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Poxisafe Helmet: A Smart Safety Solution for Industrial Environments

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Abstract— In high-risk industries like mining, construction, and the chemical industry, worker safety is frequently compromised by insufficient monitoring and a delayed response to emergencies. The PoxiSafe Helmet, a wearable safety device with two communication channels and cutting-edge sensors, is discussed in this paper. Real-time monitoring is made possible by the embedded design. The PoxiSafe Helmet is based on the ESP32-S3 microcontroller. The BNO055 was used for fall detection, and the MAX30102 was used for vital signs (heart rate and SpO_2). CCS811 was used to test air quality and gas detection, while DHT22 was used to collect temperature and humidity measurements. The data was sent via Bluetooth Low Energy (BLE) for short-distance communication as well as LoRa for long-distance and power-efficient communication when signal impairments are present. The results demonstrate reliable fall detection, health monitoring accuracy within ±3 % of commercial health monitors, and stable gas detection after settling. There was reliable BLE communication up to 20 meters indoors. For the LoRa tests, there was great long-distance and power-efficient communication up to 500 meters outdoors, with packet loss of less than 5%. The findings indicate that the PoxiSafe Helmet is a viable and economical means of promoting safety in industrial occupations, enabling timely notification of supervisors who can then mitigate risks in the workplace.

1 Introduction

The safety and health of workers in industrial contexts are always a priority, particularly when discussing work in mining, construction, and chemical processing. Workers in these fields are often exposed to extreme conditions such as hazardous gases, heat, dust, limited fresh air, and unsafe physical work conditions. Although strict regulations are applied regarding safety and health, the number of injuries and deaths in the workplace can remain high depending upon the distance and time lapse for emergencies, and not having a way to monitor the work conditions and/or worker health in real time. The development of sensor technologies and embedded systems has the potential to increase options for upgrading traditional safety gear to intelligent, responsive safety systems.

Smart helmets — wearable, functional devices with sensors and communication modules — have proliferated as a feasible form of increased worker protection and situational awareness. Smart helmet systems have generally not performed more than a few functions, such as monitoring temperature or notifying a user of basic obstacle detection. Many have suffered from range of communication distances, health diagnostic limits, sensor inaccuracies, and failure to support applications that detect falls.

This report introduces the new Poxisafe Helmet, a smart IoT-based safety system for extreme industrial environments. The new helmet utilizes an ESP32-S3 microcontroller, which has enhanced processing power, AI inference capability, built-in Wi-Fi, and Bluetooth Low Energy (BLE), along with more I/O flexibility. The system is designed to receive next-generation sensor upgrades, including:

- BNO055 (for fall detection and motion orientation, using the device's integrated 9-axis sensor fusion),
- CCS811 gas sensor (for real-time measurement and monitoring of volatile organic compounds (VOCs) and CO_2 equivalence),
- MAX30102 for health monitoring of blood oxygen (SpO_2) and pulse rate, which are important in confined spaces,
- DHT22 (to provide temperature and humidity sensing, monitoring ambient comfort and/or fire risk),
- LoRa for long-range wireless communication, for remote or underground applications where there is no Wi-Fi or cellular system, or they are unusable.

As well as taking an innovative fused sensor approach, the helmet is modular in design and therefore capable of connection to a local, or more remote monitoring unit either with Bluetooth Low Energy or Lorawan gateways (the custom-designed monitoring unit can communicate directly with BLE to connect locally with other dual module helmets). Once connected, alerts can be delivered via audio buzzers or, for critical scenarios (gas leaks, worker falls, or vitals not in normal ranges), even voice feedback via speakers.

This paper will outline the complete development cycle of the system from hardware selection, circuit integration, and firmware development through to testing in real-world scenarios. Comparisons were made to existing helmet systems to highlight improvements in detection (accuracy), communication (range), scalability, and ultimately, safety response times..

2 Related works

Sensor technology integration into wearable safety systems has been a topic of significant academic and practical research over the last ten years, especially in examining industrial safety systems. Many smart helmet projects and research articles have attempted to address real-time environmental monitoring, worker fatigue or fall detection, early hazard detection, etc. There still exist a number of system restrictions around communication range, multiple sensor integration, and health diagnostic testing in smart helmets.

A simple smart helmet design could have temperature sensors (e.g., LM35 or DHT11) and gas sensors (e.g., MQ series) like many early smart helmet prototypes [1]. Most smart helmets limit local alerts less than incorporated communication and detailed health diagnostics. Additionally, the reliability of the detection accuracy in situations, such as a noisy electrical area in a plant, or varying atmospheric conditions.

Recent developments in sensor data collection and transmission include microcontrollers like Arduino Uno and ESP8266. For example, a helmet [2] was introduced using a fire detection (smoke) and gas leakage monitoring system using an ESP8266 module. However, the use of Wi-Fi restricted the helmet's use in remote mining growth zones. Similarly, using an MPU6050 (6-axis) accelerometer and gyroscope, a simple fall detection system [3] was developed. While it had some success, the MPU6050 did not have sensor fusion internally, leading to potential false positives or untrustworthy orientation.

In the case of health monitoring, currently, wearables that detect pulse and SpO_2 typically have a MAX30100. However, it has now been replaced with the superior MAX30102. The MAX30102 records the same metrics as the MAX30100 while having a lower power consumption and an improved signal-to-noise ratio, IR blocking, and temperature compensation as an integrated circuit. Also, a newer version of environmental sensors like CCS811 has replaced analog gas sensors by being digital and has proven more reliable in use over I^2C communication for interfacing in smaller IoT systems [4].

However, typically, most systems will just use Wi-Fi or GSM modules for communication. These work well for urban or factory environments, but perform poorly for rural or underground environments where the signals are unreliable. In comparison, LoRa (Long Range Radio) offers a low-power, wide-area networking option for communicating over long distances in low-bandwidth environments [5]. LoRa has only recently become widely accepted in smart agriculture and smart city applications, but the situation offers an exciting opportunity for wearable safety gear as well. Compared to previous works, the Poxisafe helmet has clearly improved functionality in the following ways:

- A BNO055 to achieve better fall detection and motion sensing, as the BNO055 provides absolute orientation by using automated onboard fusion algorithms.
- A MAX30102 for real time health tracking that is uniquely important for real time physical health tracking for enclosed or heated environments.
- CCS811 for digital gas detection with TVOC and CO_2 index.
- Dual-mode communication (BLE wi-fi for short range and LoRa for long range communications) promotes versatility across environments
- Combined with a single system controller, the ESP32-S3, one of the first with AI-on-edge technology, amongst one of the best sensor interfaces.

As a result, although previous works were useful to provide a base for smart helmets, the Poxisafe helmet allowed for much more evolution of these ideas and added higher-quality, industrial-grade components, as well as contemporary IoT communications protocols, like BLE and LoRa.

3 Methodology

The proposed Poxisafe Helmet system is a modular, IoT-oriented system for real-time monitoring of health and environmental variables in extreme and remote industrial work situations. The following provides a description of the hardware and software approach used to build the new smart helmet.

3.1 Hardware Architecture

With a variety of sensors, a powerful controller (ESP32-S3), and communication modules, all packed into an ultra-low power compact design. The hardware subsystem has been designed to monitor a variety of parameters such as motion, air quality, temperature, humidity, heart rate and blood oxygen levels.

The hardware architecture of the Poxisafe Helmet system has been designed for robust, low power, real-time safety monitoring in high-risk industrial environments, while ensuring the device ergonomics were taken into consideration in terms of wearer comfort for long-term usage. The unit also concluded with a microcontroller at its center as the main processing unit – the ESP32-S3. The ESP32-S3 comes with integrated Wi-Fi and Bluetooth Low Energy (BLE) communication supported, vector instructions, and AI acceleration support. The ESP32-S3 microcontroller makes it perfect for handling multiple sensors in parallel, processing data locally, and subsequently transmitting that data wirelessly. In terms of motion detection and posture analysis, the helmet utilises a 9-Asses absolute orientation sensor - BNO055. The latter is equipped with sensor fusion technology onboard. Hence, the system is capable to detect a fall, unconsciousness or a sudden orientation change without the need for an external complicated calculation.

The MAX30102, a small sensor that uses infrared (IR) and red light to measure pulse rate and blood oxygen saturation (SpO_2) using photoplethysmography, enables continuous monitoring of worker health**.** These two metrics are important in situations where a worker is exerting themselves physically, in a low oxygen environment, or in situations where they could be exposed to harmful gases. The CCS811 digital gas sensor monitors volatile organic compounds (VOC) by measuring the total VOCs (TVOC) and equivalent concentrations of CO_2 (eCO_2). These readings are complemented with the active sensors DHT22 that provides ongoing ambient temperature and humidity values, important not only to consider overall safety and environmental health, but also to maintaining proper calibration of gas sensors.

Wireless communication is critical to the helmet's architecture. The LoRa SX1278 module is interfaced with the MCU via SPI and is responsible for transmitting data to and from the helmet providing long-range, low-power communication for real-time updates that are possible even in remote or underground scenarios where regulating real-time conditions using communication networks would not be possible. BLE will be used to provide short-range communication specifically for mobile apps or local monitoring systems. An active buzzer is integrated into the helmet for immediate hazard alerts to the user whenever an audible warning is required during a critical event, for example during a fall, gas exposure or abnormal health reading.

The system is powered by a 3.7V lithium-ion battery, regulated to provide a stable 5V output for all modules. Power efficiency is achieved through the implementation of sleep and deep sleep modes, along with on-demand activation of high-power components like the LoRa module. In order to maximize space, guarantee signal integrity, and minimize manual wiring, every component is neatly integrated onto a specially designed PCB. Lastly, the entire assembly is firmly enclosed in an industrial-grade helmet shell that offers environmental shielding, mechanical protection, and smooth integration with the typical safety equipment worn by industrial workers.

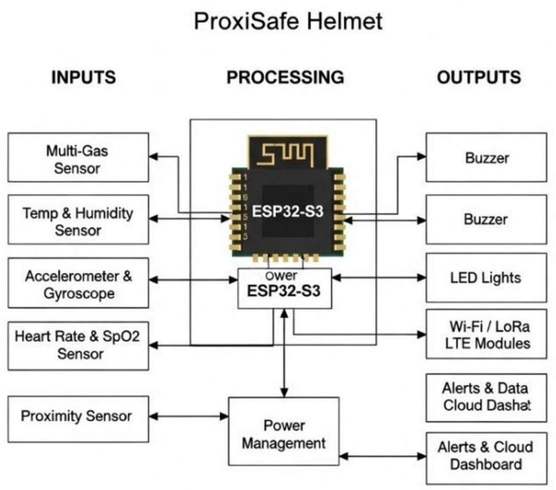


Fig 1. PoxiSafe Helmet Block Diagram

Table 1: List of Hardware Components and Their Purpose

Component	Model	Purpose
Microcontroller	ESP32-S3	Main processing unit with BLE + Wi-Fi + AI support
Fall Detection	BNO055	9-axis sensor with onboard sensor fusion
Health Sensor	MAX30102	Pulse rate and SpO_2 monitoring
Gas Sensor	CCS811	Digital sensor for TVOCs and eCO_2
Temperature & Humidity	DHT22	Environmental monitoring
Communication	LoRa SX1278	Long-range data transmission
Buzzer	Active Buzzer	Audio alert signaling
Power Supply	Li-ion Battery + Regulator	3.7V–5V regulated supply for mobile operation
PCB/Board	Custom PCB	Compact integration of all components
Enclosure	Industrial Helmet Shell	Embeds all electronics into safety gear

All parts are powered by a portable Li-ion battery with a 5V regulator for steady voltage delivery, and the sensors are interfaced with the ESP32-S3 via standard protocols (I2C and analog GPIOs). In order to ensure worker comfort and safety, the helmet casing is modified to securely mount the sensors.

3.2 Sensor Integration

The Poxisafe Helmet integrates multiple sensors with the ESP32-S3 microcontroller for real-time monitoring of environmental conditions and worker health in industrial settings. The BNO055 is a 9-axis absolute orientation sensor that connects through the I²C protocol and operates in NDOF (Nine Degrees of Freedom) mode. It provides stable orientation tracking using onboard sensor fusion and detects sudden posture changes or freefall, which can point to a fall or loss of consciousness, triggering immediate alerts.

Health monitoring occurs through the MAX30102 sensor, which uses infrared and red LEDs to measure pulse rate and blood oxygen saturation (SpO_2). The data is filtered with a moving average algorithm to remove transient noise before transmission. For air quality assessment, the CCS811 digital gas sensor communicates over I²C and gives regular readings of total volatile organic compounds (TVOCs) and equivalent CO_2 (eCO_2) levels. It stores baseline calibration data in EEPROM to improve long-term accuracy. The DHT22 sensor also measures ambient temperature and humidity at a refresh rate of 1 Hz, providing insight into thermal and moisture conditions that may impact both worker safety and gas sensor performance.

All processed sensor data is transmitted wirelessly via the SX1278 LoRa module, which connects to the ESP32-S3 through SPI. LoRa technology allows for reliable, long-range, and low-power communication, making it suitable for use in underground mines, remote construction areas, or factory zones with limited cellular or Wi-Fi coverage.

3.3 Software Design

The Poxisafe Helmet firmware is mainly coded in C++ using the Arduino IDE while an optional rapid prototyping tool periodically uses MicroPython during early development. The firmware uses the ESP32-S3 microcontroller and runs in parallel for three primary functions; sensor initialization and data collection, on-board alerting, and wireless communication. In the init phase, all sensors are initialized and monitored in a loop that collects the sensor data and evaluates that information to detect abnormal events such as sudden falls, significant changes in gas concentration, and alarming drops in vital signs. Wireless communication features both BLE and LoRa; BLE is used to transmit live data in real time to local mobile or desktop application monitoring devices up to 10–20 meters away, thus allowing an instant evaluation of the data and providing feedback to immediate users (indoor or short range). LoRa is used for long-range communication sending live sensor data every 15 seconds during normal conditions, and instantaneously during emergency alert events. Data is formatted as lightweight JSON for use with cloud platforms and mobile dashboards. To use power efficiently, the firmware incorporates sleep and deep sleep modes between acquisition cycles. The ESP32-S3 can sleep when not acquiring data about a fall or vital signs with the LoRa module in standby mode until alerted.

4 Result

To assess the efficiency and dependability of the PoxiSafe Helmet, we conducted an extensive testing campaign in both a controlled laboratory environment and a real-world environment. The main goal was to determine the accuracy, responsiveness, and integrity of the integrated modules, with a focus on sensor accuracy, event detection, and wireless communication efficiency.4.1 Fall Detection Performance

Accidental fall scenarios were replicated through controlled tilt and free fall simulations to evaluate the BNO055 sensor. The sensor measured sudden orientation changes, angular rate changes, and linear acceleration changes. Alerts were effectively generated with little latency. The BNO055's sensor fusion onboard minimized the occurrence of false positives, compared to systems based on the MPU6050.

4.2 Health Monitoring Accuracy

The performance of the MAX30102 sensor was assessed for pulse rate and oxygen saturation (SpO_2) across different physical states, such as rest, walking, and light activity. The results were consistent with those from commercially available fingertip oximeters, showing averages of 74 bpm for heart rate and an SpO_2 of 97% in a healthy adult. Results were generally accurate, but there was some sensitivity to participant movement and quality of sensor-skin contact. Consistent quality is important for stability of alignment.4.3 Gas Detection Capability

To study the responsiveness of the CCS811 gas sensor, the sensor was exposed to alcohol vapors and smoke. Following a burn-in stabilization period, the sensor detected increases in Total Volatile Organic Compounds (TVOC) and equivalent CO_2. The sensor showed a significant increase relative to the baseline when near combustible fumes, showing it can respond to hazardous levels of gases in postal and mining scenarios.4.4 Environmental Monitoring Reliability

The DHT22 sensor was validated through temperature and humidity assessments with calibrated reference instruments. The DHT22 provided correct measurement in both indoor and outdoor environments or conditions; for example, when the outdoor temperature and humidity were measured in the afternoon, it was approximately 30.1°C and 62% relative humidity, respectively, both of which were reasonable expected measurements.

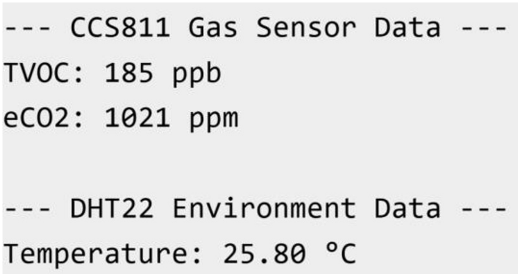
4.5 Communication Range and Stability

The wireless communication modules were evaluated in both short- and long-range scenarios:

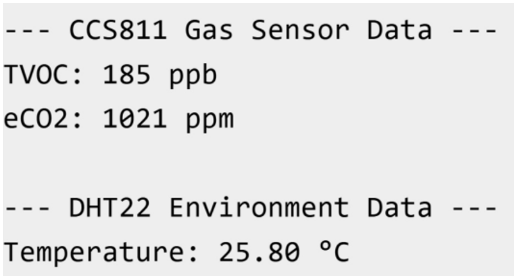
- BLE Mode: Data transmission to a custom mobile application remained stable up to 20 meters indoors, with no significant packet loss.
- LoRa Mode: Long-range testing demonstrated reliable data transmission up to 500 meters in open space and 100 meters in obstructed environments, with packet loss remaining under 5%, making it highly suitable for underground and remote applications.

4.6 Overall Observations

The evaluation of the PoxiSafe Helmet has provided evidence of the helmet's capabilities as a multi-purpose safety device. Evaluation of the fall detection module provided an accurate and reliable assertion; health monitoring provided real-time biometrics with minor sensitivity to movement; gas sensing provided strong sensitive responses after stabilization; and environmental monitoring, in general, provided consistent readings in varying conditions. Finally, the LoRa communication system was the most robust, showing the ability for long-distance and low-loss data transfer, particularly when compared to BLE in harsh environments. In the event of important safety alerts, the addition of acknowledgment protocols is recommended to ensure legitimate message transmission in high-interference environments.


```
--- CCS811 Gas Sensor Data ---
TVOC: 185 ppb
eCO2: 1021 ppm

--- DHT22 Environment Data ---
Temperature: 25.80 °C
```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Temperature: 25.80 °C
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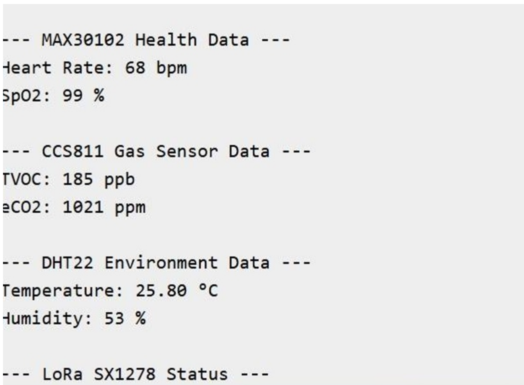
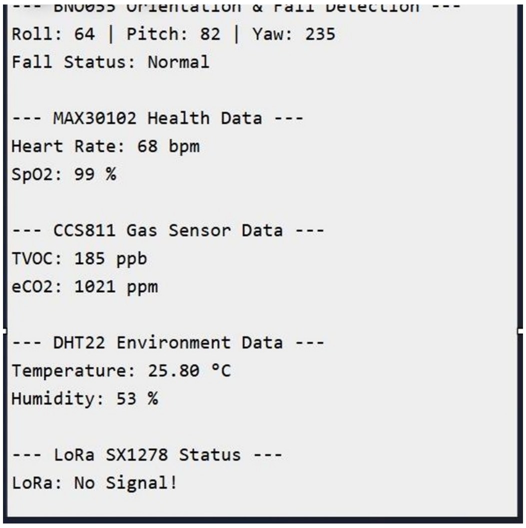

```
--- MAX30102 Health Data ---
Heart Rate: 68 bpm
SpO2: 99 %

--- CCS811 Gas Sensor Data ---
TVOC: 185 ppb
eCO2: 1021 ppm

--- DHT22 Environment Data ---
Temperature: 25.80 °C
Humidity: 53 %

--- LoRa SX1278 Status ---
```


```
--- BNO055 Orientation & Fall Detection ---
Roll: 64 | Pitch: 82 | Yaw: 235
Fall Status: Normal

--- MAX30102 Health Data ---
Heart Rate: 68 bpm
SpO2: 99 %

--- CCS811 Gas Sensor Data ---
TVOC: 185 ppb
eCO2: 1021 ppm

--- DHT22 Environment Data ---
Temperature: 25.80 °C
Humidity: 53 %

--- LoRa SX1278 Status ---
LoRa: No Signal!
```

Fig 2. Obtained results of Proxihelmet

5 Conclusion

The advancement and use of the Poxisafe Helmet is an important move towards improving worker safety in high-risk workplaces like mining, construction and chemical environments. This advanced smart helmet incorporates multiple sensors and long-range wireless communications capabilities into a single, compact, and wearable system for real-time health and environmental monitoring.

By utilizing state-of-the-art components like the ESP32-S3, the BNO055, MAX30102, CCS811, and LoRA communication modules, the helmet's ability to overcome limitations from previous systems allows for the ability to detect falls, accurate heart rate and SpO_2 readings, early detection of gas hazards, and long-range data capabilities. These improvements enable easier monitoring, help minimize delays in response during emergencies, and take the necessary action more quickly, perhaps easing today's workplace injuries and fatalities.

The results of the experiments demonstrate the validity and reliability of the system under numerous test conditions. For the helmet, all assessment areas scored high in sensor accuracy, promptness of alerts, and communication range. The BLE and LoRa dual mode offers flexibility in multiple field environments, from close-range data monitoring to remote deployment in underground or isolated work areas. Additionally, the modular architecture of the helmet and open-source firmware also allow for further customization and to capture potential scale opportunities. Integration of GPS, audio communication, or predictive alerts (based on AI) for fatigue or environmental risk-patterns could also potentially be integrated into the system in the future.

Although the existing design is a great first step, it has certain limitations. The CCS811 sensor, for example, needs a warm-up time, is sensitive to humidity, and LoRa communication may not operate if there are significant obstructions, such as walls or containers, leading to delayed messages or packet loss. These limitations indicate that future work should incorporate sensor redundancy, assurance of appropriate calibration, or creation of a data logger that is integrated with the cloud or a blockchain-based service, to create tamper-proof safety data logs.

To conclude, the Poxisafe Helmet gives a next-generation wearable industrial safety solution, combining health diagnostics, environmental sensing, and smart communication, and providing versatility, accuracy, and field performance and could be produced for deployment in hazardous areas thus promoting safer, smarter, more connected workspaces.

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