An IoT-Enabled Smart Safety Helmet for Enhancing Worker Protection on Construction Sites

Guan Chengg Wong[1*], Nurfikrizahusna Anizam[1], Nur Hadiana Nasruddin[1], and Che Zawiyah Che Hasan[2]

[1]Department of Electrical Engineering,
Politeknik Sultan Salahuddin Abdul Aziz Shah,
Persiaran Usahawan, 40150 Shah Alam Selangor, Malaysia.

[2]Department of Electrical Engineering,
Politeknik Ungku Omar,
Jalan Raja Musa Mahadi, 31400 Ipoh, Perak, Malaysia.

*Corresponding Author's Email: guanchengg.wong@gmail.com

Article History: Received 4 January 2025; Revised 20 June 2025;
Accepted 28 June 2025; Published 30 June 2025

Abstract

Construction sites are hazardous environments where workers are frequently exposed to heavy machinery, extreme temperatures, and various harmful materials. These conditions significantly increase the risk of both fatal and non-fatal accidents. Although conventional personal protective equipment such as safety helmets is widely used, it typically lacks real-time hazard detection and rapid emergency response capabilities. This study presents the design and prototype development of an IoT-enabled smart safety helmet aimed at enhancing worker protection through continuous environmental monitoring and automated hazard alerts. The helmet integrates gas, temperature, and light sensors with a NodeMCU ESP32 microcontroller. This integration enables automated activation, real-time data acquisition, and wireless transmission to a central monitoring dashboard. The system features onboard decision-making that triggers alerts when sensor readings exceed predefined safety thresholds, providing immediate feedback and facilitating prompt preventive action. Sensor data are transmitted via Wi-Fi to allow real-time supervision and automated incident logging. The prototype was initially validated under simulated hazardous conditions and subsequently tested on active construction sites to assess its functionality in real-world environments. Results indicate that the smart helmet effectively detects hazardous conditions and delivers timely alerts, thereby enhancing worker protection and situational awareness. A comparative analysis between IoT-equipped and non-equipped zones confirmed improved risk mitigation and supervisory responsiveness. These findings highlight the potential applications of IoT-based smart safety helmets as a promising wearable device for improving health and safety management in high-risk construction environments, aligned with the broader goals of Industry 4.0.

Keywords: Construction Safety, ESP32 Microcontroller, Internet of Things (IoT), Safety Helmet, Smart Wearable Device

1.0 Introduction

The construction site is globally recognised as among the most hazardous work environments that consistently report the highest number and rate of fatal work injuries, as evidenced in the 2023 reports by the United States Bureau of Labour Statistics [1], [2], [3], [4]. Workers on the construction sites are frequently exposed to multiple risks such as heavy machinery, extreme temperatures, and hazardous materials [2]. Common types of construction site accidents include falls from height, slip and trip incidents, machinery-related injuries, and head trauma [2], [3], [4]. Although the use of personal protective equipment (PPE) is mandated by safety regulations, existing PPE has not been entirely effective in mitigating on-site risks [4]. Moreover, conventional PPE lacks the capability for automatic hazard detection and real-time warning activation, particularly in unforeseen situations [3]. PPE refers to equipment designed to protect workers from workplace hazards by reducing the impact of accidents should they happen [4]. Among the most widely used PPE is the safety helmet, which primarily protects against direct impacts to the head [4]. However, traditional safety helmets provide only passive protection and cannot detect environmental threats or issue real-time alerts that could prevent serious injuries or fatalities [4], [5], [6], [7], [8].

With the rapid advancement of digital technology, worldwide researchers and industry stakeholders are increasingly integrating smart features into safety helmets through the Internet of Things (IoT) [7], [8], [9], [10], [11], [12], [13]. IoT technology enables devices to automatically collect, process, and transmit data, allowing real-time situational monitoring and rapid decision-making. Smart helmets and other PPE equipped with embedded sensors and wireless communication modules have been developed to detect hazards such as toxic gases, excessive heat, and inadequate lighting conditions [7], [10], [11]. However, many of these current systems rely on manual activation with limited sensing capabilities and are unable to deliver timely alerts when critical safety thresholds are exceeded [8], [13].

This study addresses these limitations by presenting the design and development of an IoT-enabled smart safety helmet that enhances worker protection through real-time environmental sensing and automated hazard alerts [14], [15], [16], [17], [18]. The proposed system integrates gas, temperature, and light sensors with a NodeMCU ESP32 microcontroller and Wi-Fi connectivity [19], [20], [21], [22], [23]. The helmet is designed to operate automatically when worn. In contrast to earlier systems that employed limited sensors or short-range protocols such as Zigbee [10], this prototype offers a fully integrated solution featuring multiple sensors, cloud-based alerts, and real-time monitoring [24], [25], [26], [27]. The novelty of this research lies in its fully integrated, self-contained design, incorporating onboard intelligence within a wearable device. This work contributes to the advancement of smart safety helmets as a promising smart wearable equipment for improving health and safety management on construction sites.

2.0 Methodology

This section outlines the design, prototype development, and evaluation of the IoT-enabled smart safety helmet to enhance worker protection on construction sites. The system is designed with integrated sensors and a NodeMCU ESP32 microcontroller to monitor gas, temperature, and light conditions. It employs Firebase as a cloud-based platform for real-time data transfer, alerts, and remote monitoring. The methodology includes system design, sensor calibration and field testing, and threshold parameter setting.

2.1 System Design and Workflow

Figure 1 presents the block diagram of the proposed IoT-enabled smart safety helmet, which comprises four primary input components: the gas sensor (MQ-2), temperature sensor DS18B20, light sensor module, and distress switch. These input components are interfaced with the NodeMCU ESP32 microcontroller, which functions as the central processing unit. The ESP32 processes the sensor data and generates corresponding output signals to actuators, including a buzzer, a light-emitting diode (LED), and a headlight. The system is powered by a direct current (DC) power supply and connected to a Wi-Fi network for data transmission to a Firebase IoT server and a user application for remote monitoring and real-time alerts.

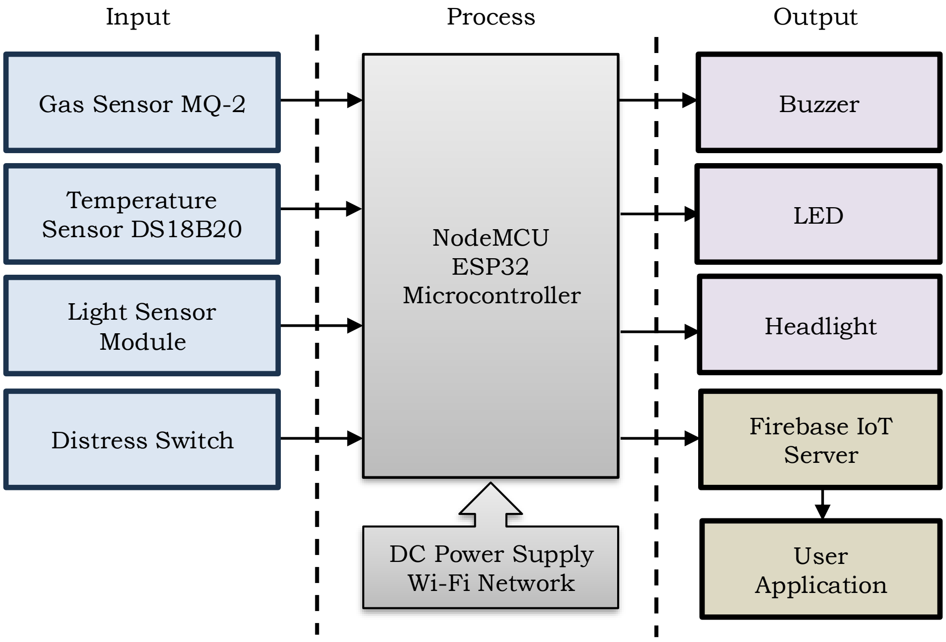

Figure 1: Block diagram of the IoT-enabled smart safety helmet for hazard detection on construction sites

The safety helmet is designed to enable real-time environmental monitoring and improve worker protection in construction settings. It detects immediate hazards and stores data locally during offline periods, which is automatically synchronised with the Firebase cloud platform once connectivity is restored. This feature ensures uninterrupted safety coverage and contributes to hazard trend analysis for planning and safety management.

Firebase is a cloud-based application development platform by Google, which is utilised as the backend system for the helmet [14]. It provides real-time database updates, user authentication, file storage, and push notifications capabilities, allowing continuous data synchronisation and immediate alert delivery. Firebase also enables scalability, enabling multiple helmet units to be managed within a single project and monitored remotely through a centralised platform [14].

Figure 2 illustrates the system workflow. The process begins with system initialisation, followed by verification of Wi-Fi and server connectivity. Once a stable connection is established, the system enters a continuous monitoring loop. At fixed intervals of 15 seconds, data is gathered from the gas, temperature and light sensors, along with the distress switch. This data is transmitted to the Firebase server for real-time tracking and cloud storage [14]. Sensor readings are continuously evaluated against predefined safety thresholds. When abnormal conditions are detected, such as excessive gas levels, high temperature, or inadequate lighting, the system triggers alert mechanisms, including activation of the buzzer, LED, or headlight. The distress switch enables the manual system to reset following an alert. This structured workflow ensures timely hazard response while minimising false alarms and maintaining reliable data logging for ongoing safety management [10], [14], [19].

2.2 Sensor Calibration and Testing

Three environmental sensors were selected to detect common hazards found on construction sites. The gas sensor is used to detect harmful gases in the air. It measures gas levels in parts per million (ppm) and has been set with threshold values that trigger alerts when unsafe levels are detected [12], [22]. The light sensor monitors ambient brightness to ensure adequate visibility. It works well in different lighting conditions, from bright daylight to complete darkness [21]. The temperature sensor helps monitor heat levels and detect dangerous conditions, such as very high or very low temperatures that could harm the worker [22].

Each sensor was calibrated according to the manufacturer's specifications using standard reference tools to ensure accurate and reliable measurements. Initial tests were conducted in a controlled laboratory environment by manually varying gas levels, temperature, and light intensity to evaluate sensor responsiveness. Subsequent field testing was performed at real construction sites to assess the system's real-time performance under dynamic conditions, where the environmental factors and potential hazards fluctuate throughout the working day [11], [15], [21].

Sensor readings from both testing phases were analysed by comparing them against predefined threshold values. Alerts were configured to trigger at 2000 ppm for gas, above 37°C for temperature, and low ambient light levels. The accuracy of the sensor output was verified against standard measuring instruments. Firebase's cloud infrastructure ensured secure and uninterrupted data logging, even during brief offline periods [14], [16], [21].

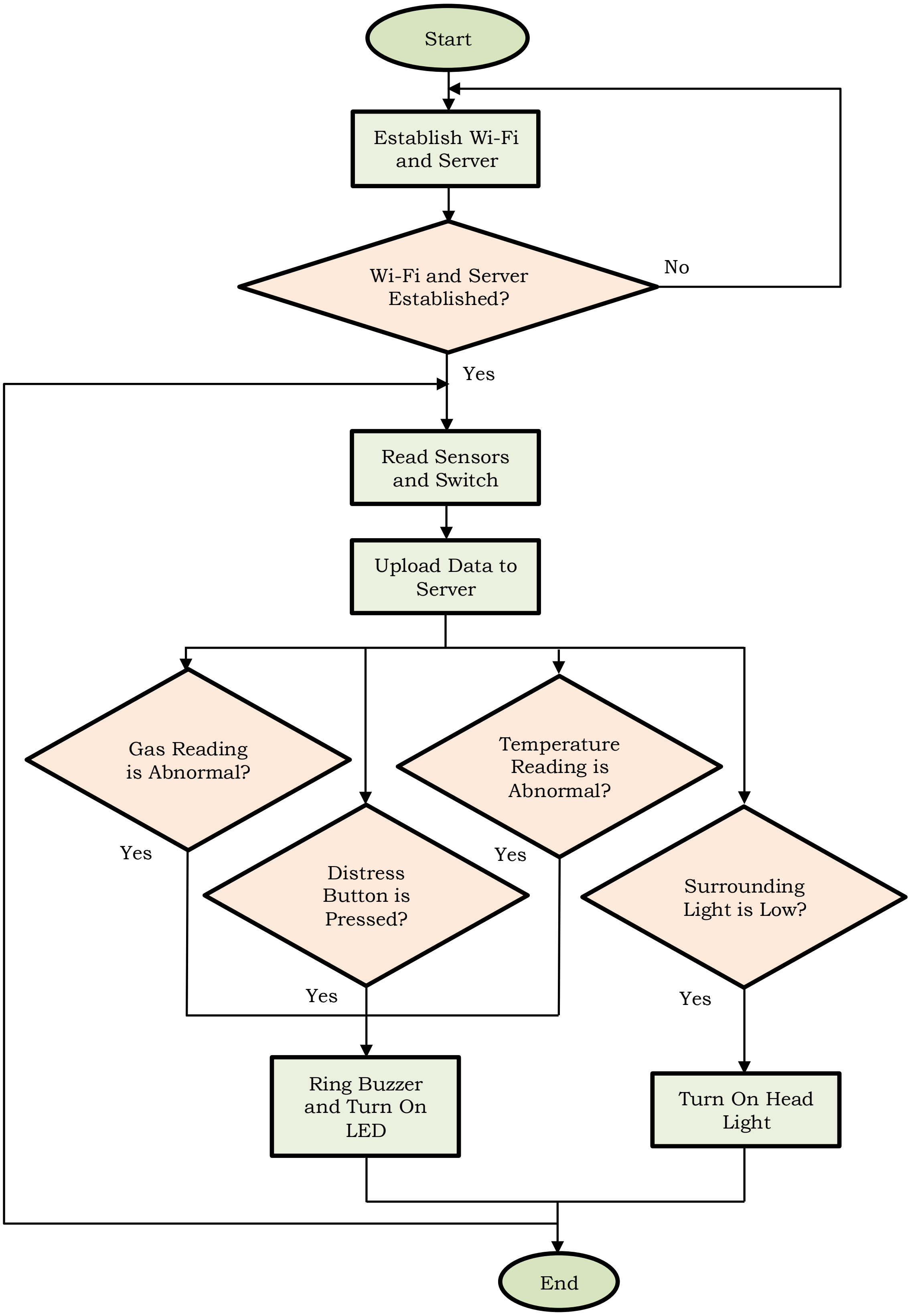

Figure 2: The system workflow of the IoT-enabled smart safety helmet for dynamic hazard detection on construction sites

2.3 Threshold Parameters and Alert System

To enable accurate hazard identification, threshold parameters were established for each sensor integrated into the IoT-enabled smart helmet. These thresholds were categorised into three levels: normal, warning, and dangerous. Each level was associated with a distinct alert colour. This design provides workers and supervisors with clear, real-time feedback on environmental safety conditions.

Table 1 summarises the sensor thresholds, corresponding alert levels, and colour indicators. These values were defined based on established occupational safety standards and validated through both controlled and field testing [22], [23], [24]. Implementing these sensor thresholds enabled prompt hazard detection and effective alert generation during high-risk conditions. The parameter framework significantly enhances situational awareness, safety responsiveness, and the overall functionality of the system within dynamic construction environments [25], [26].

Table 1: Sensor threshold parameters and alert levels

Sensor Type	Condition	Threshold	Level	Alert Colour
Light Sensor	Bright	0	Normal	Green
	Dark	1	Dangerous	Red
Temperature Sensor	Safe	< 28°C	Normal	Green
	Moderate	28°C - 37°C	Warning	Orange
	High	> 37°C	Dangerous	Red
Gas Sensor	Safe	< 1800 ppm	Normal	Green
	Moderate	1800 ppm - 2000 ppm	Warning	Orange
	Unsafe	> 2000 ppm	Dangerous	Red
Distress Switch	Pressed	1	Reset	N/A

3.0 Results and Discussion

The IoT-enabled smart safety helmet demonstrated effective performance in monitoring dynamic environmental conditions and facilitating proactive hazard response. Both controlled laboratory tests and real-world simulations confirmed its ability to accurately detect variations in light intensity, ambient temperature, and gas concentration, while triggering timely alerts for workers and supervisors. The integration of real-time monitoring, cloud-based data transmission, and automated alerts validated the system's practical utility to improve safety on construction sites.

A working prototype of the smart helmet was successfully developed with a compact integration of all components. Sensors were positioned at the top of the helmet for optimal environmental exposure. Figure 3 displays the developed prototype, highlighting the sensor integration and functional layout suitable for field deployment.

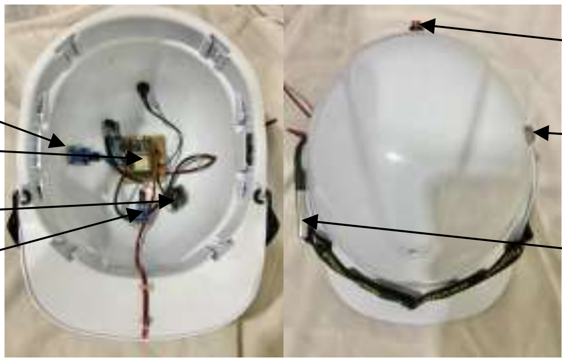

Figure 3: The developed prototype of the IoT-enabled smart safety helmet

To assess system functionality, five simulated scenarios representing common construction site conditions were reconstructed in the laboratory. Table 2 maps real-world hazards to corresponding simulated conditions. Situations A, B, and D represented hazardous conditions such as low visibility, gas presence, and high temperatures. Meanwhile, Situation C and E simulated safe environments.

Table 2: Simulated environmental situations based on construction site hazards

Situation	Real-world Hazard	Simulated Condition
A	Low light and high temperature	Dim lighting and elevated temperature
B	Presence of smoke/gas	Controlled release of non-toxic gas
C	Bright light and normal temperature	High illumination with ambient temperature
D	Low light and presence of smoke/gas	Dim lighting with gas exposure
E	Safe conditions	Normal lighting and temperature

Table 3 outlines the system's feedback and corresponding worker actions. In hazardous situations (A, B, and D), the buzzer was triggered, prompting immediate evacuation. In safe conditions (C and E), no alarm was activated. The safe conditions allow workers to proceed with their work without interruption. These results affirm the system's ability to accurately classify environmental conditions and support timely and appropriate responses.

Table 3: Worker response to system feedback

Situation	Buzzer	Worker Action
A	On	Evacuate the area immediately
B	On	Evacuate the area immediately
C	Off	Continue work as usual
D	On	Evacuate the area immediately
E	Off	Continue work as usual

Table 4 presents the supervisor dashboard alerts and responses via Firebase. The dashboard displays sensor readings, alert colours, and supervisory actions based on each situation. Hazardous conditions produced red alerts and alarms, which prompt immediate action. Safe readings generated green or orange indicators, which require no further action. This confirms the reliability of cloud integration and the system's effectiveness for remote safety monitoring. These findings confirm that the helmet enables responsive decision-making and promotes a safer working environment through real-time cloud-based alerts and data logging.

Table 4: Supervisor monitoring via the Firebase platform and corresponding supervisory actions

Situation	Sensor Readings	Alert Colour	Alarm	Supervisor's Response
A	Light: 1 Temperature: 38.52°C	Red Orange	On	Alert nearby workers
B	Smoke: 3895.00 ppm	Red	On	Initiate emergency response
C	Light: 0 Temperature: 36.55°C	Green Orange	Off	No action required
D	Light: 1 Smoke: 4190 ppm	Red Red	On	Initiate emergency response
E	Light: 0 Temperature: 30.95°C	Green Green	Off	No action required

While the system performed reliably, several areas for improvement were identified. Prolonged use in hot environments led to minor warming of internal electronics, potentially affecting user comfort. Future iterations should incorporate heat-dissipating materials or miniature cooling elements. Additionally, enhancements such as waterproof casings, impact resistance, and dust protection are essential for long-term durability in harsh site conditions [26], [28].

From a usability perspective, the helmet must remain lightweight and well-balanced to avoid worker fatigue. Visual features such as coloured indicator lights could help identify specific worker roles on-site, like supervisors or electricians. For wider industry adoption, the helmet must comply with established safety standards. Certification will support integration into workplace safety protocols and improve stakeholder confidence [28], [29].

Unlike earlier smart helmets with limited sensing capabilities and no real-time connectivity, the proposed system integrates multiple sensing technologies, structured alert mechanisms, and cloud-based monitoring through the Firebase platform [7], [10], [15], [13]. With targeted refinements, the helmet has strong potential for commercialisation and broader application in other high-risk sectors such as mining, oil and gas, and manufacturing.

4.0 Conclusion

This study presented the design and prototype development of an IoT-enabled smart safety helmet to enhance worker protection on construction sites. The system successfully integrated gas, temperature, and light sensors with a NodeMCU ESP32 microcontroller and Firebase cloud platform to enable real-time hazard detection, alert generation, and remote monitoring. Controlled laboratory and simulated field testing confirmed the system's effectiveness in identifying unsafe environmental conditions and its ability to trigger timely alerts for both workers and supervisors. The smart helmet demonstrated effective functionality in distinguishing between hazardous and non-hazardous situations. These features reduced the risk of false alarms and support proactive safety management on construction sites. Data synchronisation through Firebase ensured continuous tracking, even during temporary disconnections, which contributes to long-term hazard trend analysis and planning. Evidence from controlled experiments and field trials confirms its efficacy in identifying dangerous gas levels, extreme temperatures, and low visibility, with real-time alerts ensuring timely responses. Data transmission to the cloud supports continuous monitoring and informed decision-making. Future improvements such as the global positioning system (GPS) integration, geofencing, and enhanced power efficiency, are expected to increase system reliability and functionality. With its scalable design and alignment with Industry 4.0 and international occupational safety standards, the smart helmet demonstrates strong potential for commercialisation across other high-risk sectors, including mining and manufacturing.

Acknowledgement

The authors wish to express their sincere gratitude to the Department of Electrical Engineering, Politeknik Sultan Salahuddin Abdul Aziz Shah, for providing the facilities and technical support essential to the successful completion of this project.

Author Contributions

Wong Guan Chengg: Data Curation, Analysis, Data Validation, Writing – Original Draft, Resources, Visualisation, Writing – Review & Editing;
Nurfikrizahusna Anizam: Conceptualisation, Data Curation, Methodology, Formal Analysis, Investigation, Resources, Writing – Review & Editing;
Nur Hadiana Nasruddin: Conceptualisation, Supervision, Methodology, Software, Data Validation, Writing – Review & Editing;
Che Zawiyah Che Hasan: Writing – Review & Editing, Visualisation.

Conflicts of Interest

The manuscript has not been published elsewhere and is not under consideration by any other journals. All authors have approved the review, agree with its submission, and declare no conflicts of interest in the manuscript.

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