IoT-Enabled Helmet Solution for Improved Mining Worker Safety

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Abstract*: The IoT-Enabled Helmet for Mining Worker Safety project is designed to improve safety conditions for workers operating in high-risk mining areas. By incorporating real-time environmental monitoring, emergency alert systems, and location tracking capabilities into a compact wearable device, this smart helmet delivers a robust and comprehensive safety solution. The system architecture includes two ESP32 microcontrollers: one mounted inside the helmet for sensor interfacing and logic processing, and the other functioning as a fixed BLE beacon placed at a known safe location within the mining site. The helmet is equipped with critical environmental sensing tools, including the MQ135 sensor for detecting the presence of harmful gases like CO2, NH3, and benzene, and the DHT11 sensor to measure temperature and humidity levels. These readings are continuously analyzed by the onboard ESP32, which is programmed with safety thresholds to identify abnormal conditions. In the event of dangerous gas exposure or temperature spikes, the system activates an emergency alert mechanism composed of a push-button trigger, audible buzzer, and an LCD display to notify the worker immediately. For real-time tracking, the helmet estimates the worker's location by calculating distance from the BLE beacon using RSSI (Received Signal Strength Indicator) values. The ESP32's integrated Wi-Fi module is used to transmit sensor data and emergency alerts via HTTP protocol to a centralized web-based IoT dashboard, enabling remote supervision and timely intervention by safety personnel. The entire solution is designed to be low-power, cost-effective, and highly scalable, making it practical for continuous deployment in underground mining environments where worker safety is a critical concern.

Keywords - IoT, Worker Safety, ESP32, RSSI Localization, Gas Detection, Temperature Monitoring, Wearable Technology, Real-Time Alerts, Wi-Fi, Bluetooth, Helmet Safety System

I. INTRODUCTION

Mining personnel are routinely exposed to hazardous working conditions, including toxic gases, elevated temperatures, and risks of cave-ins. To address these challenges, this project presents a smart helmet powered by IoT that performs continuous environmental surveillance and assists during emergencies by issuing alerts and enabling proximity tracking. The helmet integrates multiple sensors such as MQ135 for gas detection and DHT11 for monitoring temperature and humidity, with an onboard ESP32 microcontroller that handles data processing, threshold analysis, and communication. Proximity to danger zones is assessed using RSSI-based distance estimation from a fixed Bluetooth beacon. When unsafe conditions are detected—such as high gas concentrations or excessive heat—the system immediately activates an alert mechanism including a buzzer, LCD display, and wireless data transmission. Unlike traditional manual safety checks, this smart helmet system offers automation, real-time notifications, historical data logging, and integration with a cloud-based IoT dashboard for remote monitoring and analytics. This enables supervisors to visualize environmental trends, respond faster to incidents, and maintain digital records of workplace safety, ultimately improving both situational awareness and preventive safety protocols in mining environments.

II. BACKGROUND & RELATED WORK

Mining is among the most dangerous occupations worldwide, often involving workers facing severe environmental threats. Ensuring their safety has long been a critical issue for both industries and researchers. The advent of IoT and wearable technologies has opened new possibilities for building safety systems that mitigate the dangers miners face.

A. Worker Safety in Mining

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B. Maintaining the Integrity of the Specifications

Advancements in IoT have made it feasible to embed sensors, microcontrollers, and wireless communication modules into compact wearable devices. These innovations allow for real-time tracking of environmental conditions, automatic data logging, and quick responses to hazardous situations. Multiple studies have investigated the integration of gas sensors and the next one is , temperature/humidity detectors, and even health-monitoring components into these devices. Microcontrollers like the ATmega series, ESP32, and Arduino platforms are widely used in such systems due to their energy efficiency, built-in communication interfaces (Wi-Fi, Bluetooth), and compatibility with numerous sensor types. Nonetheless, challenges remain—especially in underground settings including short battery lifespan, inconsistent data transmission, and lack of reliable real-time location tracking.

C. Related Work and Limitations

Various smart helmets and wearable devices leveraging IoT have been developed to improve safety in mining operations. These typically incorporate gas and environmental sensors with communication technologies like Wi-Fi, Bluetooth, or GSM. However, several limitations persist:

- **High Power Consumption**: Continuous operation of sensors and communications can rapidly drain the battery, requiring frequent charging.
- **Unstable Signal Transmission**: Wireless signals, especially Wi-Fi and GSM, often face interference or attenuation in underground mines due to rock and metal obstructions.
- **Absence of Real-Time Location Tracking**: Some solutions either lack worker positioning features or depend on GPS or radio frequency modules, which are unreliable underground.
- **Integration Challenges**: Devices attempting to consolidate various sensors often result in large, unwieldy form factors, making them impractical for daily use.

This project addresses those issues by employing an RSSI-based tracking mechanism that simplifies miner localization using a lightweight and scalable approach. It uses two ESP32 modules—one inside the helmet and one acting as a fixed beacon—to monitor the worker's proximity without the need for GPS or RF modules. The system focuses on key safety indicators such as gas concentration, temperature, humidity, and distance from the beacon. Alerts are issued through a buzzer, push button, and LCD screen. All data is processed on the device and transmitted wirelessly to a central server using Wi-Fi, aligning with modern standards for digital safety systems in mining.

III. System Design

The proposed IoT-Enabled Helmet Solution is developed as a modular, low-energy, and expandable wearable device specifically suited for harsh and dynamic mining conditions. The system design follows a distributed architecture involving two ESP32 microcontrollers—one embedded in the helmet, which is responsible for acquiring real-time sensor data, executing local processing, managing alert logic, and handling wireless communication, and another configured as a stationary Bluetooth Low Energy (BLE) beacon deployed in the mining environment to facilitate proximity estimation and boundary awareness. The helmet-mounted ESP32 integrates multiple sensors including the MQ135 gas sensor for detecting hazardous gases like CO2, NH3, and volatile organic compounds, and the DHT11 sensor for monitoring ambient temperature and humidity levels. The sensor data is digitized and processed locally to check for threshold breaches indicative of unsafe environmental conditions. Simultaneously, the ESP32 continuously receives BLE signals from the fixed beacon and computes RSSI (Received Signal Strength Indicator) values to estimate the distance between the worker and the beacon. If a worker moves beyond a designated safe zone or if dangerous conditions are detected, the system triggers alerts using an onboard buzzer, LCD display, and emergency push-button. Furthermore, the helmet uses its built-in Wi-Fi capability to transmit sensor logs and emergency data to a centralized IoT dashboard over HTTP, enabling supervisors to perform remote monitoring and take timely action. The system architecture is designed to be energy-efficient for prolonged use, ruggedized for physical durability in underground environments, and modular enough to support additional sensors or connectivity options in future enhancements.

A. Hardware Components

- **ESP32 Microcontroller (Helmet Node):**
  as the primary controller. It acquires readings from sensors, checks them against preset thresholds, and manages communication modules. Its onboard Wi-Fi and Bluetooth features are employed for wireless data exchange and location estimation.

- **ESP32 Microcontroller (Beacon Node):**
  Functions as a fixed BLE signal source, typically positioned at the mine's entry point. It continuously sends Bluetooth packets, which the helmet node uses to estimate distance by measuring signal strength via RSSI.

- **MQ135 Gas Sensor:**
  Monitors air quality by detecting harmful gases such as ammonia (NH_3), benzene, smoke, and carbon dioxide (CO_2). It outputs analog signals, which are processed and compared with defined hazard thresholds.

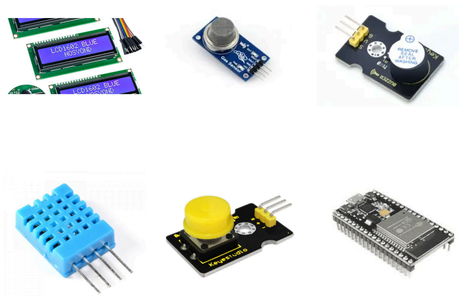
- **DHT11 Temperature and Humidity Sensor:**
  Gathers ambient temperature and humidity values. This digital sensor links directly to the ESP32 and supplies live environmental data.

- **I2C LCD Display (16x2):**
  Shows live values for gas concentration, temperature, humidity, and distance to the beacon. It offers quick visual cues to the wearer.

- **Buzzer and LED Indicators:**
  Triggered during detection of unsafe conditions. The buzzer produces sound notifications, while LEDs visually indicate warning statuses and system health.

- **Push Button (Emergency Alert):**

Allows the user to initiate an emergency signal during danger or distress. When activated, the system transmits an urgent alert to the monitoring center.



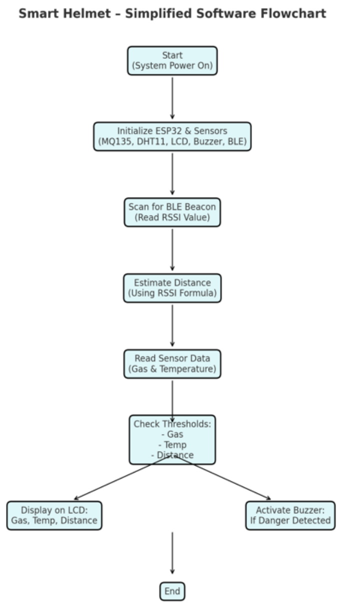
B. Architecture Overview

The system architecture is designed with a modular approach, comprising three major layers that work in synergy to ensure continuous monitoring and safety for mining personnel in hazardous environments:

1. Sensing Layer: This layer is responsible for real-time environmental data acquisition. It includes the MQ135 Gas Sensor, which detects hazardous gases like CO2, NH3, NOx, benzene, and smoke by providing analog signals that vary with concentration levels. It plays a critical role in air quality assessment. Alongside it, the DHT11 Sensor measures ambient temperature and relative humidity, helping monitor thermal conditions and ventilation quality. Both sensors are mounted within the helmet and periodically send their readings to the onboard ESP32 microcontroller via analog and digital pins. These sensor modules are chosen for their low power consumption, compact size, and compatibility with microcontrollers, making them ideal for wearable systems.

2. Processing Layer: This layer is managed by the ESP32 microcontroller integrated into the helmet. It first converts raw analog signals from the MQ135 into digital data using its internal ADC (Analog-to-Digital Converter). Noise reduction techniques, such as moving average filters, are applied to smooth data. The microcontroller then performs threshold-based analysis, comparing live data against predefined safety limits set for each gas and temperature range. Additionally, it handles proximity sensing by measuring RSSI values received from BLE beacons placed at known locations in the mine. Based on the signal strength, it calculates the estimated distance between the worker and the beacon. If the system detects that the worker is in a hazardous zone (e.g., gas concentration too high, temperature beyond safe range, or proximity beyond safe distance), it immediately flags the condition. Visual or auditory alerts may also be triggered via onboard buzzer or LEDs integrated into the helmet.

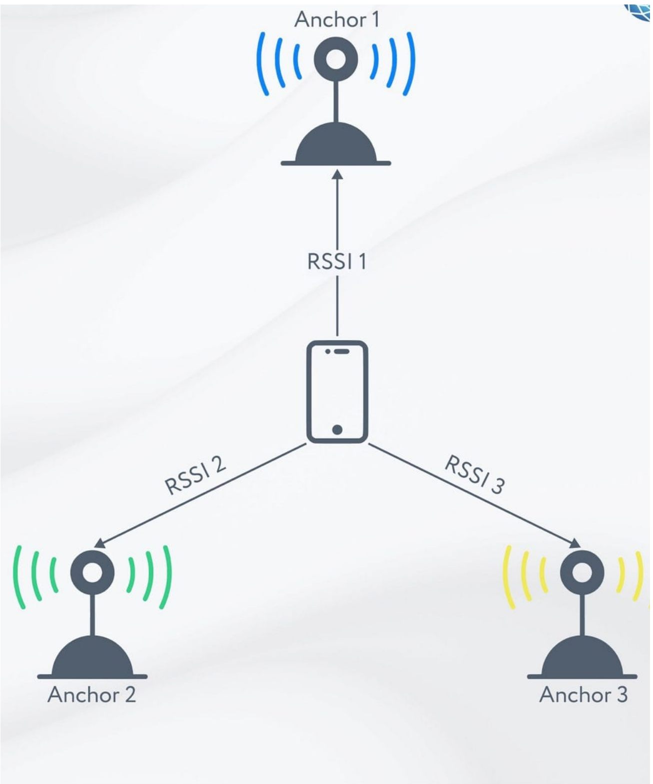
3. Communication Layer: This layer enables both local wireless interaction and long-range data transmission. Bluetooth Low Energy (BLE) ensures constant detection of nearby fixed beacons. The ESP32 evaluates real-time RSSI values to assess movement and estimate distance, helping track the worker's location relative to safety zones. Simultaneously, the onboard Wi-Fi module (integrated in ESP32) connects to a predefined wireless access point and sends collected data and triggered alerts to a central IoT platform or cloud server using HTTP POST requests. The transmitted data includes timestamped sensor readings, alert logs, and location estimates. This data can be visualized and monitored remotely via a web-based dashboard, enabling supervisors to receive instant notifications and analyze environmental conditions historically. The architecture also supports RESTful APIs for integration with safety compliance tools or reporting systems. Together, these three layers create an intelligent, responsive, and scalable safety solution that enhances situational awareness, ensures real-time hazard detection, and supports centralized monitoring and analytics in mining operations.



IV. Localization

RSSI-Based Localization: Enhancing Worker Tracking

Localization is a vital aspect in safeguarding miners, particularly in intricate and deep mining zones where standard GPS signals are ineffective due to poor satellite reception. This project leverages Bluetooth Low Energy (BLE) along with the Received Signal Strength Indicator (RSSI) method to facilitate indoor positioning and proximity awareness. The fixed beacon continuously emits BLE signals, which are detected by the ESP32 microcontroller mounted on the helmet. The ESP32 calculates the signal attenuation level, and based on the strength of the received signal (RSSI value), it estimates the distance between the worker and the beacon. The system applies a calibration-based path loss model to map RSSI values to approximate distance ranges. To enhance accuracy, RSSI readings are averaged over short time windows to reduce noise caused by reflections, obstructions, or environmental interference common in mining environments. If the estimated distance crosses a predefined safety threshold, the system immediately activates alerts via buzzer and LCD display. This proximity tracking mechanism ensures miners remain within safe operational zones and allows supervisors to remotely monitor location-related safety metrics via Wi-Fi through an integrated dashboard.



How RSSI Localization Works:

• RSSI (Received Signal Strength Indicator) evaluates the strength of signals received from a known transmitter. It is a key parameter used in proximity estimation and indoor positioning systems, especially where GPS is unreliable such as underground mining environments.

• The ESP32 microcontroller integrated in the helmet functions as a BLE receiver, constantly scanning for advertisement packets sent by a fixed ESP32 beacon positioned strategically at the mine's entry point or designated safe zones. This beacon transmits its unique ID and signal strength at regular intervals.

• As the miner moves throughout the mine, the helmet-mounted ESP32 captures these signals and uses the RSSI values to dynamically estimate the distance to the beacon. The system uses an empirical path-loss model or a calibrated look-up table to map RSSI to approximate distance.

• A stronger RSSI value (closer to 0 dBm) indicates the miner is in close proximity to the beacon, suggesting they are in a predefined safe zone.

• A weaker RSSI value (more negative, e.g., -80 dBm or lower) signifies the miner is moving farther from the beacon, possibly venturing into unauthorized or high-risk sections of the mine.

• Thresholds are defined in the software to trigger alerts if the distance exceeds a certain safety boundary, prompting visual or audible warnings to the miner and optionally notifying remote supervisors via Wi-Fi.

• This mechanism enables geofencing-like functionality without GPS, ensuring enhanced safety and real-time situational awareness in environments with limited visibility and communication infrastructure.

Importance and Benefits:

• Real-Time Worker Positioning: Utilizes Bluetooth Low Energy (BLE) signals and RSSI (Received Signal Strength Indicator) values to estimate the relative position of miners within the underground site. This GPS-independent method ensures consistent performance in environments where satellite signals are unavailable, such as deep mining tunnels. The ESP32 microcontroller interprets RSSI values from nearby fixed beacons to calculate proximity and movement patterns in real time.

• Geo-fencing: Enables the creation of virtual safety zones within the mining area by defining RSSI thresholds corresponding to specific locations. If a worker crosses the predefined range, the system immediately triggers visual and audible alerts via an onboard buzzer and LCD display while also sending notifications to the central monitoring dashboard. This helps supervisors enforce operational boundaries and prevent unauthorized access to dangerous or restricted zones.

• Emergency Management: In critical scenarios such as gas leaks, structural failures, or loss of consciousness, the system rapidly determines the miner's last known position based on beacon signals and environmental sensor data. The helmet's emergency alert mechanism activates upon detection of unsafe conditions or manual trigger (panic button), facilitating faster coordination and targeted rescue operations, thereby minimizing response time and improving survival outcomes.

• Scalability: The architecture supports seamless integration of multiple BLE beacons throughout large and complex mine layouts. With additional beacons, the system can implement triangulation techniques to improve location accuracy, track multiple workers concurrently, and expand coverage across multiple zones or levels. This modularity allows mining companies to tailor the system according to site size, complexity, and safety requirements.

V. CONNECTIVITY & FUNCTIONALITY

The smart helmet uses both Bluetooth Low Energy (BLE) and Wi-Fi for ongoing data collection and communication.

Bluetooth Low Energy (BLE):

BLE is employed for continuous distance estimation using RSSI (Received Signal Strength Indicator) values. The helmet detects signal strength from a fixed BLE beacon deployed in the mining area. By interpreting signal strength attenuation, the ESP32 estimates the wearer's proximity to critical areas. If the worker crosses predefined safety boundaries (e.g., exceeding a 10-meter radius from the beacon), an immediate alert is activated. This approach eliminates the need for GPS, which is often ineffective in subterranean environments. BLE communication is energy-efficient, which makes it ideal for battery-powered wearable devices operating in remote locations.

Wi-Fi Connectivity:

The ESP32 microcontroller embedded in the helmet leverages built-in Wi-Fi to send environmental and location data to a centralized server. Data packets include gas concentrations from MQ135, temperature and humidity from DHT11, and calculated RSSI values. This data is transmitted using HTTP POST requests to a cloud-hosted or local IoT platform, enabling real-time monitoring and data logging. The Wi-Fi module supports reconnection logic in case of signal drops and uses secure communication practices (e.g., token-based authentication) to protect sensitive operational data.

Functionality:

- Real-Time Monitoring: The helmet continuously monitors atmospheric gases, temperature, humidity, and distance from beacon points, ensuring 24/7 coverage in dynamic mining environments.
- Alerts: When any sensor value exceeds the danger threshold or if unsafe distance is detected, the system triggers an alert mechanism comprising a loud buzzer, visual indicators on the LCD screen, and data transmission to the web portal for supervisory.
- Emergency Button: A built-in emergency push button allows the wearer to instantly send distress signals regardless of environmental conditions. This is particularly useful in scenarios like falls, exposure to toxic gases, or loss of orientation.
- Data Processing: The ESP32 conducts edge-level processing by analyzing sensor inputs in real-time. It uses a combination of logic thresholds and calibrated ranges to determine whether conditions are normal or hazardous. This minimizes false positives and ensures prompt, accurate response to genuine threats. The onboard logic ensures that alerts are generated within milliseconds of detecting danger, maximizing worker safety.

VI. User Interface

1. LCD (I2C) for Real-time Data Display:

- The helmet includes a display unit that uses the I2C protocol to communicate with the controller.
- It functions as a key feedback component, constantly updating miners with relevant safety information.
- The screen presents critical sensor data including: Gas levels like CO_2 and NH_3.
- Temperature and humidity readings. Proximity readings derived from RSSI, helping indicate how close or far the miner is from safe zones.
- In addition to raw data, the LCD presents warning notifications.

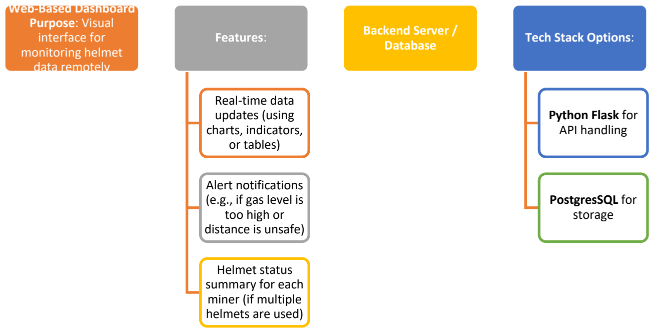
During dangerous events like high gas levels, extreme heat, or movement outside safe boundaries, the display shows immediate alert messages to warn the user.

2. Buzzer for Audio Alerts

- Alongside visual warnings, the helmet includes a buzzer for audio signals.
- The buzzer offers sound-based alerts to grab the miner's attention—especially useful in loud environments.
- It responds to dangerous situations, the same as the LCD.
- It emits an alert tone, prompting the miner to act swiftly in response to threats.

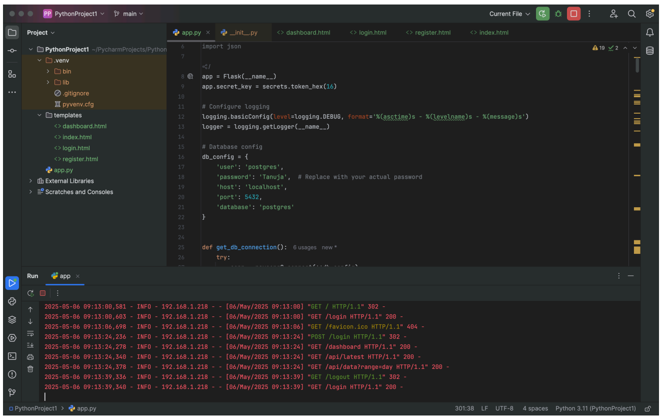
3. Push Button for Emergency Alerts

- A manual alert system is integrated using a push button.
- It provides workers the ability to independently raise an alarm when they sense immediate risk or discomfort.
- Once pressed, the system dispatches a high-priority signal to the remote monitoring dashboard for quick intervention.
- In summary, the helmet interface incorporates multiple feedback systems—visual and auditory—to keep miners informed and enable quick action during emergencies.

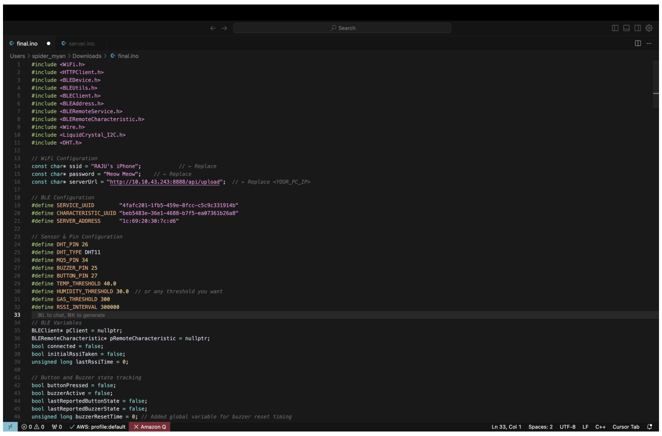


Source Code

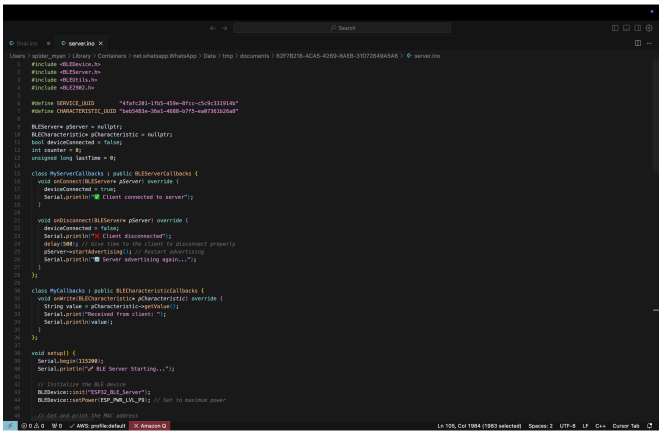
Web Page:



Client Side:



Server Side:



VI. Outcome Of The Project

The developed working of the IoT-integrated helmet validates the concept of merging sensing hardware with wireless networking to improve safety in mining operations. This model successfully demonstrates:

Environmental risk detection through real-time monitoring:

The system uses integrated MQ135 gas sensors and DHT11 modules to continuously track hazardous gases, temperature, and humidity in underground environments. Data is processed instantly on the helmet via an ESP32 microcontroller to identify any deviation from safe thresholds. This ensures prompt detection of conditions like toxic gas buildup, insufficient ventilation, or temperature extremes that pose threats to workers.

RSSI-powered proximity alerts for zone violations:

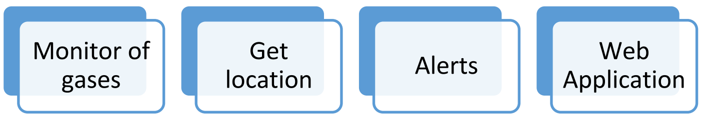
By leveraging Bluetooth Low Energy (BLE) signals from fixed beacons in the mine, the helmet estimates the distance between a worker and predefined safe zones using RSSI (Received Signal Strength Indicator) values. If the worker moves beyond a permitted area or enters a danger zone, the system triggers immediate audio-visual alerts via onboard buzzers and displays, allowing timely corrective action and minimizing the risk of accidents.

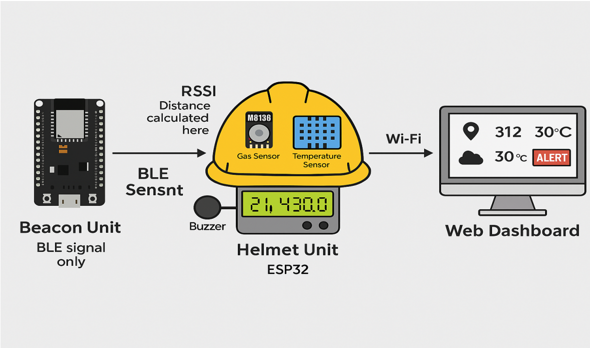
Dependable transmission of data to support remote observation

The helmet utilizes built-in Wi-Fi capabilities of the ESP32 to transmit sensor readings and alerts to a remote web-based monitoring platform via HTTP protocol. This allows supervisors to monitor multiple helmets in real time, receive emergency alerts, and track worker safety metrics, even from distant locations. The system supports scalability for cloud-based dashboards and historical data analysis for compliance and improvement.

Expandable design and budget-friendly implementation suitable for widespread use

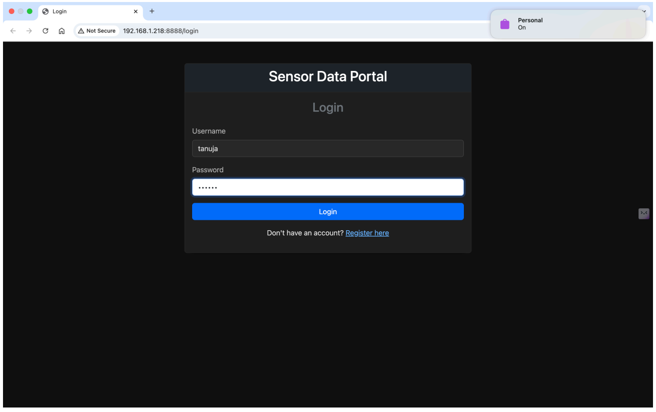
The use of low-cost, open-source components like ESP32, MQ135, and DHT11 ensures affordability without compromising reliability. Its modular architecture allows for easy upgrades—such as adding GPS modules, LoRa communication, or more advanced environmental sensors—making it adaptable to different use cases across industries like mining, construction, and emergency response. The lightweight design and energy-efficient operation make it suitable for prolonged usage in resource-constrained settings.



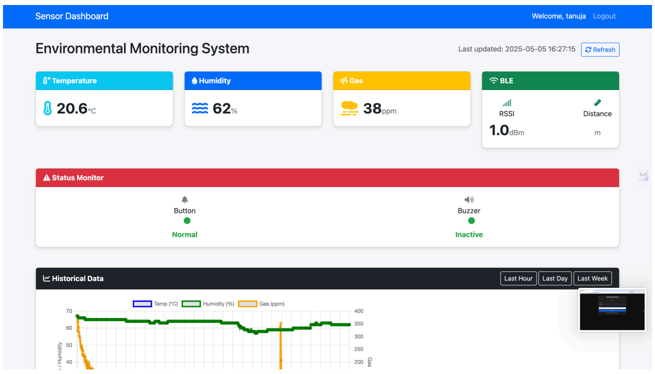


Dashboard:

Login:



Application Dashboard:



VIII. CONCLUSION

This project delivers a robust and intelligent safety solution for underground mining operations through the successful design, implementation, and validation of an IoT-enabled smart helmet. It merges multiple domains of embedded systems, wireless communication, sensor integration, and user interaction into a single wearable device aimed at protecting workers in highly hazardous environments. The helmet is equipped with a range of environmental sensors, including the MQ135 for detecting toxic gases and the DHT11 for measuring temperature and humidity, providing accurate and real-time assessment of air quality and ambient conditions. By integrating Bluetooth Low Energy (BLE) for Proximity tracking and leveraging RSSI (Received Signal Strength Indicator) values, the system effectively substitutes for GPS in environments where satellite signals are unavailable, enabling real-time indoor localization and automated zone-based alerts. This localization capability is particularly critical in mines, where worker disorientation or entry into dangerous zones can lead to fatal accidents. The system enhances emergency preparedness through a multi-modal alert mechanism that includes visual feedback on an LCD display, LED indicators for hazard status, an auditory buzzer for immediate attention, and a manual push button that empowers the miner to initiate distress signals during emergencies. All collected data is processed locally using an ESP32 microcontroller and transmitted via Wi-Fi to a centralized cloud-based dashboard, allowing supervisors to remotely monitor multiple environmental parameters and receive instant alerts. This dashboard not only supports live visualization but can also serve as a historical log for audits, safety compliance, and analytics. The entire system has been tested for responsiveness, reliability, energy efficiency, and modularity, proving its capability for continuous deployment in constrained and rugged environments. The low-cost hardware architecture and open-source software stack make it highly accessible and scalable, supporting easy adoption in economically sensitive regions or small mining operations. Furthermore, the modular design of the system leaves room for future enhancements such as biometric integration, machine learning-based anomaly detection, or expansion to multi-miner tracking using triangulation from multiple beacons. Overall, this smart helmet solution exemplifies how emerging IoT technologies can be practically applied to enhance occupational safety, reduce incident response time, improve situational awareness, and ultimately, save lives in one of the world's most dangerous industries.

XI. REFERENCES

[1] P. Druvanag, C. Eaga, N. Gatla, P. Gavini, and C. V. Nanda Kishore, "IoT Mining Tracking & Worker Safety Helmet," International Journal for Research in Applied Science and Engineering Technology (IJRASET). [Online]. Available: https://www.ijraset.com/research-paper/iot-mining-tracking-and-worker-safety-helmet

[2] U. Nagappan, H. Poladi, and B. Ireddy, "An Internet of Things-Based Mining Worker Safety Helmet Using ESP32 and Blynk App," ResearchGate, 2023. [Online]. Available: https://www.researchgate.net/publication/370824196_An_Internet_of_Things-Based_Mining_Worker_Safety_Helmet_Using_ESP32_and_Blynk_App

[3] J.-H. Kim, J. Baek, and Y. Baek, "Smart Helmet-Based Personnel Proximity Warning System for Underground Mines Using Bluetooth Low Energy (BLE) Technology," Applied Sciences, vol. 11, no. 10, p. 4342, 2021. [Online]. Available: https://doi.org/10.3390/app11104342

[4] SR Robotics, "IoT Based Mining Worker Safety Helmet." [Online]. Available: https://srrobotics.in/product/iot-based-mining-worker-safety-helmet

[5] L. Zhang and Z. Yang, "IoT Based Smart Helmet for Hazard Detection in Mining Industry," arXiv, 2023. https://doi.org/10.3390/app11104342