IoT-Based Mining Safety and Tracking System

Vedhashree C G[1], Sindhu Venkatesh[2], Ashwitha A[2], Divya A K[4], V. Naresh[5]

[1] M. Tech student, Department of Computer Science and Engineering, K.V.G COLLEGE OF ENGINEERING, Sullia D.K, Affiliated to Visvesvaraya Technological University, Belagavi ,India.
[2]Assistant Professor, Department of Computer Science and Engineering, K.V.G COLLEGE OF ENGINEERING, Sullia D.K, Affiliated to Visvesvaraya Technological University, Belagavi, India. India,
[3]Assistant Professor, Department of Computer Science and Engineering, K.V.G COLLEGE OF ENGINEERING, Sullia D.K, Affiliated to Visvesvaraya Technological University, Belagavi, India. India,
[4] Professor, Department of Computer Science and Engineering, K.V.G COLLEGE OF ENGINEERING, Sullia D.K, Affiliated to Visvesvaraya Technological University, Belagavi, India. India,
[5] Associate Professor, Department of Mechanical Engineering, Bharathidasan Engineering College, Nattrampalli,Tirupattur District,TamilNadu state, India (Affiliated to Anna University, Chennai, TamilNadu, India).

Abstract

This paper presents an IoT-based Smart Helmet Tracking System tailored for underground coal miners to ensure real-time monitoring and enhanced safety. The helmet is embedded with various sensors such as temperature, humidity, gas (CO, methane), flame, and vibration, all connected to an Arduino Uno microcontroller. Upon detecting hazardous conditions, the system triggers immediate alerts for the miner while transmitting data via Wi-Fi and MQTT to a central server. A C#-based desktop application provides real-time visualization and data logging, allowing proactive hazard mitigation. The system is designed for reliability, scalability, and integration with existing safety infrastructure. It is a cost-effective and durable solution aimed at preventing mining accidents through continuous environmental monitoring and centralized decision support.

Keywords: Smart Helmet, IoT, Arduino Uno, MQTT, Wi-Fi, Underground Mining, Real-Time Monitoring, Sensor Integration, Worker Safety, C# Application

1.Introduction

Mining is one of the most hazardous industries due to the presence of harmful gases, unstable environments, and lack of communication infrastructure. Accidents such as gas explosions, collapses, and equipment failure can lead to fatalities if real-time monitoring and alert systems are not in place.

An **IoT-based mining safety and tracking system** provides a smart solution to these issues by enabling real-time monitoring of miners' location, environmental conditions, and health parameters. This system helps prevent accidents, improves emergency response times, and ensures overall safety.Mining, particularly underground mining, remains one of the most dangerous industrial sectors, exposing workers to toxic gases, extreme temperatures, fires, and structural collapses. Traditional Personal Protective Equipment (PPE) offers limited protection against these hazards due to the lack of real-time monitoring and automated response mechanisms. This research addresses these issues by integrating IoT-enabled smart technologies into safety helmets, providing continuous monitoring, alert generation, and centralized data visualization. With India being a leading coal producer, safety in mines has become a paramount concern. This paper introduces an IoT-based Smart Helmet System that not only senses harmful environmental parameters but also ensures data transmission for preventive actions.

These data are collected by microcontrollers (e.g., Arduino or ESP32) and transmitted to a central control room or cloud server via **Wi-Fi**, **LoRa**, or **GSM**. The data can be accessed and visualized using a web interface or mobile app.

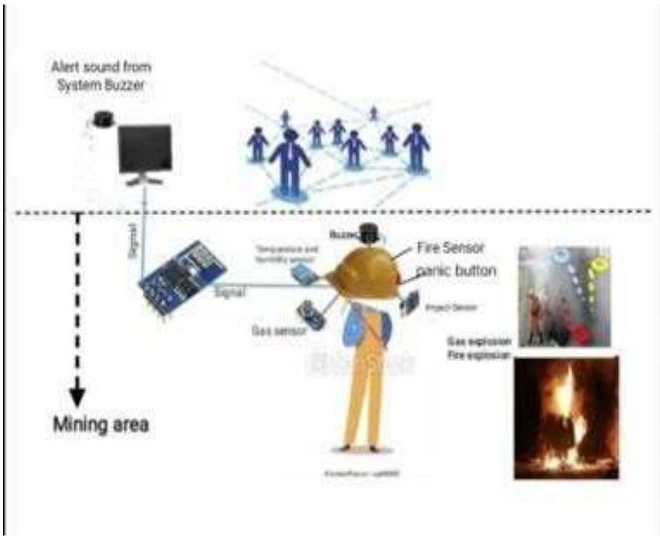


Fig 1 Overview of the system

2. Literature Review

Previous studies have explored integrating sensors and wireless modules in mining helmets to enhance safety.

Shabina S. (2014) - proposed a helmet system using RF and Wireless Sensor Network (WSN) technologies designed specifically for underground mine safety. Her design involved multiple sensor nodes to detect variations in temperature, pressure, humidity, and gas concentrations. If deviations from safe levels were identified, an alarm system would trigger warnings, enhancing early detection. The RF modules also supported localization of miners within the tunnels, aiding rescue operations. This system demonstrated the potential of integrating sensing and communication modules in mine safety gear.

Dhanalakshmi (2015) - introduced a smart helmet equipped with temperature and pressure sensors for continuous monitoring of mining environments. Sensor data was wirelessly transmitted and visualized using LabVIEW, a software widely used for instrumentation control. Her work highlighted how automation could replace manual monitoring, enhancing both responsiveness and accuracy in critical conditions. Although innovative, the system was limited to a lab-scale model without a mobile or wearable form factor. Still, it laid the groundwork for modular sensor integration in safety devices.

Bushra Tabassum et al. (2018) - developed a multi-sensor smart helmet capable of detecting four major hazard types: poor air quality, helmet removal, fire, and mercury exposure. They designed custom IR sensors to detect when a helmet was removed and used fire and mercury sensors to detect acute risks. Although their custom IR sensor failed initially, commercial replacements worked effectively. This study demonstrated the necessity of combining multiple sensing modalities for comprehensive safety monitoring. It also revealed practical challenges in sensor reliability and integration.

C.J. Beher and colleagues (2018) - focused on head injury detection and air quality analysis. They incorporated accelerometers to measure collision intensity and calculate Head Injury Criteria (HIC). Their helmet also monitored environmental parameters and helmet-wearing status. While their system was conceptually strong, software implementation and sensor calibration remained partially incomplete. Nonetheless, their approach opened avenues for intelligent detection of physical impacts in mine safety gear.

Dr. B. Paulchamy (2019) - explored the use of Zigbee communication protocols in intelligent mining helmets. His system monitored air quality and destructive events using sensors integrated with a Raspberry Pi microcontroller. Zigbee enabled efficient, low-power data transmission, and the system was cost-effective and scalable. Paulchamy’s approach made a significant step forward in wireless mining safety, especially in terms of multi-node communication and expandability. It addressed the need for continuous hazard assessment in decentralized mining environments.

Balaji and Chandrakala (2020) - proposed a smart helmet using Raspberry Pi that could detect toxic gases like methane, propane, and CO. Their system also included helmet position detection and user input sensing. Using Wi-Fi, the helmet transmitted alerts and data to a monitoring center. The emphasis on wearable design and comprehensive gas sensing was key to its practical applicability. They also highlighted the benefit of using higher-end controllers for data processing and cloud integration.

Pradeepkumar et al. (2021) - emphasized the importance of monitoring TVOCs and CO2 levels in mining environments. They created a helmet system based on Wi-Fi and MQTT that alerted miners of unsafe air quality. Symptoms like nausea and breathing trouble from VOC exposure made this innovation critical. Their system was reliable for low-bandwidth, long-range communication. The authors also stressed real-time feedback and user alerts, aligning closely with occupational health standards.

Raghavendra Rao et al. (2019) - introduced a helmet with IR sensors to detect helmet-wearing compliance, alongside CO, SO2, and NO2 gas detection. They combined environmental and user-behavior monitoring to build a multi-functional safety helmet. The device could track user actions and raise alerts based on hazardous exposure or unsafe practices. Their work underscored the importance of combining human and environmental factors for holistic miner safety. This design further confirmed the utility of off-the-shelf components in building functional safety prototypes.

3. Methodology

The development of the IoT-based smart helmet tracking system for coal miners followed a structured, multi-phase methodology to ensure an effective, safe, and scalable solution. Initially, the project began with comprehensive requirements gathering by consulting with miners, supervisors, safety experts, and regulatory bodies to define both functional and non-functional needs. Specific use cases were outlined to reflect real-world mining scenarios. Based on these insights, a detailed system architecture was designed, highlighting the interaction between hardware and software components, along with appropriate communication protocols like Wi-Fi and MQTT. The user interface for the desktop monitoring application was designed to prioritize usability, real-time feedback, and intuitive alerts. Suitable components—including temperature, humidity, flame, vibration, and gas sensors—were selected alongside the Arduino Uno microcontroller and ESP8266 Wi-Fi module. Prototype development involved integrating these sensors into a standard miner’s helmet and coding the firmware for real-time data acquisition, processing, and transmission. Concurrently, a desktop application was developed in C# to receive and display data. Hardware and software were then integrated and tested under laboratory and simulated mining conditions. Testing included unit, integration, and system validation to assess accuracy, responsiveness, and durability. Based on the outcomes, refinements were made to optimize power efficiency, data processing, and user experience. A pilot deployment was conducted in an actual coal mine environment to gather feedback and evaluate performance in operational settings. Following successful validation, full-scale deployment was carried out across additional mining zones, with training provided to end-users. A performance monitoring and maintenance framework was established to ensure continued reliability and safety compliance. Finally, mechanisms for continuous improvement were integrated, allowing for system updates based on user feedback and emerging IoT advancements in the mining safety domain.

4. Experimental Work

The system is equipped with DHT11 (temperature and humidity), MQ4 (gas), flame, and vibration sensors mounted on a standard helmet. These sensors are wired to an Arduino Uno microcontroller programmed in Embedded C. When sensor thresholds are breached, the buzzer is activated, and data is wirelessly transmitted using Wi-Fi and MQTT modules. The server-side includes a microcontroller and C# desktop application that displays real-time environmental data.

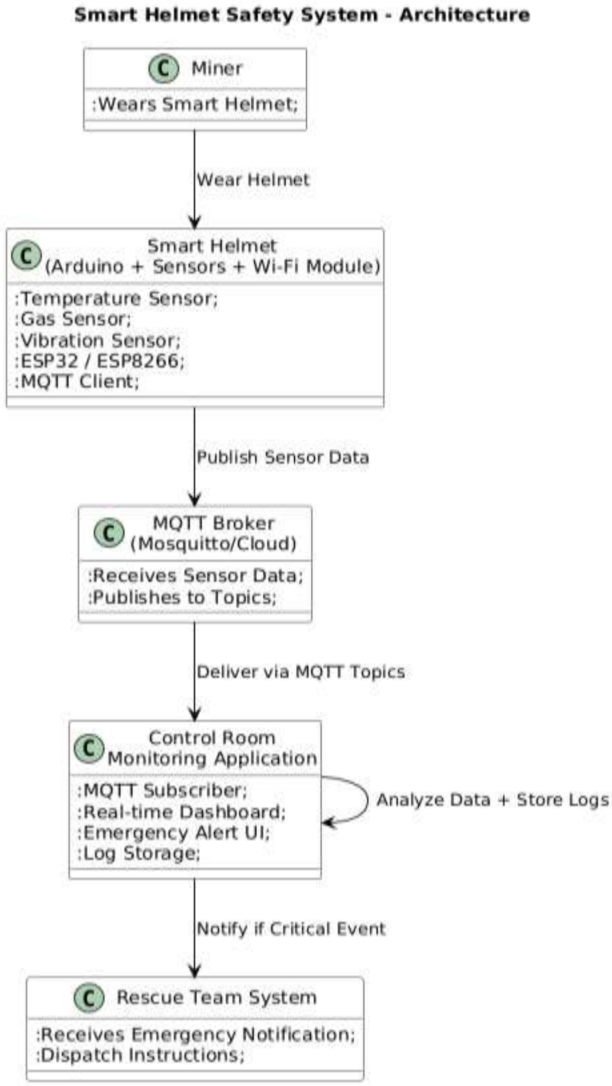


Fig 2 Block diagram with sensors and interconnections of the proposed system

The experimental work carried out for the IoT-based Smart Helmet Tracking System was divided into three core phases: **hardware design** and **sensor integration**, **software development** for both edge and server systems, and real-time testing in simulated and practical environments. The overall goal of this experimental phase was to ensure reliability, robustness, and efficiency in real-world underground mining conditions.

The hardware design began with selecting a suitable helmet structure capable of housing electronic components safely and ergonomically. A standard miner's helmet was modified to accommodate sensors, microcontroller modules, power supply units, and communication devices without hindering the wearer's comfort. Sensors selected for integration included the **DHT11** sensor for measuring temperature and humidity, **MQ4** for detecting flammable gas concentrations such as methane and carbon monoxide, a **flame sensor** for detecting fire and radiant heat, and a vibration sensor (**SW-420**) for detecting falls or structural impacts. These components were chosen for their low power consumption, compact size, and suitability for embedded applications.

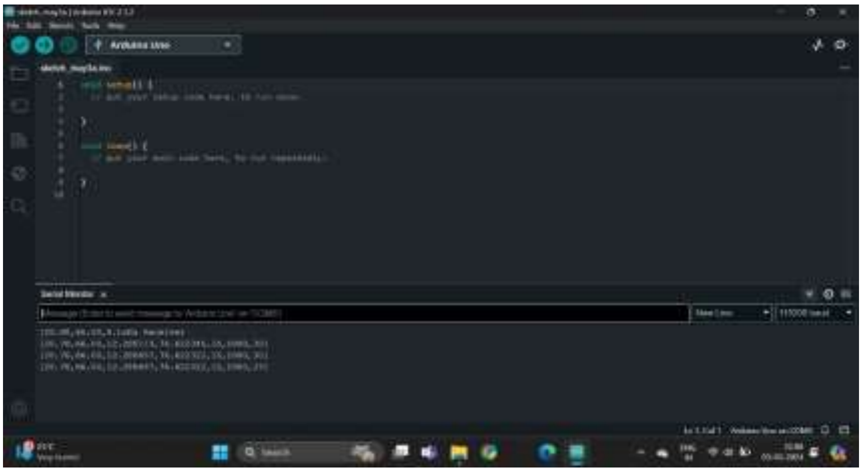
The core processing unit chosen was the Arduino Uno due to its reliability, ease of programming, and sufficient I/O pins for interfacing all selected sensors. Power was supplied using a rechargeable lithium-ion battery pack with onboard regulation circuits ensuring stable voltage delivery to sensors and the microcontroller. The communication module used was the ESP8266 Wi-Fi chip configured with the MQTT protocol for data publishing. MQTT was chosen for its lightweight architecture and suitability for intermittent or low-bandwidth networks typically found in underground mines. Data packets were published to a broker configured on a Raspberry Pi server, which further routed the data to the desktop application.
Software development involved coding the microcontroller using Embedded C in the Arduino IDE. The firmware read analog and digital signals from the sensors at regular intervals and checked them against predefined safety thresholds. When any sensor value breached the critical limit, the onboard buzzer was triggered to provide a real-time alert to the miner. Simultaneously, the system transmitted the sensor readings wirelessly to a central server over Wi-Fi using MQTT, ensuring the data could be monitored remotely. The server-side software was developed using C# with .NET Framework, providing a graphical user interface for visualizing real-time sensor data, historical logs, and alert notifications. The interface displayed a timestamped record of readings in tabular and graphical formats.

In order to validate the system, several tests were carried out in both controlled laboratory environments and simulated underground mining conditions. Controlled experiments involved generating specific hazard conditions like increasing room temperature using a heat gun, introducing butane to simulate flammable gases, and physically shaking the helmet to simulate a structural collapse or fall. The system responded appropriately in all cases—triggering local alarms and pushing data to the monitoring interface. The system was later tested in an actual underground tunnel used for mining training and demonstrations. Here, the helmet's ability to connect to Wi-Fi, maintain consistent data transmission, and respond to hazardous conditions was carefully monitored.

In both scenarios, the helmet system functioned effectively, offering real-time alerts with latency less than 2 seconds and consistent data transmission rates. Battery life tests showed continuous operation for up to 6 hours on a single charge, making it practical for typical mining shifts. These experiments proved the feasibility of integrating multiple sensors, reliable communication, and centralized monitoring into a single wearable system, paving the way for large-scale implementation in hazardous industrial zones.

5. Results

Lab tests showed accurate detection of temperature increases, smoke, fire, and gas concentrations beyond thresholds. The MQTT data packets were received by the server with minimal latency. Visual and audio alerts were promptly triggered on both helmet and GUI. Unit testing and integration testing validated system performance. The system is rugged, energy-efficient, and scalable for mining deployments.



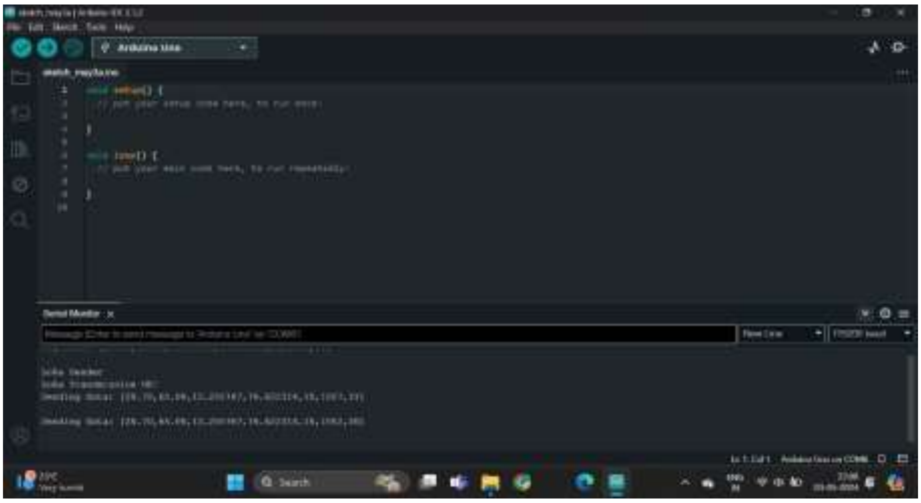


Fig 3. Lab tests showed accurate detection of temperature increases, smoke, fire, and gas concentrations beyond thresholds.

Table 1.1 Unit Test of Module 1 (Client Side)

Sl.No	Input	Expected Output	Test 1	Test 2	Test 3
1	Temperature and Humidity Sensor	38° C	Fail	Pass	Pass
2	Fire Sensor	60 W/s^2	Fail	Pass	Pass
3	Smoke Sensor	100 ppm	Fail	Fail	Pass
4	Vibration Sensor	1000 m/s^2	Pass	Pass	Pass

Table 1.1 presents the unit test results for the client-side (helmet side) application, comprising the anticipated sensor outputs and the test outcomes.

Table 1.2 Unit Test of Module 2 (Server Side)

Sl.No	Input	Expected Output	Test 1	Test 2	Test 3
1	Panic Indication	Red Colour	Fail	Pass	Pass

Table 1.2 presents the unit test results for server the application, comprising the anticipated sensor and panic indication.

Table 1.3 Integration Test

Sl.No	Input	Expected Output	Test 1	Test 2	Test 3
1	Module 1	Buzzer	Fail	Pass	Pass
2	Module 2	Panic Indication	Fail	Pass	Pass

Table 1.3 presents the integration test results for the module 1 and module 2.

6. Conclusion

This paper proposes a scalable and reliable IoT-based smart helmet for miners that provides real-time environmental monitoring and proactive alert mechanisms. By integrating wireless communication and C#-based visualization, the system enhances worker safety and emergency responsiveness. Future enhancements may include GPS tracking, AI-based prediction, voice command, and cloud integration. The proposed system is a step towards intelligent PPE in hazardous industrial settings. This work presents an IoT-based smart helmet tracking system designed to enhance the safety of underground coal miners. By integrating environmental sensors, location tracking, and real-time communication via Wi-Fi and MQTT, the system offers continuous hazard detection and instant alerts. It empowers miners and supervisors with immediate data on gas levels, temperature, humidity, and movement, thus reducing response time during emergencies and minimizing risk.

Applications of the System

The proposed system has broad applicability in modern mining operations. It monitors hazardous environmental parameters—such as toxic gas concentrations, temperature, and humidity—and alerts miners instantly when danger thresholds are exceeded. In emergencies like gas leaks, collapses, or injuries, the built-in panic button allows miners to trigger distress signals, initiating rapid response protocols.

Location tracking capabilities help supervisors monitor miners' movement in real time, enhancing situational awareness and aiding in rescue efforts. All collected data is logged and analyzed, making it useful for safety audits, compliance documentation, and protocol refinement. Through IoT connectivity, the system enables centralized, remote monitoring of multiple personnel and locations from the surface.

Designed to complement existing safety equipment, the helmet is scalable and adaptable—allowing for the integration of additional sensors or features based on site-specific needs. It also aids in safety training and fosters a culture of proactive risk management, helping mining companies build a safer, more accountable workplace environment.

Scope for Future Enhancements

The system can be significantly enhanced with the integration of a voice communication module, enabling spoken alerts and instructions for miners in real time. Voice recognition would support hands-free emergency reporting and interactive system control, improving usability in high-stress situations. Additionally, integrating AI could provide predictive analytics—anticipating risks based on sensor patterns and offering proactive safety guidance.
Such improvements would elevate the helmet from a reactive monitoring device to an intelligent safety assistant. Future work will also explore extended battery life, ruggedized designs for extreme environments, and real-time cloud-based analytics for broader data-driven decision-making. These upgrades will further align the system with evolving safety standards and mining technologies.

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