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Smart Helmet Using Non – Newtonian Fluid for Enhanced Impact Protection and Safety Monitoring

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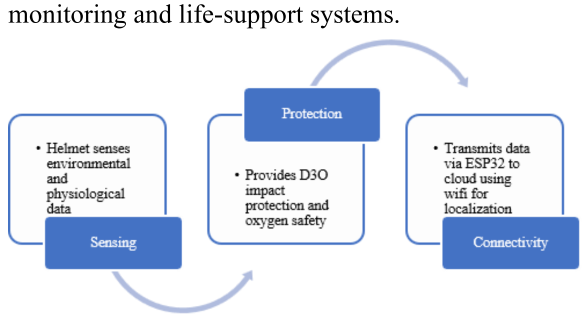
***Abstract*—Underground mining environments expose workers to serious hazards such as falling objects, toxic gases, extreme temperatures, and oxygen deficiency. This project introduces a Smart Helmet designed to enhance laborer safety by combining advanced protective materials with intelligent monitoring systems. A layer of oobleck (non-Newtonian fluid) is embedded within the helmet, providing superior impact resistance by remaining flexible under normal conditions and hardening instantly on sudden impact. To improve situational awareness, the helmet integrates a GPS module for real-time worker tracking, enabling faster emergency response. It is also equipped with toxic gas sensors to detect harmful gases such as carbon monoxide and methane, along with a temperature sensor to monitor unsafe environmental conditions underground. Additionally, the helmet incorporates an oxygen cylinder with an integrated mask, ensuring breathable air supply during emergencies such as gas leaks, fire, or oxygen-deprived situations. This feature offers vital respiratory support in critical conditions. By merging physical protection, environmental sensing, and life-support capabilities into one device, the proposed smart helmet provides a comprehensive safety solution for underground laborers.**

***Index Terms*—Underground mining safety, Oobleck, Digital and mechanical safety**

I. INTRODUCTION

The combination of physical risks, environmental perils, and unexpected underground conditions has long made mining one of the most dangerous occupations. Inhaling harmful gasses like methane, carbon monoxide, and hydrogen sulfide, as well as falling rocks, crashes, and heat stress, are all constant hazards for workers in the mining industry. Frequently, these hazards lead to long-term health issues, injuries, or fatalities. The whole range of risks that miners face cannot be adequately addressed by traditional helmets and protective gear, even though they offer a certain degree of safety.The incorporation of smart technologies into personal protection equipment has drawn a lot of interest in response to these issues. In addition to providing physical protection, a smart helmet integrates cutting-edge monitoring technologies to protect miners in real time. The goal of the proposed project is to create a smart helmet with a combination of digital and mechanical safety measures. The helmet's coating of oobleck, or non-Newtonian fluid, reduces the chance of head injuries by acting as a shock-absorbing substance that can solidify in the event of a violent contact. The incorporation of smart technologies into personal protection equipment has drawn a lot of interest in response to these issues. In addition to providing physical protection, a smart helmet integrates cutting-edge monitoring technologies to protect miners in real time. The goal of the proposed project is to create a smart helmet with a combination of digital and mechanical safety measures. The suggested smart helmet is a complete safety solution designed to meet the demands of mining workers thanks to the combination of these elements. The project's goal is to reduce occupational risks, stop accidents, and raise overall safety standards in the mining sector by combining cutting-edge materials with sensor-based monitoring and life-support systems.



II. LITERATURE REVIEW

The evolution of head protection in hazardous work environments has transitioned from basic mechanical barriers to highly integrated, sensor-enabled smart systems that enhance worker safety through impact mitigation, environmental monitoring, communication, and life-support functions. Traditional mining helmets primarily relied on rigid outer shells and crushable foam liners to absorb the energy of falling objects and blunt impacts.

However, modern research highlights that underground mining environments expose workers to a combination of mechanical impacts, toxic gases, heat stress, and potential entrapment, necessitating a new generation of helmets that integrate physical protection with sensing and communication technologies. The concept of the helmet has thus shifted from being a passive personal protective device to an intelligent, human-mounted safety platform capable of detecting hazardous conditions, supporting evacuation, and connecting to respiratory and localization systems.

A major material innovation driving this evolution is the use of shear-thickening fluids (STFs), which are non-Newtonian colloidal suspensions that remain flexible during normal motion but stiffen instantly under high shear or impact. These fluids, commonly composed of silica nanoparticles dispersed in polyethylene glycol or other polymeric carriers, offer a unique combination of comfort and protection. When impregnated into textile liners or encapsulated between the helmet shell and foam layers, STFs significantly reduce impact acceleration and improve resistance to both linear and rotational forces. Studies demonstrate that STF-treated liners outperform conventional expanded polystyrene (EPS) foams in multi-impact scenarios by enhancing energy dissipation and maintaining protective capacity across repeated strikes.

However, environmental factors such as humidity, temperature variation, and long-term stability affect STF performance. To overcome these limitations, researchers are developing encapsulated and hydrophobic formulations, hybrid structures combining STFs with 3D-printed lattice cores, and slip-plane layers that minimize rotational acceleration transferred to the head.

III. PROPOSED PLANNING AND ARCHITECTURE

The planning and architecture of the proposed smart helmet system are designed to enhance the safety and health monitoring of underground workers by integrating advanced protective materials, embedded electronics, and IoT technology. The helmet incorporates a shear thickening fluid layer, a subclass of non-Newtonian fluid, within its inner lining to provide superior impact resistance by remaining flexible during normal use and instantly stiffening under sudden impact.

The system is planned with multiple functional modules, including health and environmental sensors, a processing unit, communication interfaces, and an emergency oxygen support mechanism. An ESP32 microcontroller acts as the central control unit, collecting data from sensors such as heart rate, SpO_2, temperature, and gas sensors, and processing this information efficiently with low power consumption. For location tracking, the system uses RSSI-based indoor navigation along with GPS for outdoor positioning, ensuring continuous worker tracking even in underground environments where GPS signals are weak. The collected data is transmitted wirelessly via Wi-Fi or Bluetooth to a cloud platform, where it is stored, analyzed, and displayed on a monitoring dashboard for supervisors. In emergency conditions such as hazardous gas detection or abnormal health parameters, alerts are generated and the oxygen cylinder with mask provides immediate respiratory support.

This well-planned, modular architecture ensures reliability, scalability, real-time monitoring, and improved safety for underground working labourers.

IV. MATERIALS AND SOFTWARE USED

The smart helmet system is designed to improve the safety of underground workers by integrating advanced protective materials, embedded electronics, and real-time monitoring technologies into a single wearable unit. The helmet structure consists of a high-impact-resistant outer shell made of ABS or polycarbonate material, which serves as the first line of defense against falling objects and mechanical shocks. Inside the shell, an expanded polystyrene (EPS) foam liner absorbs impact energy by controlled compression, thereby reducing the force transmitted to the wearer's head. An additional layer of shear-thickening fluid material, such as D3O, is incorporated to provide adaptive protection; this non-Newtonian fluid remains soft and flexible during normal conditions but instantly hardens upon sudden impact, effectively dissipating kinetic energy and minimizing head injuries. Comfortable padding and adjustable straps ensure proper fit, stability, and long-duration wearability. The electronic and sensing architecture of the helmet enables continuous monitoring of both the worker's health and the surrounding environment. An ESP32 microcontroller acts as the central processing and communication unit, collecting data from various sensors including a pulse oximeter for heart rate and blood oxygen (SpO_2) measurement, gas sensors for detecting oxygen deficiency and toxic gases, an IMU sensor for fall and impact detection, and temperature and humidity sensors to assess environmental comfort. Outdoor location tracking is achieved using a GPS module, while indoor positioning in underground environments is performed using RSSI-based techniques, where signal strength from wireless nodes is analyzed to estimate the worker's location.

The processed data is transmitted wirelessly through Wi-Fi or Bluetooth to a cloud platform, where it is stored, analyzed, and visualized on monitoring dashboards for supervisors. To address emergency situations, the smart helmet includes an integrated oxygen support system consisting of a portable oxygen cylinder, pressure regulator, and a comfortable breathing mask. This system ensures an immediate supply of oxygen during hazardous conditions such as toxic gas leakage or low-oxygen environments.

Visual and audible alerts using LEDs and buzzers notify the worker of abnormal health or environmental parameters, while emergency alerts are simultaneously sent to the cloud for rapid response. A rechargeable battery with proper voltage regulation powers all electronic components, ensuring reliable and safe operation. Overall, the planned architecture of the smart helmet is modular, scalable, and robust, combining mechanical protection, intelligent sensing, indoor and outdoor location tracking, cloud connectivity, and emergency respiratory support to significantly enhance the safety and efficiency of underground working labourers.

V. METHODOLOGIES

The development of the smart helmet for underground workers follows a systematic methodology to ensure safety, monitoring, and operational efficiency. The first step involves selecting appropriate materials for protection and comfort. The helmet's outer shell is constructed from durable ABS or polycarbonate, providing impact resistance, electrical insulation, and long-term durability. Inside, an Expanded Polystyrene (EPS) foam liner cushions impacts, while a shear-thickening fluid (D3O) layer absorbs and disperses high-energy forces during sudden impacts, enhancing head protection without compromising comfort or mobility. The helmet design accommodates the integration of electronic components, oxygen supply, and user ergonomics.

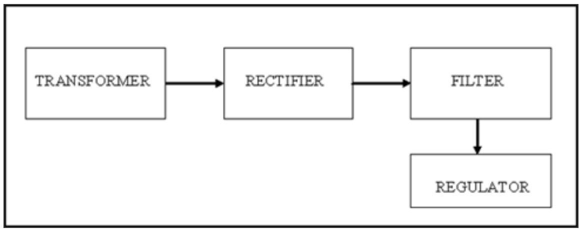
The next step is electronics integration. The ESP32 microcontroller acts as the central processing unit, interfacing with various sensors such as IMU for motion and fall detection, gas sensors for O_2, CO, and CO_2 levels, pulse oximeter for heart rate and SpO_2, and temperature and humidity sensors. A mini oxygen cylinder and face mask provide life-support in low-oxygen or hazardous conditions. All electronic components are mounted securely, with waterproof enclosures, insulated wiring, and proper ventilation to maintain durability and reliability.

Data acquisition and processing form the next phase. Sensor outputs are collected by the ESP32, filtered to remove noise, calibrated for accuracy, and structured with timestamps and location information. This data is transmitted wirelessly via Wi-Fi or MQTT protocols to cloud platforms like Thing Speak for real-time monitoring, visualization, and analysis. The system enables supervisors to track worker location, environmental conditions, and physiological parameters, with automated alerts triggered if readings exceed predefined safety thresholds.

Finally, the helmet undergoes rigorous testing and validation. Impact tests verify the D3O layer's performance, oxygen flow is checked for reliability, and all sensors are calibrated for precise measurements. Indoor positioning is validated for accuracy, and full system integration ensures that mechanical, electronic, and life-support components work seamlessly. This methodology ensures that the smart helmet delivers comprehensive protection, environmental monitoring, and health tracking for underground workers in demanding and hazardous environments.

VI. DATA PREPARATION

1. Data Acquisition and Preprocessing



This stage involves continuous collection of raw data from all sensors integrated into the smart helmet, including gas sensors (O_2, CO, CO_2), temperature and humidity sensors, pulse oximeter sensors for heart rate and SpO_2, respiration sensors, IMU sensors for motion and impact detection, and RSSI or GPS modules for location tracking. Since the raw data may contain noise due to environmental interference, vibrations, or worker movement, initial preprocessing is carried out. Signal conditioning and filtering techniques such as averaging, smoothing, and threshold-based filtering are applied within the ESP32 microcontroller to reduce noise and stabilize sensor outputs. This ensures that only meaningful and usable data proceeds to the next stage.

2. Calibration, Validation, and Data Structuring

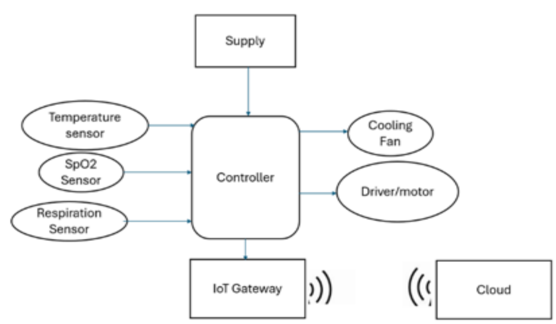
After preprocessing, the sensor data undergoes calibration to align measured values with real-world reference standards, compensating for sensor drift, aging, and environmental variations. Validation checks are performed to identify missing, invalid, or out-of-range values, which are discarded or flagged to prevent false alarms. The validated data is then processed and structured into a standardized format. Each data packet includes sensor identification, measured values, timestamps, and location information derived from RSSI-based indoor positioning or GPS. This structured format ensures consistency, efficient storage, and seamless transmission to cloud platforms.

3. Local Storage and Wireless Transmission

The processed and structured data is temporarily stored in local memory or on a microSD card integrated into the helmet system. This local storage acts as a backup, ensuring that no critical data is lost during network interruptions or connectivity failures common in underground environments. Simultaneously, the data is transmitted wirelessly to the cloud server using the ESP32's Wi-Fi capability and communication protocols such as MQTT or HTTP. This enables real-time monitoring of worker health, environmental conditions, and location while maintaining system reliability and energy efficiency.

4. Cloud Processing, Visualization, and Alerts

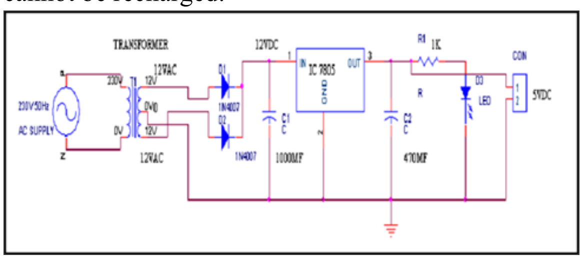
Once the data is received by the cloud server, it is securely stored and processed using IoT platforms such as Firebase or AWS IoT. These platforms provide reliable data management, scalability, and secure access control. Real-time dashboards present sensor readings, trends, and worker location information in the form of graphs and charts, allowing easy interpretation and continuous monitoring. Analytical tools continuously evaluate incoming data to identify abnormal patterns related to worker health, environmental conditions, or safety risks. When any parameter exceeds predefined safety limits, the system automatically generates alerts and notifications, enabling supervisors and safety personnel to respond quickly and take appropriate emergency actions.



5. Single Power Supply

Power supply gives supply to all components. It is used to convert AC voltage into DC voltage. Transformer used to convert 230V into 12V AC.12V

AC is given to diode. Diode range is 1N4007, which is used to convert AC voltage into DC voltage. AC capacitor used to charge AC components and discharge on ground. LM 7805 regulator is used to maintain voltage as constant. Then signal will be given to next capacitor, which is used to filter unwanted AC component. Load will be LED and resister. LED voltage is 1.75V. if voltage is above level beyond the limit, and then it will be dropped on resister. Most electronic circuits require DC voltage sources or power supplies. If the electronic device is to be portable, then one or more batteries are usually needed to provide the DC voltage required by electronic circuits. But batteries have a limited life span and cannot be recharged.



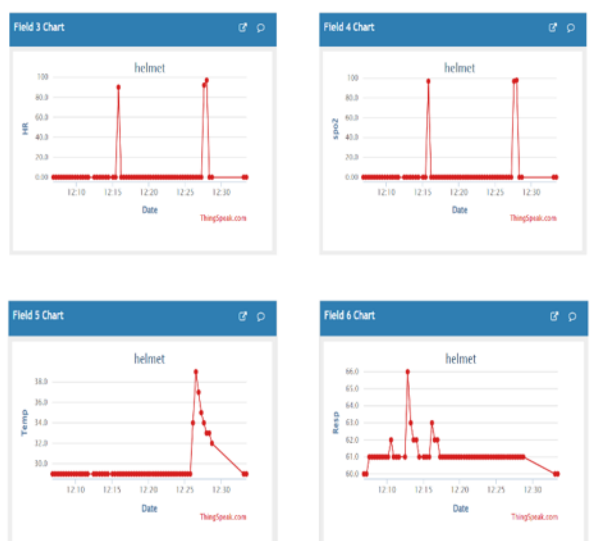
6.Importing Data into MATLAB visualizations

To visualize ThingSpeak data in MATLAB, you first need to install the ThingSpeak Support Toolbox, which allows MATLAB to communicate directly with your ThingSpeak channels. Each channel has a unique Channel ID and Read API Key, which are used to securely fetch the sensor data. Once connected, MATLAB can read data from specific fields corresponding to each sensor, such as temperature, heart rate, SpO_2, respiration rate, or gas levels. Using the thingSpeakRead function, you can retrieve the latest data points or historical readings. After importing the data, MATLAB's plotting functions enable the creation of detailed graphs and charts, with options for time-series visualization, legends, axis labels, and multiple sensor overlays.

For real-time monitoring, loops can be set up to continuously update the plots, effectively creating a live dashboard. This setup allows advanced analysis, threshold-based alerts, trend evaluation, and comprehensive monitoring of environmental and physiological parameters collected by the smart helmet, providing a flexible and powerful platform for both real-time and historical data visualization.

VII. RESULTS AND ANALYSIS

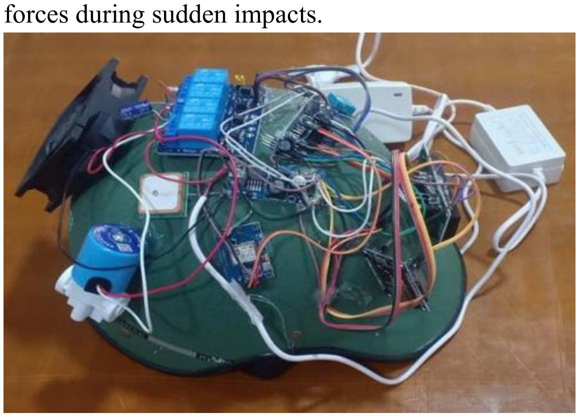
The smart helmet prototype was tested for multiple parameters to evaluate its performance, safety, and reliability in simulated underground conditions. Environmental Monitoring was assessed by exposing the sensors to varying gas concentrations, oxygen levels, temperature, and humidity. Gas sensors accurately detected O_2, CO, and CO_2 levels, triggering alerts when concentrations exceeded safety thresholds. Temperature and humidity sensors provided stable readings under dynamic conditions, enabling early identification of potentially hazardous environments. The pulse oximeter and heart rate sensors monitored simulated worker physiological parameters and displayed consistent, real-time readings on ThingSpeak dashboards.



Indoor Positioning and Tracking were evaluated using Wi-Fi-based localization. The ESP32 microcontroller accurately calculated worker location within confined spaces using Wi-Fi beacons, with minimal deviation from expected positions. Real-time visualization of location data on the cloud enabled supervisors to monitor worker movement efficiently. Oxygen Supply System performance was also validated. The portable oxygen cylinder, regulator, and mask maintained stable oxygen delivery under low-oxygen conditions. Flow rates were consistent, and alarm systems effectively notified simulated low oxygen levels. Overall, the results indicate that the smart helmet successfully integrates impact protection, environmental monitoring, life-support, and tracking features. Analysis of collected data confirms that the system can reliably detect hazards, provide alerts, and enhance worker safety in underground conditions.

VIII. DISCUSSION AND VALIDATION

The smart helmet prototype was systematically evaluated to validate its performance in simulated underground conditions. The impact protection system, combining a high-strength ABS/polycarbonate shell, EPS foam liner, and D3O shear-thickening fluid, effectively reduced transmitted forces during sudden impacts.



The environmental monitoring system was also tested for reliability and accuracy. Gas sensors detected variations in O_2, CO, and CO_2 levels within expected ranges, triggering timely alerts when unsafe conditions were simulated. Temperature and humidity sensors provided stable readings under changing conditions, supporting proactive safety management. Continuous monitoring of heart rate, SpO_2, and respiration through the pulse oximeter confirmed the system's suitability for real-time health tracking. Validation through repeated trials ensured sensor calibration was accurate, worker positions were accurately estimated within confined areas using Wi-Fi beacons, and deviations from expected positions were minimal.

The oxygen supply system was tested for consistent flow under low-oxygen scenarios. Pressure regulators maintained steady output, and alarm thresholds responded appropriately to simulated emergencies. The system's real-time response, reliability, and integrated design ensure it can be deployed effectively in hazardous work environments, enhancing operational safety and emergency preparedness.

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