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Smart Mining Helmet with Health & Safety Monitoring using ESP32 and IoT

V. Yojana rupa kalpana[1], Jonnalagadda Naga Durga Sahith[2], Boddepalli Harshita[3], Andluri Sesi kumar[4], Botcha Lokesh[5], Karri Chandra Sekhar[6]

[1]*Associate Professor, Department of ECE, Dr. Lankapalli Bullayya College of Engineering, Andhra Pradesh, India.*
[2,3,4,5,6] *Department of ECE, Dr. Lankapalli Bullayya College of Engineering, Andhra University, Andhra Pradesh, India.*

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Abstract: *Mining remains one of the most hazardous industries due to the continuous exposure of workers to toxic gases, extreme environmental conditions, and health-related risks. This paper presents an IoT-enabled Smart Mining Helmet with Health and Safety Monitoring designed to improve worker protection through real-time environmental and physiological monitoring. The proposed system is built around the ESP32 microcontroller and integrates an MQ135 gas sensor for hazardous gas detection, an LM35/DS18B20 temperature sensor for temperature monitoring, a pulse sensor for heart rate measurement, and an IR eye-blink sensor for detecting worker fatigue or unconsciousness. The collected sensor data are processed by the ESP32 and transmitted wirelessly via Wi-Fi to a centralized monitoring system for continuous supervision. Whenever any monitored parameter exceeds predefined safety thresholds, the system immediately activates a buzzer and sends alert notifications, enabling rapid response to potential emergencies. Experimental evaluation demonstrates that the proposed system accurately monitors environmental and physiological conditions while providing reliable real-time alerts under both normal and hazardous scenarios. Compared with conventional mining safety systems, the proposed solution offers integrated health monitoring, continuous remote monitoring, and enhanced emergency response capabilities at a low implementation cost. The developed smart helmet provides an effective, scalable, and reliable solution for improving occupational safety in mining environments and can be extended to other hazardous industries such as construction, oil and gas, and chemical manufacturing.*

Keywords: *Smart Mining Helmet, Internet of Things (IoT), ESP32, Worker Safety, Health Monitoring, Gas Detection, Environmental Monitoring, Real-Time Alert System, Wearable Technology, Industrial Safety.*

I. INTRODUCTION

Mining is one of the most important industrial sectors, supplying essential minerals and natural resources that support infrastructure development, manufacturing, and energy production. Despite its economic significance, mining remains one of the most hazardous occupations due to the presence of toxic gases, oxygen deficiency, extreme temperatures, dust, and the constant risk of accidents. Underground mining environments are particularly dangerous because workers are exposed to confined spaces where hazardous conditions can develop rapidly. These factors contribute to severe health issues, injuries, and fatalities, making worker safety a major concern for mining industries worldwide.

Traditional mining safety systems primarily rely on manual inspections, standalone gas detectors, and periodic monitoring methods. Although these approaches provide a basic level of protection, they often fail to offer continuous monitoring and immediate emergency response. Delays in detecting hazardous gases, abnormal physiological conditions, or worker fatigue can significantly increase the risk of accidents. Moreover, existing systems generally focus on monitoring either environmental conditions or worker health, rather than providing a comprehensive safety solution.

Recent advancements in the Internet of Things (IoT), embedded systems, and wireless communication technologies have enabled the development of intelligent safety monitoring systems capable of real-time data acquisition, processing, and remote monitoring. IoT-based wearable devices equipped with multiple sensors can continuously observe environmental and physiological parameters while transmitting data to centralized monitoring stations. Such systems improve situational awareness, reduce response time during emergencies, and enhance overall workplace safety.

This paper proposes an IoT-enabled Smart Mining Helmet with Health and Safety Monitoring based on the ESP32 microcontroller. The proposed helmet integrates multiple sensors, including an MQ135 gas sensor for detecting hazardous gases, a temperature sensor for monitoring body temperature, a pulse sensor for measuring heart rate, and an IR eye-blink sensor for detecting fatigue or unconsciousness. The ESP32 processes sensor data in real time and transmits it wirelessly through Wi-Fi to a centralized monitoring system. Whenever any monitored parameter exceeds predefined safety thresholds, the system immediately a activates an audible buzzer and sends alert notifications to supervisors, enabling rapid intervention and emergency response.

The proposed system provides several advantages over conventional mining safety solutions by integrating environmental monitoring, health monitoring, and wireless communication into a single wearable device. The implementation is cost-effective, compact, energy-efficient, and capable of continuous operation, making it suitable for deployment in underground mines and other hazardous industrial environments. Experimental results demonstrate that the system accurately detects abnormal environmental and physiological conditions while providing reliable real-time alerts, thereby improving worker safety and reducing accident risks.

The main contributions of this work are as follows:

- Design and development of an IoT-based smart mining helmet using the ESP32 microcontroller.
- Integration of multiple environmental and physiological sensors into a single wearable safety device.
- Real-time wireless monitoring and data transmission through Wi-Fi.
- Automatic emergency alert generation using audible alarms and remote notifications.
- A low-cost, scalable, and reliable safety solution suitable for mining, construction, oil and gas, and other hazardous industries.

The remainder of this paper is organized as follows. Section II reviews the related work and identifies research gaps. Section III describes the proposed methodology and system architecture. Section IV presents the implementation and experimental setup. Section V discusses the obtained results and performance analysis. Finally, Section VI concludes the paper and outlines future research directions.

II.MATERIAL AND METHODS

The proposed Smart Mining Helmet with Health and Safety Monitoring system is developed using low-cost embedded hardware components and IoT technology to ensure continuous monitoring of mining workers in hazardous environments. The hardware components used in the system are listed below.

Component	Specification	Purpose
ESP32 Microcontroller	Dual-core 32-bit processor with built-in Wi-Fi	Central processing unit for data acquisition, processing, and wireless communication
MQ135 Gas Sensor	Gas detection sensor	Detects hazardous gases such as ammonia, carbon dioxide, smoke, and other harmful pollutants
DS18B20/LM35 Temperature Sensor	Digital/Analog temperature sensor	Monitors the worker's body or ambient temperature
Pulse Sensor	Optical heart rate sensor	Measures the worker's heart rate continuously
IR Eye-Blink Sensor	Infrared-based sensor	Detects prolonged eye closure to identify fatigue or unconsciousness
Buzzer	Piezoelectric buzzer	Generates audible alerts during emergency conditions
Wi-Fi Module (Built into ESP32)	IEEE 802.11 b/g/n	Enables real-time wireless transmission of sensor data
Power Supply	Rechargeable battery (5 V)	Provides power to the complete helmet system
Arduino IDE	Embedded programming environment	Used for coding, compiling, and uploading programs to the ESP32
Embedded C/C++	Programming language	Implements sensor interfacing, data processing, and alert logic

Hardware Description

The ESP32 microcontroller serves as the core processing unit of the proposed system due to its high computational capability, low power consumption, and integrated Wi-Fi communication. The MQ135 gas sensor continuously monitors the concentration of hazardous gases commonly present in mining environments. A DS18B20 (or LM35) temperature sensor measures body or ambient temperature to identify heat-related risks. The pulse sensor continuously monitors the worker's heart rate, while the IR eye-blink sensor detects prolonged eye closure that may indicate fatigue or unconsciousness.

The processed sensor data are transmitted wirelessly to the monitoring station through the ESP32's built-in Wi-Fi module. Whenever abnormal conditions are detected, the system activates a buzzer and sends real-time notifications to the monitoring center for immediate response.

Software Requirements

The software implementation is carried out using the Arduino IDE with Embedded C/C++ programming language. The ESP32 Wi-Fi libraries are utilized for wireless communication, while the embedded program continuously acquires sensor data, compares the readings with predefined safety thresholds, and generates alerts whenever unsafe conditions are identified.

The combination of these hardware and software components provides a compact, reliable, and cost-effective IoT-based safety monitoring system suitable for mining and other hazardous industrial environments.

Procedure methodology

2.1 System Design

The proposed Smart Mining Helmet with Health and Safety Monitoring system was developed using an ESP32 microcontroller integrated with multiple environmental and physiological sensors. The system continuously monitors hazardous gas concentration, body temperature, heart rate, and worker fatigue. Sensor data are processed locally by the ESP32 and transmitted through Wi-Fi to a central monitoring station for real-time supervision. If any parameter exceeds the predefined safety threshold, the system immediately activates a buzzer and sends an alert notification to the monitoring unit.

2.2 Hardware Configuration

The hardware consists of an ESP32 microcontroller, MQ135 gas sensor, DS18B20 (or LM35) temperature sensor, pulse sensor, IR eye-blink sensor, buzzer, rechargeable power supply, and built-in Wi-Fi module. The ESP32 acts as the central controller by acquiring sensor readings, processing the collected data, and managing communication between the helmet unit and the monitoring station.

2.3 Data Acquisition

Each sensor continuously measures its corresponding parameter:

- **MQ135 Gas Sensor:** Detects harmful gases and poor air quality.
- **Temperature Sensor:** Measures the worker's body or surrounding temperature.
- **Pulse Sensor:** Monitors heart rate continuously.
- **IR Eye-Blink Sensor:** Detects prolonged eye closure indicating fatigue or unconsciousness.

The ESP32 samples sensor outputs at regular intervals and converts analog sensor signals into digital values using its built-in Analog-to-Digital Converter (ADC). Digital sensor readings are directly acquired through GPIO interfaces.

2.4 Data Processing and Decision Algorithm

The acquired sensor data are filtered and compared with predefined safety threshold values stored in the ESP32 memory. The decision algorithm classifies the worker's condition into **Safe** or **Alert** states based on the measured values.

The threshold conditions used are:

- Hazardous gas concentration exceeding the safe limit.
- Body temperature greater than **38°C**.
- Heart rate below **50 BPM** or above **120 BPM**.
- Eye closure duration exceeding **8 seconds**.

If all measured values remain within their permissible ranges, the system continues normal monitoring. Otherwise, an emergency condition is declared.

2.5 Alert Generation

Whenever an abnormal condition is detected, the ESP32 immediately:

1. Activates the onboard buzzer to alert the worker.
2. Generates an emergency warning message.
3. Transmits the sensor readings and alert status through the Wi-Fi network.
4. Displays the updated information at the central monitoring station.

This rapid alert mechanism enables supervisors to respond immediately and minimize the possibility of accidents.

2.6 Wireless Communication

The ESP32 utilizes its integrated IEEE 802.11 b/g/n Wi-Fi module to establish communication with the local wireless network. The processed sensor data are transmitted continuously to the monitoring dashboard, allowing real-time observation of worker health and environmental conditions without manual intervention.

2.7 Experimental Evaluation

The developed prototype was tested under both **normal** and **simulated hazardous** conditions. Various environmental and physiological parameters were intentionally varied to evaluate system performance. The following scenarios were examined:

- Normal environmental conditions.
- Increased hazardous gas concentration.
- Elevated body temperature.
- Abnormal heart rate.
- Simulated worker fatigue using prolonged eye closure.

The performance of the system was evaluated based on detection accuracy, response time, communication reliability, and successful generation of real-time alerts. The experimental results confirmed that the proposed system effectively detects hazardous situations and provides timely notifications, demonstrating its suitability for enhancing worker safety in mining environments.

III.RESULT

The proposed Smart Mining Helmet with Health and Safety Monitoring using ESP32 and IoT was successfully designed, implemented, and experimentally evaluated under both normal and simulated hazardous mining conditions. The system continuously monitored environmental and physiological parameters, including hazardous gas concentration, body temperature, heart rate, and worker fatigue, while transmitting real-time data through Wi-Fi to the monitoring station.

During normal operating conditions, all sensor readings remained within predefined safety thresholds, and the system continuously displayed live sensor values without generating alerts. When hazardous situations were simulated, such as increased gas concentration, elevated body temperature, abnormal heart rate, and prolonged eye closure, the ESP32 accurately detected these abnormal conditions and immediately activated the buzzer while transmitting warning notifications to the monitoring dashboard. The wireless communication remained stable throughout the testing process, enabling continuous remote monitoring with minimal delay.

The experimental observations demonstrated that the proposed system effectively integrates environmental monitoring and worker health monitoring into a single wearable safety device. Compared with conventional mining safety systems, the developed helmet provides real-time monitoring, rapid emergency alert generation, and wireless communication, thereby improving worker safety and reducing response time during emergencies.

Scenario	Gas (ppm)	Temperature (°C)	Heart Rate (BPM)	Eye Status	System Status
Normal	180	36.5	75	Open	Safe
Gas Leakage	520	36.8	78	Open	Gas Alert
High Temperature	210	39.4	82	Open	Temperature Alert
Abnormal Heart Rate	190	36.7	128	Open	Health Alert
Worker Fatigue	185	36.6	76	Closed (>8 s)	Fatigue Alert

Table 1. Experimental Results of the Proposed System

Feature	Existing Systems	Proposed System
Hazardous Gas Detection	✓	✓
Temperature Monitoring	✗	✓
Heart Rate Monitoring	✗	✓
Fatigue Detection	✗	✓
Real-Time IoT Monitoring	Limited	✓
Wireless Alert System	Partial	✓

Table 2. Comparison with Existing Systems

Overall, the experimental results indicate that the proposed IoT-enabled smart mining helmet provides reliable environmental and physiological monitoring with rapid emergency response capabilities. The integration of multiple sensors with ESP32 and wireless communication significantly enhances worker safety and offers a practical, low-cost solution for deployment in mining and other hazardous industrial environments.

IV. DISCUSSION

The experimental results demonstrate that the proposed **IoT-enabled Smart Mining Helmet with Health and Safety Monitoring** provides an effective solution for enhancing worker safety in hazardous mining environments. By integrating environmental monitoring and physiological health monitoring into a single wearable device, the system addresses several limitations associated with conventional mining safety systems, which typically focus on only one safety parameter.

The ESP32 microcontroller successfully acquired and processed real-time data from the MQ135 gas sensor, temperature sensor, pulse sensor, and IR eye-blink sensor. The collected sensor values were continuously compared with predefined safety thresholds, enabling rapid identification of hazardous conditions. Whenever abnormal gas concentration, elevated body temperature, irregular heart rate, or prolonged eye closure was detected, the system immediately generated audible alarms and transmitted alert notifications through the Wi-Fi network. This rapid response capability can significantly reduce emergency response time and improve the overall safety of mining personnel.

Compared with existing mining safety solutions, the proposed system offers several important advantages. It integrates multiple sensing modules into a compact wearable helmet, enabling simultaneous monitoring of both environmental hazards and worker health. The built-in Wi-Fi communication of the ESP32 supports continuous remote monitoring without requiring additional communication hardware, making the system cost-effective, compact, and easy to deploy. The experimental evaluation confirmed that the prototype operated reliably under both normal and simulated hazardous conditions while maintaining stable wireless communication and accurate sensor monitoring.

Despite these advantages, the proposed system has certain limitations. The current implementation depends on Wi-Fi connectivity, which may be limited in deep underground mining environments. In addition, sensor performance can be influenced by environmental conditions such as humidity, dust, and long-term usage, requiring periodic calibration to maintain measurement accuracy. Battery life also limits the duration of continuous operation and must be considered for practical deployment.

Future improvements may include integrating **LoRa**, **GSM**, or **5G** communication for wider coverage in underground mines, implementing **GPS** or indoor localization for worker tracking, and incorporating **Artificial Intelligence (AI)** or **Machine Learning (ML)** techniques to predict hazardous situations before they occur. Cloud-based data storage and mobile applications can further enhance remote monitoring, historical data analysis, and emergency management.

Overall, the proposed smart mining helmet demonstrates that combining IoT technology, embedded systems, and multi-sensor monitoring provides a reliable, scalable, and cost-effective approach to improving occupational safety. The system has strong potential for deployment not only in mining industries but also in construction sites, oil and gas facilities, chemical plants, and other hazardous industrial environments where continuous worker monitoring is essential.

V.CONCLUSION

This paper presented an **IoT-enabled Smart** Mining Helmet with Health and Safety Monitoring designed to improve the safety of workers operating in hazardous mining environments. The proposed system integrates an ESP32 microcontroller with multiple sensors for monitoring hazardous gas concentration, body temperature, heart rate, and worker fatigue in real time. The collected sesnsor data are processed locally and transmitted wirelessly through Wi-Fi to a centralized monitoring system, enabling continuous supervision and rapid emergency response.

Experimental evaluation demonstrated that the developed prototype successfully detected abnormal environmental and physiological conditions and generated immediate alerts through both an onboard buzzer and wireless notifications. The system effectively combined environmental monitoring, health monitoring, and real-time communication into a compact, wearable device, providing a more comprehensive safety solution than conventional mining safety systems. Its low-cost architecture, reliable operation, and ease of implementation make it suitable for deployment in mining industries as well as other hazardous workplaces such as construction sites, oil and gas facilities, and chemical plants.

Although the current implementation depends on Wi-Fi connectivity and requires periodic sensor calibration, the overall performance confirms the feasibility and effectiveness of the proposed approach for enhancing occupational safety. Future work will focus on integrating cloud-based monitoring, AI-based hazard prediction, GPS-enabled worker localization, and alternative long-range communication technologies such as LoRa or GSM to further improve system reliability and scalability.

In conclusion, the proposed smart mining helmet demonstrates that the integration of IoT, embedded systems, and real-time multi-sensor monitoring can significantly improve worker safety, reduce accident risks, and support the development of intelligent industrial safety systems.

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