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Intellihat: "Smart Headgear for Real-Time Hazard Detection" A Systematic Review

Mithun M Biju[1], Amal Krishnan S[2], Abhishek M S[3], Aadhil Mohammed M R[4], Neethu Susan Alex[5]

[1,2,3,4]B.Tech, Department of Electronics and Communication Engineering, Dr. APJ Abdul Kalam Technological University Kerala, India
[5]Asst Professor, Department of Electronics and Communication Engineering, Dr. APJ Abdul Kalam Technological University Kerala, India

ABSTRACT

Coal mining is one of the most hazardous activities in the world. They frequently encountered unexpected emergencies. The use of the Internet of Things (IoT) and artificial intelligence (AI) in mining helps improve worker health management and prevent injuries. In this study, a personal protective equipment (helmet) is proposed, which can provide alert signals to the control center to inform the miner about the risk. With the use of several sensors integrated into the STM32 module, it continuously analyzes ambient conditions (toxic gases, temperature, and humidity), as well as the worker's health conditions, such as heart rate and vibration generated by excavation and blasting, which are subsequently relayed to the control center using a low- energy Bluetooth module. This system also has a panic button that may alert the control unit if there are any dangers to the workers. The DHT11 (digital temperature humidity sensor) can measure the temperature and humidity levels with a degree of accuracy that falls within a range of ±5%. The MQ135 sensor, on the other hand, can sense gas concentrations with 85% accuracy. In coal mines, high gas concentrations can cause miners to feel dizzy and disoriented. To address this issue, miners can press a panic button located on their helmets, which alerts the control center staff and speeds up rescue operations. In addition, a heart rate sensor was integrated with the STM module using the inter integrated circuits (I2C) protocol. If the heart rate reading falls below 60 or exceeds 100, it is considered an abnormal condition that requires attention. Furthermore, a machine learning algorithm with a convolutional neural network helps to train the artificial intelligence model to recognize the worker's gestures. Here, four types of gestures were fixed, which helped the workers communicate. These gestures have been labeled GOOD, NOT GOOD, DOING FINE, and EMERGENCY EVACUATION. A receiver air position indicator (API) is proposed to visualize the results from various sensors and take appropriate action to safeguard miners.

Keywords: IoT-Based Monitoring, Artificial Intelligence (AI), Toxic Gas Detection, Gesture Recognition, Worker Safety

INTRODUCTION

Mining plays a crucial role in sustaining global industries by supplying raw materials used in power generation, construction, electronics, and large-scale manufacturing. Despite its importance, it remains one of the most hazardous occupations worldwide. Workers often operate deep underground or in remote locations where they face harsh and unpredictable environmental conditions. Toxic gases, high temperatures, excessive humidity, dust, and limited ventilation create a constant threat to their health and safety. In addition, the structural instability of mines increases the risk of sudden roof collapses, fires, equipment failures, and gas explosions. These dangers highlight the urgent need for advanced safety mechanisms that go beyond traditional protective gear.

Conventional personal protective equipment (PPE) such as helmets, boots, gloves, and lamps provide only basic physical protection. While essential, they cannot detect invisible hazards like gas leaks, poor air quality, elevated body stress, or early signs of worker fatigue. As mining environments become deeper and more complex, relying solely on manual monitoring or periodic inspections is no longer effective. This gap in safety monitoring has encouraged the adoption of emerging technologies capable of providing smart, automated, and continuous surveillance of the working environment.

To address these limitations, the integration of the Internet of Things (IoT) and Artificial Intelligence (AI) has paved the way for intelligent safety solutions. One such innovation is the AI-Based Safety Helmet for Mining Workers, designed to act as an advanced personal monitoring device. The helmet incorporates an array of environmental and physiological sensors that measure temperature, humidity, toxic gas concentration, heart rate, movement, and overall worker activity.

This real-time data collection allows the system to detect abnormalities or dangerous trends long before they reach critical levels.

At the core of the device is an ARM Cortex-M microcontroller, which ensures low-power, high-efficiency data processing suitable for long working shifts. The collected sensor data is transmitted wirelessly to a centralized monitoring unit using Bluetooth communication, enabling supervisors to track worker safety instantly. If any parameter exceeds safe thresholds, the system triggers immediate alerts to both the worker and the control room, allowing quick decision-making and timely evacuation when necessary.

METHODOLOGY

The development of an AI-based smart helmet presents a significant advancement in enhancing the safety and well-being of mining workers operating in hazardous underground environments. By integrating multiple IoT sensors—including temperature, humidity, gas detection, heart rate monitoring, and motion sensing—the system offers a comprehensive and continuous assessment of both environmental and physiological parameters. This real-time monitoring capability addresses critical gaps in traditional safety equipment, which often fails to detect invisible risks or provide timely alerts.

Furthermore, the incorporation of wireless communication and AI-driven gesture recognition improves the reliability and responsiveness of emergency communication between miners and control personnel. The use of Bluetooth Low Energy ensures efficient data transmission, while the CNN-based gesture recognition module enables miners to convey essential signals even in situations where visibility or verbal communication is compromised. This combination of smart sensing and intelligent interaction significantly enhances situational awareness and supports faster, more informed decision-making during emergencies.

Overall, the proposed smart helmet represents a powerful fusion of IoT, AI, and wearable technology, offering a practical and scalable solution for modernizing mining safety practices. With additional improvements— such as cloud integration, long-range communication, and predictive analytics—the system has the potential to evolve into a fully automated safety ecosystem. Ultimately, this work contributes to reducing accident rates, improving hea The gesture recognition unit incorporates a compact camera module positioned at the front of the helmet to capture hand gestures in real time. Using Micro Python and Tensor Flow Lite Micro, the camera feed is processed frame-by-frame to extract hand landmarks using MediaPipe's pretrained gesture detection model. The extracted features are then passed into a convolutional neural network trained on a dataset of predefined gestures—GOOD, NOT GOOD, DOING FINE, and EMERGENCY EVACUATION. The CNN classifies the gesture based on hand pose and landmark similarity, and the corresponding output label is sent to the control unit. This lightweight AI model is optimized to run efficiently on microcontroller-class hardware, enabling fast inference with minimal power consumptionlth outcomes, and creating safer working conditions for miners across the industry.

To validate system performance, extensive testing was conducted under controlled indoor conditions simulating underground mining environments. Temperature and humidity sensors were tested by exposing the helmet to varying climatic conditions, while gas detection accuracy was evaluated using calibrated sources of CO_2, NH_3, and SO_2. The heart rate sensor was validated using human volunteers under different physical activities. Vibration sensing was tested using mechanical equipment capable of generating controlled oscillations. For gesture recognition, multiple subjects performed the four predefined gestures in various lighting and background conditions, ensuring model robustness. The consistency and responsiveness of Bluetooth communication were assessed over different distances and obstacles. Test results confirmed that the smart helmet provides reliable, accurate, and fast monitoring suitable for mining applications.

COMPARITIVE ANALYSIS

Existing research on mining safety systems has predominantly focused on monitoring specific environmental parameters such as temperature, humidity, and toxic gases using IoT or wireless sensor networks. While these systems provide essential information about hazardous underground conditions, they often lack integration with physiological monitoring of the worker, such as heart rate or motion-based stress indicators. In contrast, the proposed AI-based smart helmet introduces a more comprehensive approach by combining both environmental and human-centric sensing. This dual-layer monitoring enhances overall situational awareness, allowing early detection of risks that earlier systems—limited to single-parameter sensing—were unable to capture effectively.

Communication and interaction mechanisms also show significant differences across existing works. Many prior systems rely on traditional wired communication or low-speed wireless protocols, which are prone to failure in deep tunnels due to interference and structural complexity. Furthermore, earlier designs do not incorporate intuitive emergency communication features. The proposed system addresses these limitations through a low-energy Bluetooth module that ensures more reliable real-time data transmission and by integrating AI-driven gesture recognition, enabling miners to communicate quickly and effectively even in low-visibility or noisy conditions. This represents a major improvement over earlier approaches that lacked interactive or fail-safe communication methods.

From a usability and technological standpoint, previous smart helmet prototypes often remained confined to lab simulations, used bulky hardware, or required high processing power, limiting their feasibility in harsh underground environments. The proposed system overcomes these constraints by utilizing efficient ARM Cortex-M microcontrollers, Tiny ML-based gesture recognition, and lightweight hardware integration, ensuring greater portability, comfort, and energy efficiency. Compared to earlier solutions that focused mainly on environmental monitoring or lighting improvements, the AI-based smart helmet offers a more advanced, practical, and user-friendly platform. Its integration of multi-sensor data, real-time alerts, ergonomic design, and intelligent features positions it as a more effective and holistic safety system for modern mining operations.

RESEARCH GAP

Although numerous studies have explored IoT-based monitoring in underground mines, most existing systems focus on either environmental parameters such as toxic gases, temperature, and humidity, or on physiological conditions like heart rate and motion. Very few works combine both aspects into a single, integrated platform capable of providing a complete assessment of miner safety. Additionally, many proposed systems remain limited to simulations or conceptual frameworks without real-time deployment.

This creates a gap in achieving reliable, continuous, and holistic safety monitoring that can operate effectively in harsh underground environments.

Another significant gap lies in communication and emergency response mechanisms. Earlier systems relied on wired connections or low-bandwidth wireless networks, which are highly unreliable in deep mining tunnels due to interference, obstacles, and dynamic structural changes. Moreover, most existing research lacks intuitive emergency communication tools such as gesture recognition. In extreme conditions where sound, light, or mobility is restricted, miners need alternative ways to convey distress signals—but current solutions do not adequately support such real-time, hands-free interaction on low-power wearable devices. Wearability and practical implementation also remain major shortcomings in previous works. Many prototypes use bulky sensors, high-power processors, or complex setups unsuitable for long working hours in confined spaces. There is a notable gap in developing lightweight, ergonomic, and low-power smart helmets that miners can comfortably use without affecting mobility or adding to heat stress. Furthermore, existing AI-based systems often require high computational resources and are not optimized for microcontrollers, limiting their deployment on portable mining gear.

Finally, there is a lack of advanced data fusion, long-range communication, and centralized data analytics in prior studies. Most systems treat sensor readings independently and do not utilize AI to analyze combined patterns that could predict hazardous conditions before they become critical. Similarly, cloud integration and long-distance communication technologies like LoRa WAN are rarely implemented, restricting large-scale monitoring and historical analysis. These limitations highlight the need for a comprehensive, AI-assisted, IoT-enabled smart helmet capable of real-time sensing, processing, alerting, and communication in extreme industrial environments.

CONCLUSION

The development of an AI-based smart helmet for mining workers presents a significant advancement in ensuring safety within one of the world's most hazardous work environments. By integrating multiple sensors capable of monitoring temperature, humidity, toxic gases, vibration levels, and heart rate, the system offers a comprehensive and continuous assessment of both environmental and physiological conditions. This real-time monitoring fills a critical gap left by traditional protective equipment, enabling early detection of unsafe situations and reducing the likelihood of unnoticed risks. The incorporation of wireless communication and AI-driven gesture recognition further enhances the responsiveness and usability of the system. Through Bluetooth-based data transmission and machine learning algorithms deployed on microcontroller platforms, the smart helmet facilitates instant alerts and intuitive emergency communication between miners and the control room. This combination of IoT sensing and AI- based interaction provides a reliable mechanism for swift decision-making, which is essential for timely rescue operations and preventing escalation of hazardous incidents underground.

Overall, the proposed smart helmet demonstrates the potential of integrating IoT and AI technologies to significantly improve health and safety standards in underground mining. Its lightweight, ergonomic design ensures practicality for daily use, while its intelligent monitoring capabilities contribute to a safer, more efficient mining environment. With further enhancements such as cloud integration, long-range communication, and advanced predictive analytics, this system can evolve into a robust, industry-wide safety solution that protects workers and supports modern digital mining operations.

FUTURE SCOPE

The proposed smart helmet system can be further enhanced by integrating advanced long-range communication technologies such as LoRa WAN, 5G, or mesh networking to extend coverage deep into underground tunnels. This would enable centralized monitoring across multiple mining zones and improve data reliability even in complex geological structures. Additionally, cloud integration can allow long-term storage, analytics, and trend visualization, helping mine operators identify recurring hazards and implement preventive strategies based on historical data.

In terms of intelligence and automation, the system can benefit from more sophisticated AI models capable of predicting hazardous conditions before they occur. Machine learning algorithms could analyze combined sensor patterns to detect early signs of gas build-up, structural weaknesses, or worker fatigue. Future versions of the helmet could also incorporate thermal imaging, respiratory monitoring, GPS alternatives for underground tracking, and fall detection algorithms, creating an even more comprehensive safety ecosystem.

To improve usability and adaptability, the smart helmet can be further optimized for comfort, power efficiency, and modularity. Solar-assisted charging, ultra-low-power processors, and replaceable sensor modules can help extend battery life and reduce maintenance costs. The system could also be expanded for use in other hazardous industries such as construction, firefighting, oil and gas, and chemical plants. With continued advancements, the smart helmet has the potential to evolve into a complete wearable safety platform, supporting predictive maintenance, automated rescue coordination, and industry-wide digital safety transformation.

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