Design and Implementation of a GSM-based IoT Smart Safety Helmet for Construction Workers

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ABSTRACT

The construction industry is recognized as one of the most hazardous occupational sectors, particularly in developing countries, where workplace accidents frequently result in serious injuries and fatalities. Falls from height, exposure to toxic gases, extreme environmental conditions, and inadequate supervision at remote sites are among the most common risks faced by construction workers. In most cases, personal protective equipment offered is usually inadequate, especially in the case of remote locations where construction supervision is not available. In light of these issues, this study proposes an IoT-based smart safety helmet intended for construction workers. The proposed system is designed with the ESP32 microcontroller as its core combining several sensors, such as the MPU6050 accelerator and gyroscope to identify falls, the DHT22 sensor to monitor temperature and humidity, the MQ-2 gas sensor to detect hazardous gases, and the NEO-6M GPS module to track real-time location. Remote construction sites are often devoid of Wi-Fi or cloud service and the proposed system relies on a GSM module for data transmission. The sensor data are sent to a web dashboard in ThingSpeak, based on the HTTP protocols, and the critical conditions cause the multi-channel alerts with the use of the onboard buzzer, dashboard notifications, and SMS messages to site managers. Experimental results demonstrate that the proposed helmet provides accurate real-time monitoring and dependable data transmission. The design of the helmet enhances its practicality and efficiency, especially in construction settings where workplace hazards and the risk of accidents are prevalent by merging low-cost, lightweight, and dependable communication technologies.

Keywords: IoT, Smart Safety Helmet, Construction Worker Safety, GSM Communication, Real-Time Monitoring

INTRODUCTION

A developing country such as Sri Lanka depends on the construction industry as one of the key economic growth drivers. Conversely, it has been identified as one of the riskiest industries in many countries worldwide, with a massive number of occupational accidents, injuries, and deaths. Construction site workers must perform various tasks that can involve multiple risks such as falling objects, slipping down a higher elevation, breathing of toxic gases and exposure to extreme temperatures. Falls from height were the most prevalent form of accidents that took place at construction sites in Sri Lanka, and this form of accident made up about 22% of the on-the-job accidents experienced by the construction workers [1]. Beyond this, 17% of accidents have occurred due to falling debris or objects [1,2]. The data showed that 13% of the incidents were located in the categories of the machinery accidents and the electrocution [1,2]. Moreover, among all incidents that occurred on Sri Lankan construction sites during the last decade, 11%, 7%, and 6% were the results of being caught between objects, slips/trips and falls, and fire and explosions, respectively [1,2]. Therefore, the most critical issues on a construction site are safety to eliminate numerous accidents that can lead to the loss of priceless lives and severe injuries. Nonetheless, the majority of accidents are associated with inadequate use of personal protective equipment and reliance on low-quality equipment. Additionally, there is no effective monitoring mechanism at the time of a possible accident at most sites. Therefore, it is highly essential to provide appropriate protective equipment to the workers of the sites as well as to secure the hazardous events detecting mechanism in real time, ensuring the safety of the workers.

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Most of the existing systems are based on AI-powered systems or IoT cloud platforms [3,4]. However, they are powerful and not suited to a resource constrained environment since they need more expensive costs, access to the internet, and consume more power. The other reason makes use of short-range communication units like the RF and HC12 that limit the reach and are likely to interfere with within the complicated site environment [5,6]. Helmets for mining purposes have convenient gas and temperature measurements but are heavily dependent on clouds and generally lack some features like fall or impact detection [7]. Similar to smart helmets with Wi-Fi and LoRa connectivity, the topic of which has received significant research interest, their application in the context of construction is severely lacking. The Wi-Fi systems depend on the unending internet connection that is never possible in temporary or remote construction sites [8]. Although LoRa systems provide extended communication ranges and low interference in high-density environments, their low data rates and high latency limit their suitability for real-time applications in construction sites [9]. Although cheap and effective, Bluetooth systems can only offer low bit rate and limited range and hence they are useless to construction sites [10]. All these lack identification of the issue why most of the designs cannot provide the correct coverage with low latency to be safe in the construction sites. The proposed system is unique with a GSM based method of communication unlike the available smart helmets. This can be applied in construction sites where there is no possibility of having stable Wi-Fi or cloud connection.

To address these challenges, this study proposes an IoT enabled smart safety helmet utilizing GSM based communication to ensure reliable data transmission in remote environments. The system focuses on real-time environmental monitoring, fall detection, and location tracking, enabling rapid response to hazardous events and improving overall worker safety.

SYSTEM DESIGN AND METHODOLOGY

Block diagram of the design

The functional block diagram of the system is shown in Figure 1.

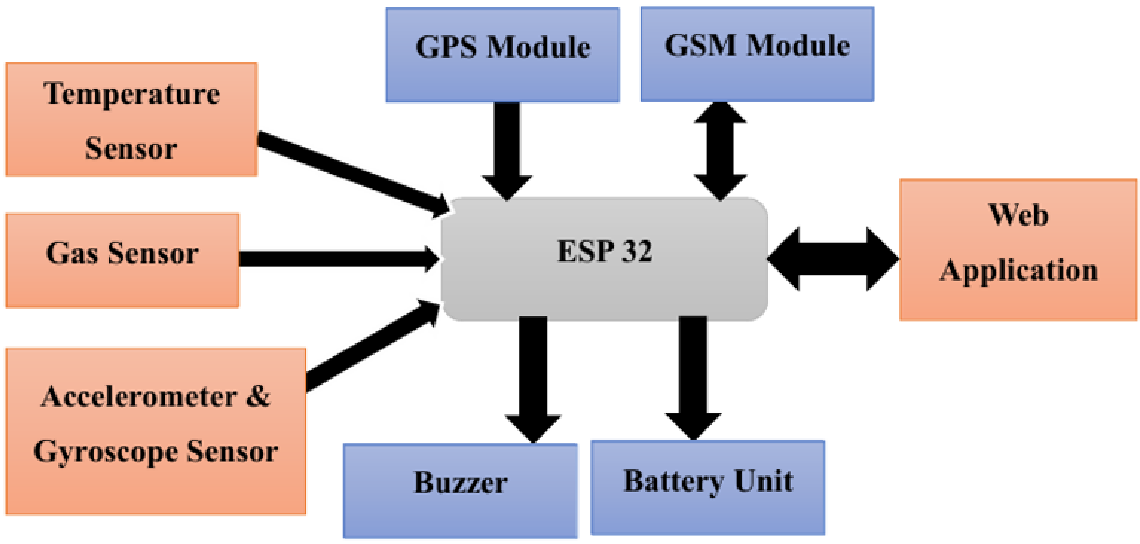

Figure 1: Block diagram of the system

The system introduces a gyroscope and accelerometer to detect sudden falls or impacts, a GPS module for real-time worker location tracking to identify the location when a sudden emergency occurs [11,12]. Temperature, humidity, and certain flammable gases are monitored and measured using environmental sensors [13,14]. In this system, the microcontroller acts as the central processing unit for the data collected from the sensors [15]. It manages the control logic, processes sensor data, and interfaces with the other system elements through command messaging. A GSM module is used for continuous data transmission to site managers. This ensures that the data coming from sensors on the helmet continuously reaches the control center in very remote or less developed areas. The SIM800L module is powered by a 3.7 V battery, while the rest of the system is powered separately by another 3.7 V battery.

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Circuit diagram

The development of the smart helmet system integrated sensing, processing, communication, and power modules into a single, compact, and wearable platform. ESP 32 was selected as the microcontroller to coordinate all system operations. MQ2 gas sensor, NEO-6M GPS module, Buzzer module, DHT 22 temperature and humidity sensor, MPU6050 gyroscope and accelerometer sensor, SIM800L GSM/GPRS module with antenna were used as the sensor modules for the smart safety helmet. A 2 A-rated LM2596 DC-DC buck converter was used to provide a stable 4 V output with a current capacity of up to 2 A [16]. Figure 2 below illustrates the circuit diagram of the system.

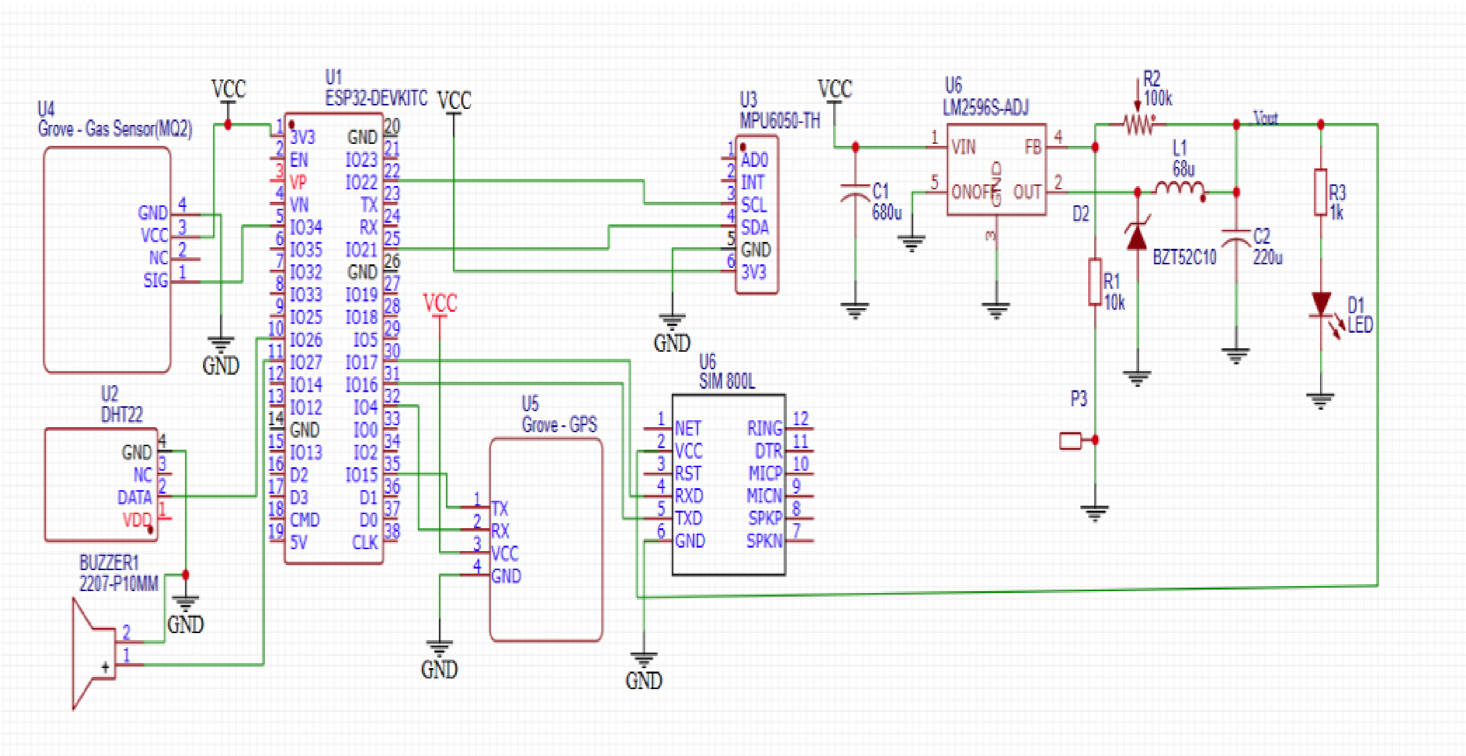

Figure 2:Circuit diagram of the system

The circuit diagram was implemented in a dot-board as shown in Figure 3.

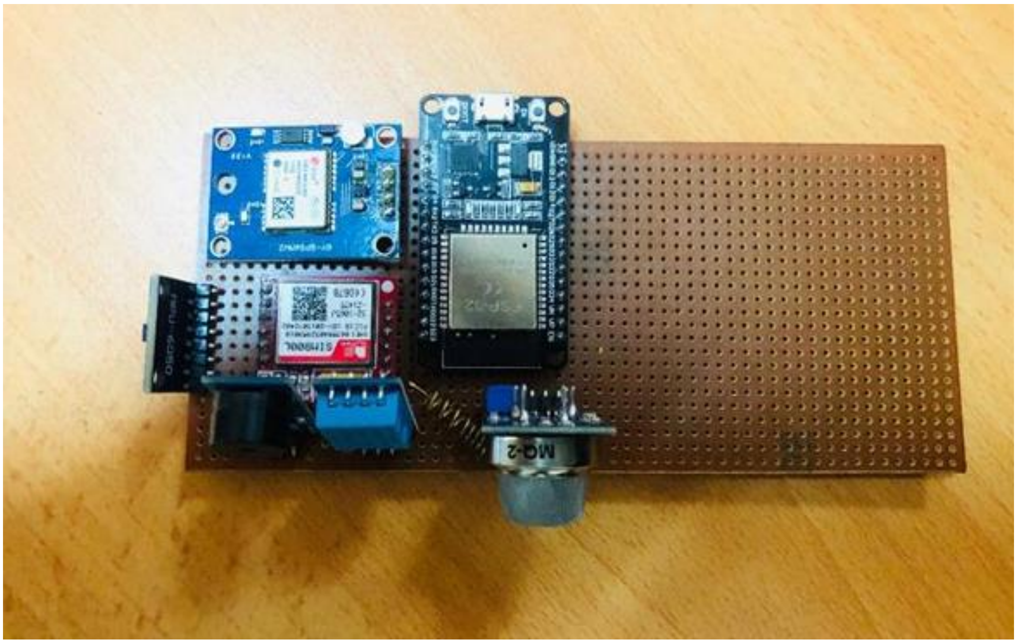

Figure 3: Prototype implementation of the circuit on a dot board

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Web Dashboard and Cloud Integration

The proposed smart safety helmet integrates with a web-based dashboard hosted on the ThingSpeak IoT platform, as shown in Figure 4, enabling real-time monitoring of worker safety. Sensor data including fall detection status, environmental parameters such as temperature, humidity, and gas concentration, and GPS location are transmitted via the ESP32 microcontroller using HTTP POST requests through the GSM module, ensuring reliable operation even in remote construction sites without Wi-Fi.

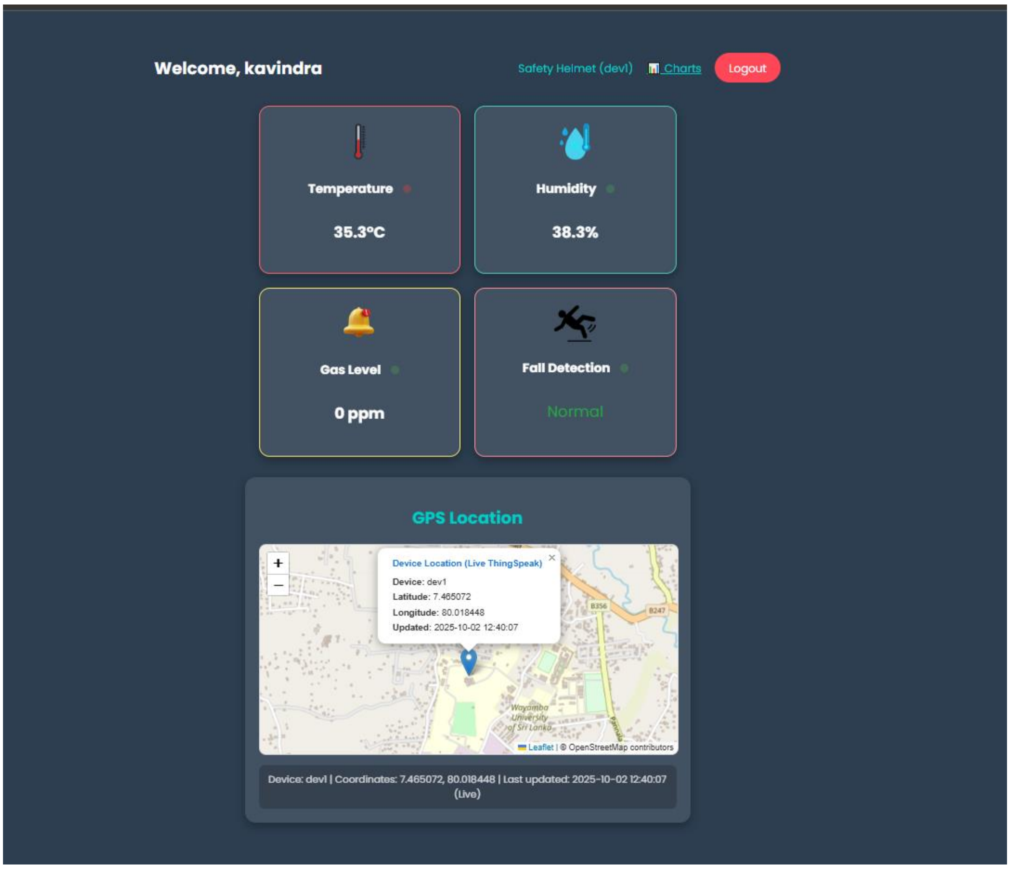

Figure 4:User sensor data view displaying temperature, humidity, gas levels, location view and fall detection alerts.

The dashboard displays environmental data through charts and gauges, while GPS coordinates allow real-time worker tracking. Critical events such as falls or hazardous environmental conditions trigger multi-channel alerts: an on-board buzzer, SMS notifications to site managers, and dashboard notifications indicating the worker's status and location. This integration provides timely hazard reporting, historical data storage for safety analysis, and potential scalability for advanced analytics and alerting systems.

Calibration and Detection Algorithms

Fall detection can be calculated through a combination of acceleration magnitude and tilt angle analysis. The total acceleration was calculated as:

$$A_m = \sqrt{a_x^2 + a_y^2 + a_z^2} \quad \text{--------} \ [1]$$

where ; A_m = Total acceleration

a_x = Acceleration along the x axis

a_y =Acceleration along the y axis

a_z = Acceleration along the z axis

A fall event was identified when the following conditions were simultaneously satisfied: (i) the total acceleration exceeded 2.5 g within a 300 ms interval, and (ii) the MPU6050 gyroscope recorded a tilt angle greater than 150°, indicating full inversion. These dual conditions were applied to minimize false positives.

Environmental sensors were calibrated using standard smartphone sensors as references. Hazardous conditions were defined as temperatures above 40 °C, relative humidity exceeding 85%, and gas concentrations greater than 250 ppm. The GPS module's performance was validated against smartphone geolocation data, with positional accuracy measured in meters.

RESULTS AND DISCUSSION

Sensor data analysis

All modules were tested individually and compared with corresponding smartphone sensor readings. GPS and environmental sensor validation is shown in Table 1.

Table 1: Environmental and GPS Sensor Accuracy

Parameter	Sensor Value	Smartphone Value	Accuracy (%)
Temperature (°C)	37.0	36.5	98.6
Humidity (%)	83	80	96.3
GPS Error (m)	±3.2	±3.0	93.8

The results of fall detection are summarized in Table 2.

Table 2: Fall Detection Performance

Test Condition	Acceleration (g)	Tilt Angle (°)	Detected Fall	Correct Detection (%)
Drop from 1.0 m (upright)	2.8	160	Yes	95
Drop from 1.5 m (side)	3.1	170	Yes	96
Sudden head tilt only	1.4	120	No	–
Running motion	2.2	<150	No	–

The system was initially tested in relatively controlled conditions that replications of real life and a realistic test was done to examine the performance of the system before its implementation in an actual construction setting. Each sensor was taken against the relevant benchmarks. For example, the DHT22 temperature and humidity sensor was validated using real-time weather data obtained from a smartphone weather application, whereas the MQ-2 gas sensor was tested under controlled conditions using liquefied petroleum gas (LPG) sourced from a lighter. The accelerometer-based fall detection system was tested using simulated controlled falls of different heights, and location tracking was tested at an open and partially covered location. It was also confirmed that the system had the capability of real-time transfer of data to the ThingSpeak cloud. The current prototype achieved approximately three hours of continuous operation using a single 3.7 V lithium-ion battery. While sufficient for proof-of-concept validation, this duration is not adequate for full construction shifts. Future work will incorporate power optimization techniques such as duty cycling, deep sleep modes of the ESP32, adaptive sensor sampling, and reduced GSM transmission frequency to significantly extend battery life. The extra weight of about 150 g of the electronic components was not deemed to be problematic since that weight did not have significant influence on the comfort of the users. The prototype IoT-based smart safety helmet, presented in Figure 5 was made possible by incorporating these sensors and modules into a small design.

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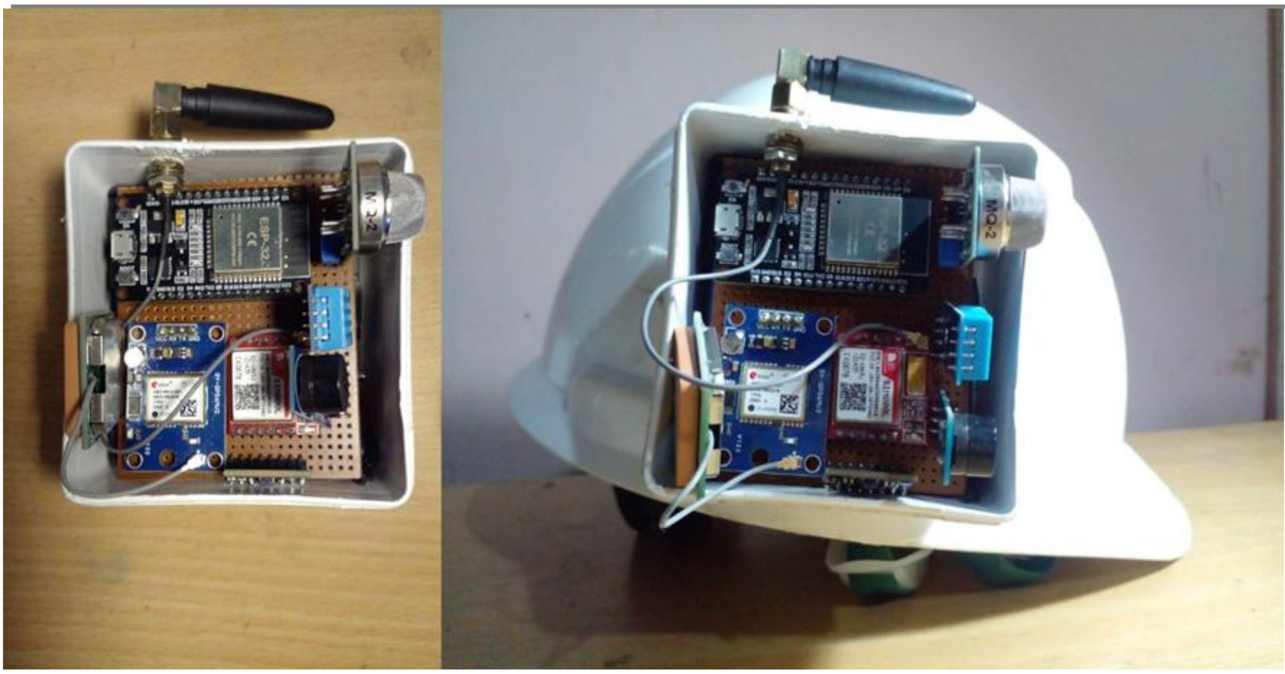

Figure 5:Final design of the system

The experimental validation of the proposed system was conducted under controlled and semi-field conditions with a limited number of participants. Although the results demonstrate reliable sensing and communication performance, large-scale field testing involving a greater number of construction workers and diverse site conditions is required to achieve higher statistical significance. This will be addressed in future deployments of the system.

Web application results and usability evaluation

Figure 6 illustrates the web-based IoT device management dashboard displaying real-time sensor data and hazard alerts.

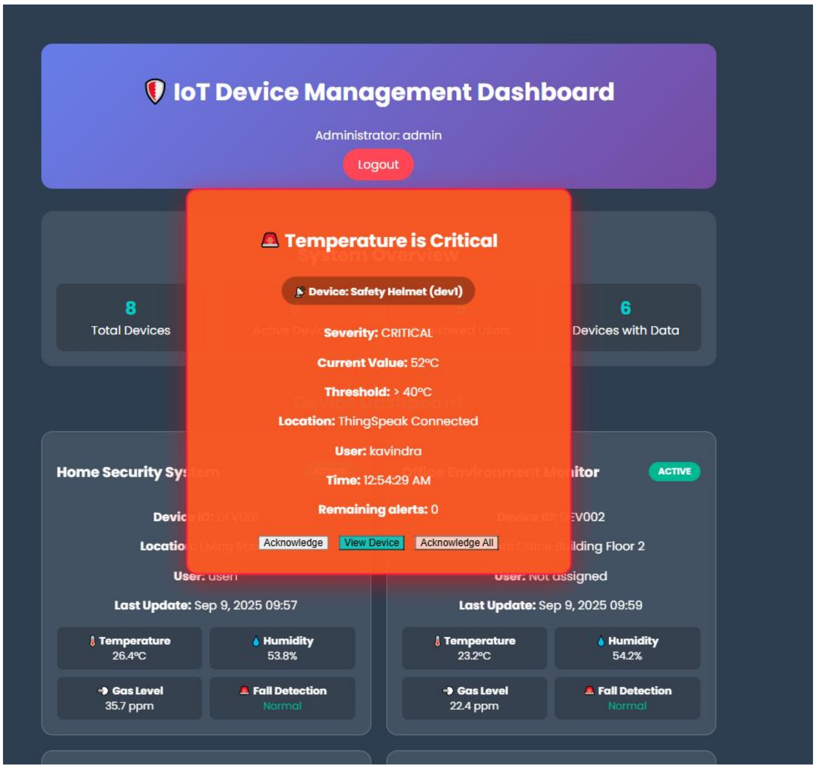

Figure 6:Web dashboard pop-up alert showing hazardous event details for timely user response.

The created web application was able to interact with ThingSpeak to deliver real-time monitoring and hazard alerts. The application enabled workers to enroll in the system and the site managers could view several workers at the same time via the administrative dashboard. Access to a registered worker's dashboard was also granted to their respective family members. Two participants were involved in the usability test to determine the level of ease of use and to confirm the user-friendly nature of the system. These findings revealed that the web application was successful in the usability test and provided an easily accessible platform on which the safety monitoring could be performed.

CONCLUSION

The study aimed to develop and introduce a smart safety helmet that has the ability to record environmental and activity-based parameters, which apply to the safety of construction workers. The prototype used several sensors as DHT22 temperature and humidity sensor, MQ-2 gas sensor, MPU6050 accelerating sensor, and GPS module. A GSM module was used to transmit data to the cloud, and ThingSpeak platforms were used to visualize the data. It also created a web application that helped the site managers and the family members to receive real-time information and hazard alerts. The system was tested in a semi-field environment to verify its functionality and performance. The prototype achieved its functions successfully and this was confirmed by the results of the experiment. The temperature sensor and the humidity sensor have been found accurate with acceptable error margins, and the gas sensor effectively responded to dangerous gas levels and gave alerts when the threshold was crossed. The fall detection system which used the accelerators was reliable in detecting falls and reducing false alarms. GPS tracking was useful in open places, but the accuracy deteriorated in partially covered areas. It was also observed that the GSM module was efficient in real-time data transfer with insignificant latency and acceptable loss of packets in weak signal areas. The web application has provided a convenient interface to the different stakeholders, which fosters situational knowledge and accessibility. Overall, this research contributes to the field by integrating multiple sensing, communication, and monitoring features into a single wearable device, offering a more comprehensive safety solution than conventional helmets, which typically monitor only a single parameter.

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