availability of data and enhance decision-making in mining safety management [7].

**Wearable Safety Devices for Industrial and Mining Applications:** The current paper explores wearable safety devices that are used to safeguard workers working at dangerous industrial settings, such as underground mines. Some of the wearable technologies mentioned in the study include smart helmets and smart vests fitted with the sensors that collect and track environmental conditions and health parameters of workers. The system enhances the safety of workers by allowing pertinent real time monitoring as well as automated alert systems. The study shows the possibility of the wearable technology in preventing work-related accidents and enhancing the level of occupational safety [8].

**Deep Learning Approaches for Worker Safety Monitoring:** The paper examines how deep learning methods can be utilized in safety monitoring of workers in a work setting. Computer vision algorithms are trained to recognize the presence or absence of workers wearing personal protective gear including helmet and other protective equipment. With the system, safety violations are detected using real time camera feed, and alerts are delivered to the supervisors. The paper reveals that AI-monitors can positively influence adherence to safety standards and decrease riskiness in the workplace [9].

**Integrated Smart Helmet System for Mine Safety:** This paper proposes the concept of Smart Helmet to enhance mine safety by installing a system of underground mining safety. The helmet has a variety of sensors such as gas sensors, temperature sensors, and motion sensors to track both the atmosphere and miner bearing. The data acquired by the sensors are sent by wires to a monitoring system where the safety conditions are examined. Dangerous situations are sensed and alerts are issued to alert miners and supervisors. The system proposed shows that the combination of sensor technology, wireless communication, and intelligent monitoring can be used to increase safety in the mining environment [10].

## 2.1 Research Gap

The analyzed literature review depicts that the sphere of smart helmets and mining safety systems, which are based on the IoT, has serious progress. The majority of studies mainly involve sensor-based monitoring of the environment (e.g., gas

detection, methane, carbon monoxide), temperature, and humidity, as well as wireless communication systems to send alerts. Nevertheless, there are some important restrictions that are not addressed.

To begin with, most of the current systems have a fixed threshold-based detection system that can not learn to interpret a combination of sensor parameters. This tends to cause high rates of false alarms and lose of reliability in complicated underground scenarios.

Secondly, in the case that there are studies that use the term IoT and cloud-based monitoring, they rely mostly on central processing, which can introduce delays and cannot be applied in decision making on devices in real-time in case of emergency scenarios.

Third, minimal focus has been placed on incorporating worker movement analysis which includes fall detection with environmental hazard monitoring in a single system. The major solutions address these areas in isolation as opposed to offering a holistic approach to safety.

Moreover, recent works address the AI techniques often with complex models or cloud computing, which is unsuitable where the power consumption is low and embedded systems are used in wearable devices. Minimally sized and interpretable AI models are lacking sufficient scientific investigation into being able to run effectively on microcontrollers.

Moreover, several current systems do not have custom-made, wearable protection measures, being either built-in or partly wearable yet not entirely real-time intelligent and self-sufficient.

## 3. Proposed Methods

MineGuard is developed as a combination of hardware and smart software modules to collaborate and provide real-time hazard observations and emergency response system in underground mining. The system creates a unique combination of environmental sensing, built-in artificial intelligence, and wireless communication to offer quicker, smarter, and more dependable safety monitoring on a 1-on-1 worker level.

### 3.1 Sensing and Data Acquisition Module

This module is charged with a role to incessantly gather environmental and movement-related information about the mining environment. MineGuard has a combination of sensors to scan dangerous conditions at real-time. MQ-4 gas sensor is

used to detect a highly flammable gas that is a common occurrence in coal mines, methane (CH<sub>4</sub>). The **MQ-7** gas sensor detects a poisonous gas, carbon monoxide (CO), which is very dangerous to human health. The two sensors produce analog signals in proportion to the concentration of gases, and are read at the **ESP32** ADC pins.

To monitor motion, the **MPU6050** accelerator gyroscopes unit measures acceleration in the X, Y and Z directions. To detect the fall, the system calculates the total acceleration magnitude to identify any abnormal movements (or other unexpected impacts). The measurements of sensors are captured at a fixed time interval, which guarantees continuous monitoring of the environment. This module ensures reliable recording of raw environmental and physical condition data and sending it to the processing layer.

### 3.2 Data Processing and Feature Extraction Module

Raw sensor signals are then collected and they are preprocessed and intelligent decision-making is then done with these obtained signals. The basic filtering techniques are used to stabilize gas sensor readings, minimizing noise and abrupt changes. The values obtained through acceleration sensor (MPU6050) are manipulated to calculate the total acceleration magnitude with the help of vectors calculations. Other characteristics like the rate of change in gas concentration can also be obtained to indicate the trends of increasing danger. The processed values constitute an organised set of features comprising of:

- Methane concentration level
- Concentration level of carbon monoxide.
- Total acceleration magnitude Optional gas trend indicators
- Optional gas trend indicators

This ordered information will then be sent to the AI classification unit where it will be analyzed

### 3.3 AI-Based Hazard Classification Module (Core Intelligence)

This module is known as the smart divide of MineGuard. The system does not just use prepared-detection using fixed-threshold because it uses a Decision Tree-based classification model to interpret the combined sensor data and establish risk levels. There are two phases of operation: Training Phase Sensor pictures are taken in the conditions of Safe, Warning, and Emergency. These samples are labeled and to train a Decision Tree classifier by using supervised learning methods. Learning boundaries to decisions in the model are acquired concurrently over a number of parameters as opposed to separate threshold comparisons. Deployment Phase The trained model produces interpretable conditions (rule-based) that are inbuilt into the ESP32 microcontroller. In real time running, the processed

sensor values are compared using these rules that are learned to determine the system state as;

- Safe
- Warning
- Emergency

The approach is an AI-based one, enhancing contextual awareness, minimizing false alarms, and allowing multi-parameter risk assessment with limited embedded resources.

### 3.4 Alert and Emergency Communication Module

Upon detecting a hazard condition, MineGuard sets off its warning systems.

In Warning conditions, a short time buzzer sound is used to alert the worker. The buzzer in Emergency conditions works by being programmed to send a specific length of time and an automated SMS message is sent to an authorized supervisor or control room number over the SIM800L GSM module.

The communication between the GSM module and the ESP32 will occur via the UART (TX/RX pins), which ensures dependable emergency notification even without the internet connections. This module assures quick reaction and improves the safety of workers with an immediate communication

### 3.5 PDF Export

There is an 18650 Li-ion battery to energize the system, and to have safe charging and battery control, there is a TP4056 charging and protection module. Voltage control guarantees a stable work of the ESP32, gas sensors, MPU6050 and GSM module. Each of the components has a common base to ensure stability of signals and lower the effects of noise. These components are closely incorporated in a simple frame of a helmet, making it mobile, sustainable, and relevant in the underground conditions.

## 4. Technical Architecture and Implementation Details

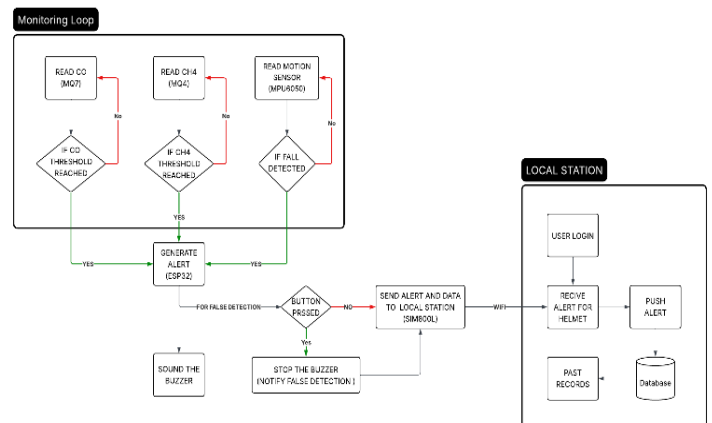


Fig 4.1 : System Architecture

The MineGuard system is structured as a compound of various modules which collaborate to keep a check on the conditions of the environment and safety of the workers in underground mining conditions. Its architecture is primarily defined as two components: the Monitoring Loop within the smart helmet and the Local Station where the alerts and records are received and kept.

#### 4.2 Monitoring Loop

The current module constantly checks the mining conditions by using sensors attached to the ESP32 microcontroller. The MQ-7 sensor will be used to measure the concentration of carbon monoxide (CO) and the MQ-4 sensor will be used to measure the level of methane (CH<sub>4</sub>). The MPU6050 motion sensor can record acceleration measurements of three directions to detect fall or violent impacts.

All sensor values are registered in real time and compared to the safety thresholds that are defined in the ESP32. In case the CO or CH<sub>4</sub> level surpasses the limit, or an fall is detected, the system emits an alarm. The warning system can activate a buzzer to alert the worker. The monitoring loop operates 24 hours in order to have round the clock safety monitoring.

#### 4.3 Alert and Communication System

In case a dangerous situation is identified the mechanism activates an alarm with the help of buzzer and transmits a message to the control station in the area. The SIM800L GSM module will be utilized to communicate the control station and the helmet.

The ESP32 is used to transmit the alert message via the GSM unit to enable the supervisors to get information concerning the hazard detected. This will take care of emergency action being taken expeditiously. In the case of a false detection in the alert, one can turn off the buzzer, and the system resumes its monitoring

#### 4.4 Local Monitoring Station

The MineGuard device provides alert to the local monitoring station where supervisors can monitor the safety events. Guidelines in use can access the system and see the warnings that have been issued by the helmet. The previous alerts and incidences in the past are stored in a database and stored in the station so that safety events can be reviewed in the future. This assists in the analysis of the accident trends and enhancing safety protocols in the mining setting.

#### 4.5 Power and Hardware Integration

A rechargeable 18650 lithium-ion battery is used to power MineGuard and is attached by TP4056 charging and protection module. The power system guarantees a safe charging and stable supply of voltage to the ESP32, sensors and GSM module. Each of the elements is linked with a common platform and put together into a small wearable fabricated in such a way that the equipment can operate as a smart mining safety helmet.

### 5 Result and Discussion

MineGuard can work well being an intelligence-based safety helmet to be used in the mine. The MQ-4 and MQ-7 sensors are used to pick up the level of methane and carbon monoxide and the sensor MPU6050 helps to detect an event of sudden movement or fall. These sensor readings are processed in real time by ESP32 and the safety condition is observed.

The AI model based on the Decision Tree assists the system in the combinatorial analysis of the various sensor inputs jointly enabling the system to determine a situation as safe, warning or emergency. In case a dangerous situation has been observed, the buzzer notifies the worker and the GSM system forwards a notification to the local monitoring station.

The system is general lightweight, responsive and can be used in real-time safety monitoring. Immature problems can be seen in extremely noisy settings or aberrant motion patterns and should be ameliorated behind future versions by enhanced calibration and enhanced AI models.

5.1 Comparison Table

Paper	Technology Used	Key Features	Limitations Compared to MineGuard
Saha et al., 2019 [1]	IoT-based smart helmet	Gas detection, wireless monitoring	No AI-based analysis, limited hazard prediction
Patil et al., 2020 [2]	Sensor-based monitoring system	Gas sensors, temperature monitoring	No accident detection or intelligent alert system
Kumar et al., 2021 [3]	IoT safety monitoring	Environmental monitoring, wireless alerts	Lacks AI-driven decision making and miner motion detection
Srinivas et al., 2023 [9]	IoT + LoRa communication	Long-range communication, gas monitoring	No AI hazard prediction or integrated intelligent safety analytics

## 5.5 Alert History

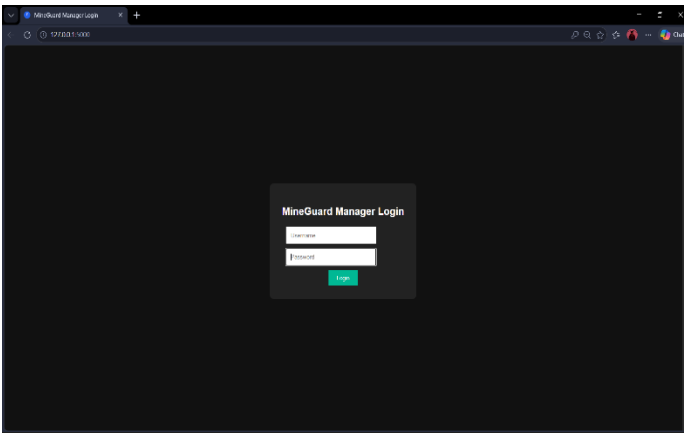
## 6 Conclusion

The use of MineGuard is a novel concept that can enhance safety in underground mines, which brings a combination of embedded sensors, artificial intelligence and wireless communications. The system offers an intelligent and a dependable safety helmet that can be able to monitor dangerous gasses and record fall incidents of workers in real time. MineGuard will consist of MQ-4 and MQ-7 gas sensors combined with the MPU6050 motion sensor and ESP32 microcontroller to constantly assess the safety of both the environment and workers.

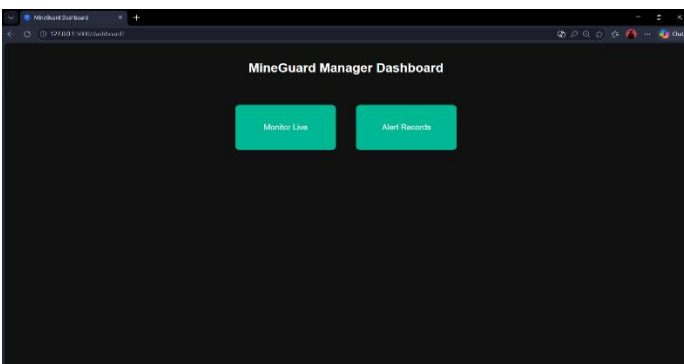
The application of an AI model that is based on a Decision Tree enables the system to use a variety of sensor input types and categorize situations as a safe state, a warning state, or an emergency state. The GSM communication log and buzzer alarm system make sure that the worker and the local monitoring station get timely alerts in the event of hazardous situations. The design is overall small, economical, and viable to real-time safety monitoring in the mining operations. MineGuard can show how artificial intelligence and embedded systems may be utilized to establish intelligent safety devices that enhance hazard recognition and effectiveness in emergency response. The modular nature also enables the system to be augmented with new technologies to provide more functionality in the future mining safety application

### Future Enhancements :

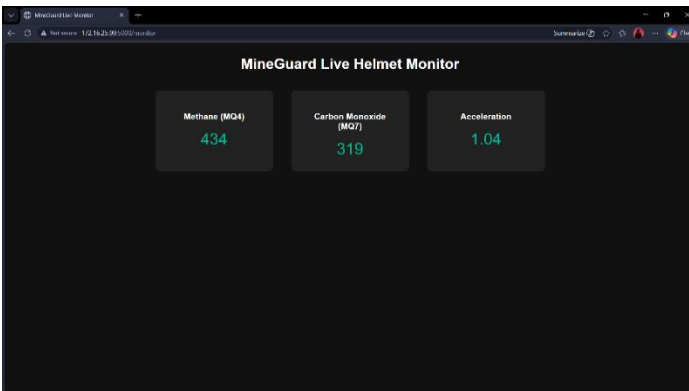
- GPS or indoor localization system integration to trace miners real time location in case of an emergency.
- Creation of a cell phone surveillance program, to be used by supervisors to get notifications and keep track of accident statistics at any time.
- More advanced machine learning models on the prediction of hazards and false alarms minimization.
- Enhancement of environmental sensors (temperature, humidity, air quality sensors) so as to have a more comprehensive monitoring.
- Connection to an IoT cloud framework to visualize the information in real time and to provide long-term analytics on the safety.
- Design of a hardware platform that is small in size by making smallest PCB that will minimise the size of the unit and enhances easier integration of the helmet.
- Predictive safety analytics implemented to detect feasible hazards at an early stage when they are not critical.
- Inclusion of the voice-based or vibration indicator to enhance awareness of the workers in very noisy work areas.



5.2 Login page



5.3 Dashboard



5.4 Live monitoring

Date	MQ4	MQ7	Acceleration
2026-03-05 17:20:36.907389	220	132	1.0
2026-03-05 17:20:31.876243	240	114	1.0
2026-03-05 17:20:07.983544	240	146	1.01
2026-03-05 17:18:34.306026	228	155	1.01
2026-03-05 16:26:20.902455	900	800	1.02
2026-03-05 16:02:17.855420	900	800	1.01

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