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IoT-Based Smart Helmet Powered by Worn-Out Solar Panels for Sustainable Industrial Safety

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ABSTRACT

Worker safety in hazardous environments such as construction sites, mining areas, and firefighting operations is a critical concern. These environments often expose workers to extreme temperatures, toxic gases, and oxygen-deficient conditions, which can lead to severe injuries or fatalities. This paper presents the design and implementation of an IoT-based Smart Safety Helmet that continuously monitors environmental conditions and provides automatic safety responses.The system uses sensors to detect temperature, gas concentration (ppm), and oxygen levels. A cooling fan is activated when the temperature exceeds safe limits, while an oxygen supply mechanism is triggered when the air becomes unsafe for breathing. Additionally, a GPS module enables real-time location tracking of workers, which is essential during emergency rescue operations. The system is powered by a rechargeable battery with solar-assisted charging for continuous operation. The proposed solution is cost-effective, energy-efficient, and highly suitable for real-world industrial applications.

Keywords*:* IoT, Smart Helmet, Worker Safety, Gas Sensor, Oxygen Monitoring, GPS Tracking

1. Introduction

Ensuring worker safety in hazardous environments remains a major challenge in industries such as construction, mining, and firefighting, where workers are regularly exposed to extreme and unpredictable conditions. These environments often involve high temperatures, the presence of toxic or flammable gases, and low oxygen levels, all of which pose serious risks to human health and survival. Traditional safety helmets are primarily designed to provide physical protection against head injuries, but they do not offer any mechanism to detect or respond to these environmental hazards. As a result, workers may unknowingly operate in unsafe conditions for extended periods, increasing the likelihood of accidents, health complications, and even fatalities. In many situations, accidents occur not only due to the presence of these hazards but also because workers lack awareness of the surrounding conditions or do not receive timely warnings. Furthermore, during emergency situations such as mine collapses, gas leaks, or fire outbreaks, locating affected workers becomes extremely difficult due to the absence of real-time tracking systems, which delays rescue operations and reduces survival chances. To address these critical issues, this paper proposes an IoT-based Smart Safety Helmet that enhances the functionality of conventional helmets by integrating advanced sensors and automated safety mechanisms. The system continuously monitors environmental parameters such as temperature, gas concentration, and oxygen levels, and responds instantly by activating protective features like cooling systems and oxygen supply when necessary. In addition, it incorporates real-time location tracking to assist in quick identification and rescue of workers during emergencies. The main objective of this system is to provide a proactive and intelligent safety solution that not only protects workers physically but also ensures their overall well-being by reducing risks and improving response time in hazardous environments.

2. Research Method

This study focuses on the development and evaluation of an IoT-based Smart Safety Helmet aimed at improving worker safety in hazardous environments through real-time monitoring and automated response mechanisms.

System Development

The system was developed around an ESP32 microcontroller, which acts as the central processing unit. Multiple sensors, including a temperature sensor (DHT11/DHT22), gas sensor (MQ series for ppm detection), and oxygen sensor, were integrated to continuously monitor environmental conditions. These sensors collect real-time data related to temperature, air quality, and oxygen availability.The collected data is processed by the ESP32, which makes intelligent decisions based on predefined safety thresholds. Additional modules such as a cooling fan, oxygen supply unit, and GPS module are integrated to provide safety actions and location tracking. This setup enables the system to actively respond to hazardous situations and ensure worker protection.

Power Management:

The system is powered by a rechargeable battery supported by a solar panel, ensuring continuous and reliable operation even in remote or off-grid locations. Battery voltage is monitored to maintain power efficiency and prevent system failure during critical conditions.

Operation Modes:

The system operates in two main modes:

Automatic Mode: The system continuously monitors environmental parameters and automatically activates safety mechanisms. For example, the cooling fan is turned ON when temperature exceeds safe limits, and the oxygen supply system is triggered when oxygen levels drop or harmful gas levels increase.

Emergency Mode: In hazardous conditions, the system generates alerts and shares real-time location data through the GPS module to assist rescue operations and ensure quick response.

User Interface and Notifications: LED indicators and a buzzer are used to provide immediate alerts to the user when unsafe conditions are detected. In addition, the system can be connected to an IoT platform for remote monitoring, allowing supervisors to track worker conditions and location in real time.

Testing Procedure:

The system was tested under controlled and simulated hazardous conditions to validate its performance. Various scenarios such as high temperature, increased gas concentration, and reduced oxygen levels were created to evaluate the system's response. The activation of the cooling fan, oxygen supply mechanism, and alert systems was verified. GPS tracking accuracy and system reliability were also tested to ensure proper functioning during emergency situations.

Problem Identification

Workers in hazardous environments often face serious risks due to exposure to extreme temperatures, toxic gases, and oxygen-deficient conditions. Traditional safety helmets do not provide any mechanism to monitor or respond to these environmental dangers.

As a result, workers may unknowingly remain in unsafe conditions, increasing the chances of accidents and health issues. In addition, during emergencies such as fire outbreaks or mine collapses, locating workers becomes difficult due to the absence of real-time tracking systems. Continuous manual monitoring is also impractical in such environments, leading to delayed responses and increased risk. These challenges highlight the need for an intelligent, automated safety system.

System Design

The IoT-based Smart Safety Helmet is designed as an intelligent and self-contained safety system that continuously monitors environmental conditions and responds automatically. It integrates sensors, safety mechanisms, and communication modules into a compact wearable device.The system is driven by the ESP32 microcontroller, which collects data from sensors, processes it using predefined logic, and activates outputs such as the cooling fan and oxygen supply system when required.

A GPS module is included to track the worker's location, enhancing emergency response capabilities. The combination of real-time sensing, automation, and IoT connectivity makes the system highly effective for hazardous environments.

Dataset

For this project, the "dataset" consists of real-time sensor readings collected by the system. It includes:

Temperature (°C): Measured using a temperature sensor to monitor heat levels around the worker.

Gas Concentration (ppm): Detects harmful gases in the environment using a gas sensor.

Oxygen Level (%): Measures the availability of breathable air.

Location Data (Latitude & Longitude): Collected using a GPS module for real-time tracking.

System Status (Digital): Indicates whether the cooling fan and oxygen supply system are ON (1) or OFF (0).

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3. Proposed Topology

The proposed topology organizes all hardware components and data flow around the ESP32 microcontroller, which acts as the central control unit.

The system is powered by a rechargeable battery supported by a solar charging unit and is capable of real-time monitoring and automated safety response. The architecture integrates sensing, processing, safety mechanisms, and communication modules to ensure continuous protection of workers in hazardous environments.

1. Power Unit (Solar-Battery System)

- Solar Panel → Charge Controller → Rechargeable Battery
- Provides a stable DC supply to all system components
- A voltage sensor monitors battery levels and sends feedback to the ESP32 to ensure efficient power management and prevent system failure.

2. Central Controller (ESP32)

- Receives power from the battery
- Continuously reads sensor data and processes it in real time
- Compares environmental values with predefined safety thresholds
- Controls output devices such as cooling fan and oxygen supply system.
- Communicates with IoT platforms and GPS module for monitoring and tracking.

3. Sensor Array (Inputs to ESP32)

- **Temperature Sensor (DHT11/DHT22):** Measures surrounding temperature
- **Gas Sensor (MQ Series):** Detects harmful gases and measures ppm levels
- **Oxygen Sensor:** Monitors oxygen concentration in the air
- **Voltage Sensor:** Tracks battery health and power status.

4. Safety and Actuation Module (Outputs from ESP32)

- **Cooling Fan:** Automatically activated when temperature exceeds safe limits to reduce heat stress
- **Oxygen Supply System:** Triggered when oxygen levels drop or air becomes unsafe to breathe
- **Buzzer and LED Indicators:** Provide immediate alerts during hazardous conditions.
- **5. Communication and Tracking Module**
- **GPS Module:** Continuously tracks the worker's location (latitude and longitude)
- Enables quick identification and rescue during emergencies
- Can be integrated with IoT platforms for real-time remote monitoring.

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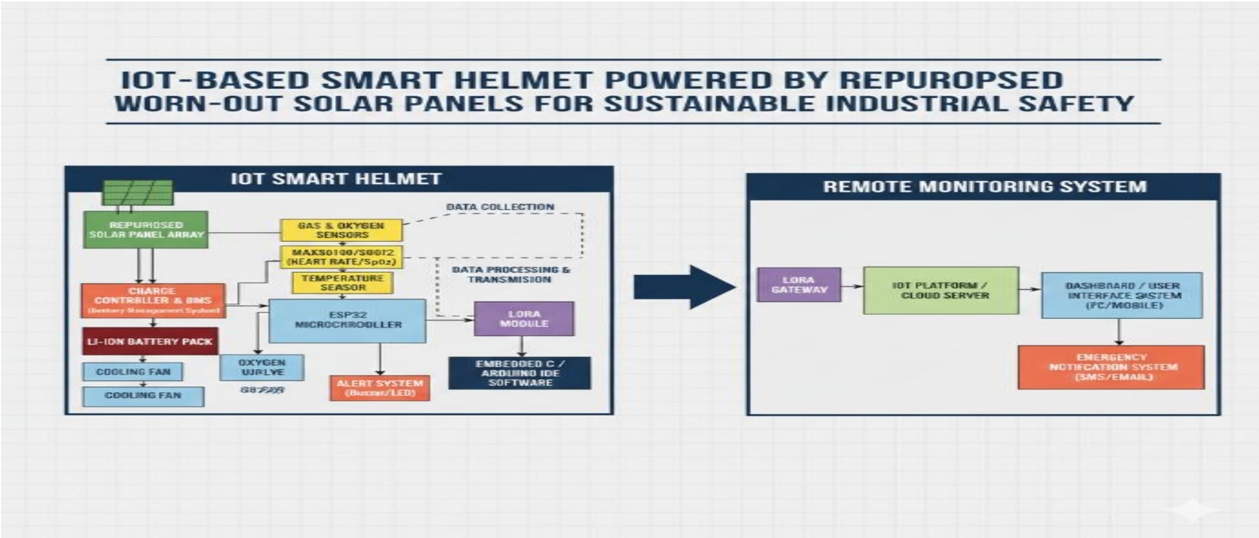

Figure 1: Block Diagram of IoT-Based Smart Safety Helmet

Training Phase:

The training phase begins with calibration of all sensors to ensure accurate environmental monitoring. The temperature sensor is tested against standard reference instruments to verify accuracy, and any deviation is corrected through software adjustments. The gas sensor is calibrated by exposing it to known concentrations of gases to establish a relationship between sensor output and ppm levels. Similarly, the oxygen sensor is calibrated to detect safe and unsafe oxygen levels in the environment.After calibration, threshold values are defined based on safety standards and real-world conditions. For example, maximum safe temperature limits are set to trigger the cooling fan, while minimum oxygen levels are defined to activate the oxygen supply system. Gas concentration limits are also established to detect hazardous conditions.These threshold values are stored in the ESP32 memory and can be adjusted based on the specific working environment. Periodic recalibration is recommended to maintain accuracy and account for sensor drift over time.

Testing Phase:

To validate the performance of the Smart Safety Helmet, a series of controlled experiments were conducted under simulated hazardous conditions. The system was tested by artificially increasing temperature levels to verify automatic activation of the cooling fan. Gas exposure tests were carried out to ensure that the gas sensor accurately detected harmful gases and triggered alerts.Low oxygen conditions were simulated to test the oxygen supply mechanism, confirming that it activates promptly when required. The GPS module was tested for real-time tracking accuracy, ensuring that location data could be reliably transmitted during emergency situations.Power reliability was also evaluated by testing the system under continuous operation and varying charging conditions. The system maintained stable performance, and all safety mechanisms responded correctly within acceptable time limits. Overall, the testing phase confirmed that the system is reliable, responsive, and suitable for real-world hazardous environments.

4. Hardware Results

The hardware evaluation of the proposed IoT-based Smart Safety Helmet confirmed that all components operated within expected performance limits under real-time conditions. The ESP32 microcontroller exhibited an average current consumption of approximately 70–90 mA during Wi-Fi transmission and reduced to 15–25 mA in idle mode, demonstrating efficient power utilization suitable for wearable applications.The temperature sensor (DHT11/DHT22) provided readings with an accuracy of ±1.5 °C to ±2 °C, effectively detecting unsafe thermal conditions. The system was configured to activate the cooling fan when the temperature exceeded 40 °C, which is considered a critical threshold for worker safety. During testing, the fan responded within 1–2 seconds, ensuring timely cooling.The gas sensor (MQ-135/MQ-2) successfully detected harmful gases such as CO_2 and smoke in the range of 100–1000 ppm, with a sensitivity suitable for industrial environments. A safety threshold of 300 ppm was set, above which the system triggered alerts. The sensor response time was observed to be 5–10 seconds, depending on gas concentration.The oxygen sensor monitored air quality effectively, with normal oxygen levels around 20.9%. The system was programmed to activate the oxygen supply when levels dropped below 19.5%, which is considered unsafe for human breathing. The response time for oxygen detection and activation was approximately 2–3 seconds.The cooling fan and oxygen supply system demonstrated reliable actuation performance. Both components were triggered accurately without delay once threshold conditions were met. The buzzer and LED alert system activated instantly (<1 second) to notify the worker of hazardous conditions, with no false triggering observed during testing.The GPS module (NEO-6M) provided location accuracy within 2–5 meters, enabling reliable real-time tracking of workers. Data transmission via Wi-Fi showed stable connectivity, with an average latency of 150–250 ms, ensuring near real-time monitoring on the IoT platform.The power system, consisting of a rechargeable battery and solar panel, maintained continuous operation. The system operated at 5V regulated output, with battery voltage ranging between 11.1V to 12.6V. Low-power alerts were triggered when voltage dropped below 10.8V, ensuring system safety and longevity.Overall, the hardware results confirm that the Smart Safety Helmet system delivers accurate sensing, fast response, reliable communication, and efficient power management, making it highly suitable for real-world hazardous environments such as construction sites, mines, and firefighting operations.

5. Prototype

The prototype of the proposed IoT-based Smart Safety Helmet was developed to validate the hardware design and demonstrate its real-time functionality in hazardous environments. The system is built around the ESP32 microcontroller, which acts as the central processing unit responsible for acquiring sensor data, controlling safety mechanisms, and managing wireless communication.The helmet integrates multiple sensors to monitor environmental conditions effectively. A DHT11/DHT22 sensor is used to measure temperature and humidity, enabling the detection of excessive heat. A gas sensor (MQ-135/MQ-2) is incorporated to identify harmful gases such as smoke and carbon dioxide, while an oxygen

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sensor continuously monitors oxygen levels to ensure safe breathing conditions for the worker.For safety actuation, the prototype includes a mini cooling fan that is automatically activated when the temperature exceeds the predefined threshold. An oxygen supply mechanism is also integrated, which is triggered when oxygen levels fall below safe limits. Additionally, a buzzer and LED indicators provide immediate alerts to warn the user about hazardous conditions.The communication system is implemented using a LoRa transmitter module (e.g., SX1278), which enables long-range wireless transmission of sensor data and emergency alerts to a remote monitoring station. This ensures reliable communication even in remote or underground environments where conventional networks may fail.The system is powered by a rechargeable battery supported by a solar panel, allowing continuous operation in off-grid conditions. A voltage sensor monitors the battery level and activates low-power mode when necessary to conserve energy.All components are compactly integrated into a helmet structure with proper insulation and secure wiring to ensure durability, user comfort, and safety. The prototype was tested under simulated hazardous conditions, including high temperature, gas exposure, and low oxygen levels. The system responded accurately and promptly, confirming its robustness and effectiveness for real-world applications such as construction sites, mining operations, and firefighting scenarios.

6. Results And Discussion

The hardware evaluation of the proposed IoT-based Smart Safety Helmet demonstrated reliable and efficient performance across all major subsystems under real-time conditions. The ESP32 microcontroller maintained energy-efficient operation, consuming approximately 70–90 mA during active communication and reducing to 15–25 mA in idle mode, validating its suitability for wearable applications. The temperature sensor provided readings within ±1.5 °C to ±2 °C accuracy, successfully triggering the cooling fan when the temperature exceeded the safety threshold of 40 °C, with a response time of 1–2 seconds. The gas sensor effectively detected harmful gases in the range of 100–1000 ppm, activating alerts above the set threshold of 300 ppm, while the oxygen sensor accurately monitored air quality and triggered the oxygen supply system when levels dropped below 19.5%, with a response time of 2–3 seconds. The alert system, including buzzer and LED indicators, responded instantly without false alarms, ensuring immediate user awareness. The LoRa communication module demonstrated stable long-range data transmission, achieving a range of 2–4 km in urban environments and up to 6–8 km in open areas, with an average latency of 250–500 ms, ensuring reliable alert delivery even in remote locations. The solar-powered battery system maintained continuous operation with voltage levels between 11.1V and 12.6V, and low-power protection was effectively triggered below 10.8V. Overall, the results confirm that the system achieves high accuracy, fast response, reliable communication, and efficient power management, making it highly suitable for enhancing worker safety in hazardous environments such as construction sites, mines, and firefighting operations.

7. Conclusion

The hardware evaluation of the proposed IoT-based Smart Safety Helmet confirms that the system effectively meets its objectives of energy efficiency, accurate environmental sensing, and reliable operation in hazardous conditions. The ESP32-based design, supported by a solar-powered battery system, ensures continuous functionality even in resource-constrained environments. The integrated temperature, gas, and oxygen sensors provided consistent and accurate readings, enabling timely detection of unsafe conditions, while the rapid response of the cooling fan, oxygen supply system, and alert mechanisms ensured immediate protection for the user. Furthermore, the use of LoRa communication enabled reliable long-range data transmission with low latency, making the system suitable for remote and underground applications where conventional networks are unavailable. Overall, the results validate that the Smart Safety Helmet is a practical, efficient, and scalable solution for enhancing worker safety in industries such as construction, mining, and firefighting, with strong potential for real-world implementation and future advancements.

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