Design, Deployment, and Validation of Smart Safety Gear for Risk Mitigation for building Sustainable Urban Infrastructure

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Abstract. The Construction Industry has always been allied with high-risk construction activities due to its fast pace of infrastructure development, and as a result of which the safety of workers has become a grave concern. Recent research developments indicate that integration of advanced technology within the conventional safety equipment used in the conventional process of construction presents a promising solution for risk management in real-time on various multifunctional sites [12], [21], [22].
The main focus of this research was to highlight and appraise how wearable safety devices can be implemented while confronting these safety issues and also building sustainable infrastructure. The device operates on a range of cautiously chosen environmental and physiological sensors that detect the various threats common on a construction site, thereby reducing the occurrence of accidents, and draft mitigation strategies, thereby enabling advancements in safety practices within construction industry.
The research methodology was implemented in different phases, which includes preliminary literature review, identification of Research gaps, prototype development of various smart sensors for temperature, motion, and gaseous emissions, deployment of a prototype in varied site circumstances for testing its effectiveness in hazard detection, natural performance, and user experience being recorded. These visibly reduced incidence rates and improved safety were confirmed through Field validation. These findings are a clear indication that enhancement of workers' well-being through smart safety wear can be a monumental breakthrough in construction safety practice norms.

Keywords: Smart Safety Gear, Personal Protective Equipment (PPE), Sustainable Building, Sensors, Urban Infrastructure

1 Introduction

The construction industry is also referred to as one of the most perilous workplaces globally [9]. In the light of the frequency of critical accidents, despite safety legislations and enforcements in place, such as the Building and Other Construction Workers Act of 1996, statistical data indicates that it still remains excessively high in the Indian Industry where more than 71 million workforces toil day in and out. Death rate due to falling, electrocution, and getting struck-by remain amongst the leading causes of fatalities in the construction industry [10]. Globally, the figures of occupational deaths in the construction industry account to nearly 20%, so it is

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imperative that immediate and arduous measures be adopted including the most recent safety technologies to tackle these staggering figures and concerns [22].

Despite the mandatory criterion of use of Personal Protective Equipment (PPE) in the construction sites, the traditional apparel functions largely as a passive protection, with provision of active protection being very limited [10]. Low technological intervention along with the lack of proper enforcement of safety measures on-site in India, along with accident avoidance remaining highly dependent on manual verification and manual monitoring. All this further adds to strict safety measures required for the advancement and wellbeing of the safety concerns of the construction industry.

Recent advancements in the field of technology, IoT sensors, wireless communication, and predictive analytics has flourished and enabled the rise of "smart PPE." These devices monitor site conditions in real time, detect anomalies, and send automated alerts, thereby transforming safety management from a reactive process to a proactive one [23], [24]. Research further indicates that smart safety systems not only reduce accident frequency but also contribute to sustainability by aligning with green construction protocols [12], [18]. This study therefore proposes a multi-sensor, ergonomic safety system compliant with standards such as ISO 45001 [9], specifically tailored for Indian and other emerging market contexts.

2 Literature Review

2.1 Introduction

The literature reviewed lays out the technological, methodological, and contextual basis for the design and validation of these safety systems.

2.2 Intelligent Systems and Construction for IoT Applications

Nagarajan et al. [13] in the paper, "Experimental Investigation of Advanced Smart Concrete Curing by Application of Internet of Things (IoT) Technology" [2] [3] presents that curing productivity can be heightened through the usage of real-time data gain and computer-controlled regulation that is safe and precise. This example illustrates the significance of IoT-based monitoring in supporting situational awareness, one of the main sensor-integrated protection gear requirements in constructions.

It was then succeeded by another paper titled "Real-Time Water Leakage Monitoring System Using IoT Based Architecture" by Nagarajan et al. in 2019. It created a sensor network system utilizing low-cost IoT devices and communication technologies. It demonstrated that real-time system monitoring and real-time notifications could be combined for both wearable and infrastructure safety systems to detect potential threats such as gas leaks or excessive heat [8] [22].

2.3 Risk Identification and Management Frameworks

"Risk Management Appraisal – A Tool for Successful Infrastructure Project" and "Multi-Analytical Approach for Risk Identification and Its Management for Successful Infrastructure Projects" [12] [15][16] are studies which indicates multi-criteria systems and analytical schemes that help in risk assessment, prioritizing, and mitigation. Extending such structured methods to the project-worker safety level enables a solid foundation for quantifying the effectiveness of smart protection attire in reducing hazard exposures.

Moreover, "Risk Assessment and Challenges Faced in Repairs and Rehabilitation of Dilapidated Buildings" [5] [17] confronted case-centric issues in building rehabilitation and presented real-time monitoring solutions for safety improvement. This is in alignment with PPE integration based on sensors that can offer real-time feedback and mitigate risk during rehabilitation and demolition activities.

2.4 Design Thinking and Innovation in User-Focused Safety

The research paper, "Smart Multi-Purpose Disaster Management Kit Configured by Design Thinking Approach for Community Use" [2] [14], mentions the need for integrating design thinking in the safety innovation sector. User-centricity is of particular importance in developing smart safety attire, such that ergonomics, usability, and contextual fitting become important factors. [3] [13]

2.5 Safety and Efficiency through Technological Integration

In the study titled "Enhancing Construction Safety and Efficiency in Brownfield Petroleum Refinery Expansion: A Feasibility Study of Modular Construction in India" [11] [18], the use of modular construction was examined as a strategy to mitigate worker exposure to hazards. The results indicated that the integration of engineering advancements with digital safety systems leads to a substantial reduction in risk, thus endorsing the use of smart wearables as supplementary safety devices within both modular and traditional construction endeavors. [25]

Similarly, "Emerging Software Techniques in Construction Industry" [19] explored the integration of artificial intelligence, IoT, and Building Information Modeling (BIM) for the creation of safety analytics and decision-making. The study revealed the ways in which data-driven methods form the basis for predictive PPE systems that could sense anomalies and alert workers before their occurrence.

2.6 Human Factors and Safety Performance

Nagarajan et al. [20], in "Analysis of Labour Productivity and Determining the Parameters Which Affect It in Aluminum Formwork System," [5] examined productivity and safety and determined that productivity and safety were affected by significant factors including environmental stress, site conditions, as well as fatigue. The integration of biometric and environment sensors with wearable PPE addresses these factors by monitoring workers' health and environment in real time, thereby enhancing performance as well as accident avoidance.

2.7 Advancements in Modular Construction, Risk Management, and Intelligent Systems in Infrastructure Projects

The diverse exposition of research contributions by Nagarajan and Narwade along with their colleagues ranges from modular construction to risk management, digital innovation, to intelligent systems for infrastructure. The use of modular construction to improve safety, efficiency, and sustainability in sustainable urban and smart city developments was presented by Sawant et al. (2025) and Yadav et al. (2025). Risk management techniques for effective project delivery were stressed by Shankarrao et al. (2023), followed by the use of new software methods to redefine the construction industry, presented by Kulkarni et al. (2023). Some previous examples of contributions toward 4D GIS applications for planning purposes were presented by Mohanlal et al. (2019) for effective planning, along with resource optimization techniques for future cities, presented by Patil et al. (2019). Moving on to the applications involving IoT, the use of helmets, vests, and sensors for hazard detection was presented by Rasouli et al. (2025)'s work, followed by IMUs, safety vests, and prevention of musculoskeletal disorders, presented by Purushothaman et al. (2025).

2.8 Intelligent Systems and IoT for Construction Applications

Rasouli et al. [23] documented the functionalities of helmets and vests equipped with sensors that can identify hazardous gas levels and structural deficiencies, swiftly transmitting notifications to supervisors. Furthermore, Purushothaman et al. [21] highlighted the use of advanced technologies—such as wearable Inertial Measurement Units (IMUs) and interconnected safety vests—in tracking movement and reducing the likelihood of musculoskeletal disorders within the workplace. [22]

2.9 Systems of Risk Identification and Management

The models of Smart Construction Safety Technology (SCST), as examined by Kim et al. [26], entail integrating environmental sensors, CCTV surveillance, and wearable technologies with the aim of realizing connected safety observation. Real-world implementations in South Korea indicated improved effectiveness in small to medium constructions but also hinted at the requirement for user collaboration as well as ergonomics. All the studies analyzed recommend digital risk management strategies that integrate real-time observation with predictive modeling with the aim of lowering the occurrence rate.

2.10 Design Thinking and User-Centered Innovation in Safety

Research for the industry emphasizes that smart safety gear adoption is reliant on user comfort, cultural acceptability, and ease of use being addressed as design priorities. Purushothaman et al. [21] push for products to follow multi-phase development strategies—ideating with site experts, prototype development, and repeated testing—in order for gear to fit real-world construction realities and achieve maximum take-up.

2.11 Safety and Effectiveness through Technology Integration

Rasouli et al. [23], in their work titled "Smart Personal Protective Equipment (PPE) for Construction," highlighted that the implementation of smart PPE systems enhances incident response and mitigates disruptions in work by effectively communicating hazards to supervisors, thereby elevating overall project efficiency. Purushothaman et al. [21], in their article "SMART Technologies that Influence Construction Health and Safety," examined how the convergence of IoT with BIM and machine learning enables real-time predictive safety protocols, which in turn fosters efficient and environmentally conscious operations. The AZoBuild publication [25] underscored the significance of smart wearables in reducing downtime and bolstering safety management across construction sites.

2.12 Human Factors and Safety Findings

Kim et al. [26] in "Effectiveness Analysis for Smart Construction Safety Technology" determined that fatigue management and site adaptability were key to successful smart gear implementation with notably lower injury rates through bespoke ergonomic solutions. Purushothaman et al. [21] reinforced in their design-oriented studies that user-friendly practical features, such as cultural and ergonomic design, were key to enhanced safety performance and mass adoption. Rasouli et al. [23] reinforced these findings with empirical research into workers' behavioral adaptation through advanced PPE, verifying significant safety compliance and reduced incidents. [28]

3 Research Gap and Contribution

Conventional Personal Protective Equipment (PPE) used in the construction industry lacks the capability for real-time hazard detection and response. Such equipment generally lacks modern technologies like embedded sensors for immediate hazard detection, proactive alerting, and two-way communication capabilities, limiting its effectiveness in averting accidents [10], [23]. Moreover, conventional PPE often disregards ergonomic design, which affects worker comfort and adoption, and it lacks modularity for adaptation across varied site conditions [24], [26]. These deficiencies are particularly a grave concern in India, where statistics show the poor implementation of PPE and significantly lagging safety practices contributes to high accident rates [22]. The use of advanced sensor-integrated PPE in construction industry is emerging in the current Global scenario; however, the adoption of the same practice still remains limited and unpopular in Indian construction, which is mostly caused due to budget constraints and regulatory enforcement challenges [18], [21].

This study addresses these gaps by developing a smart safety gear solution presenting integration of multiple sensors for real-time environmental and physiological monitoring [10] [13][19]. It employs a live dashboard for continuous monitoring and user-friendly interfaces to enhance functionality and compliance [8]. The gear's ergonomic and modular design ensures adaptability to diverse work environments, aiming to shift safety practices from passive to proactive [14], [21]. Additionally, the system aligns with international standards and emerging privacy frameworks [9], [11], facilitating scalable and responsible deployment. The research gaps addressed by this study are detailed in Table 1.

Table 1. Research Gap and Contribution

Identified Gap	Addressed In	Font size and style
No real-time alert system in existing PPE	Sensor Integration + Dashboard	GSM, push-button alerts; dashboard alerts in 3–5 sec
Absence of two-way communication	Methodology, Sensor Design	SIM900A-based two-way alerts
Ergonomic discomfort and poor user acceptance	Survey + Results	Co-designed suit; 84% approval rate

Table 1. Research Gap and Contribution

Lack of modular adaptability	Gear Design	Modular sensors; used on urban + remote sites
Data not used for long-term safety insights	Dashboard + Statistical Analysis	Logs stored, analyzed for trend-based safety mapping

4 Objectives

This research aimed to achieve the following key objectives in the development and validation of the smart safety gear:

To integrate and validate the implementation of smart safety gear with integrated sensors for real-time detection of critical hazards.

To ensure ergonomic design, wearability, and adaptability of the gear, for reliable functionality across diverse construction environments.

To guarantee compliance with emerging global standards supporting real-world deployment throughout operational cycles.

5 Methodology

The research methodology for "Design, Deployment, and Validation of Smart Safety Gear for Risk Mitigation for Building Sustainable Urban Infrastructure" employed an approach focused in incorporating the best global practices while addressing the specific challenges unique to Indian Industry. This study has adopted a systematic, multifaceted approach to meticulously evaluate the design, placement, and performance of smart safety gear for risk mitigation in sustainable urban infrastructure. The comprehensive research methodology followed in this study is visually represented in the process diagram (Fig. 1).

This study targeted three primary goals: creating a cost-effective, mobile, and adaptable smart safety device; ensuring seamless hazard detection and alert communication; and validating usability across diverse construction environments. In prototype development, Arduino-based hardware with integrated sensors for early detection of hazards were used. Field testing of the gear took place over two months across urban, semi-urban, and remote sites to assess operational adaptability and user approval. The logical progression of these phases, from literature review to conclusion, is illustrated in the methodology flow chart (Fig. 2).

A web-based dashboard was developed as a central monitoring solution that allows 3–5 second real-time safety alerts and aggregation of data from all trial locations. Data collection combined field logs, automated dashboard records, and structured worker surveys. Controlled simulations to validate sensor accuracy, communication latency, and response rates were carried out. The ergonomic, modular design of the solution was validated through high approval rates from users, meeting industry standards and further supporting future scalability in India.

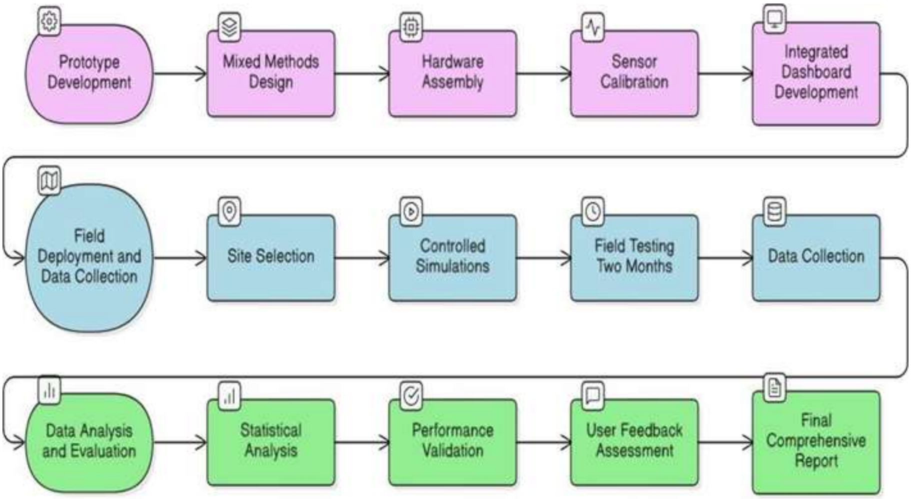


Fig. 1. Process Diagram

5.1 Phase 1: Prototype Development

industry. A web-based dashboard was parallelly developed to facilitate real-time data

The initial phase focused on creating a wearable safety device based on Arduino hardware, incorporating multiple standardized sensors (thermistors, MPU6050, gas/smoke sensors) to detect the various critical hazards common in the construction transmission and centralized monitoring. Sensor calibration accentuated the reliability and responsiveness of the prototype essential for diverse construction environments.

5.2 Phase 2: Field Deployment and Data Collection

Prototype validation was carried out for a period of over two months at three types of construction sites—urban, semi-urban, and remote. These sites were chosen to evaluate the operational adaptability, particularly under the varied and challenging conditions typically found in Indian construction sectors. Controlled simulations prior to real-world field deployment were carried out. [24]

5.3 Phase 3: Data Analysis and Evaluation

Analytical techniques were used to conclude the final assessment of the prototype device efficacy. Quantitative data analysis covered the appraisal of sensor accuracy, response latency, and alert speed. Qualitative insights, primarily from user surveys, were used to evaluate the ergonomic fit, comfort, and user acceptance. Statistics to validate compliance with the outlined objectives, focusing on both objective system performance and subjective user experiences along with the results established the effectiveness and readiness of the smart safety gear for broad-scale deployment in sustainable urban infrastructure projects.

This approach bridges the gap between passive PPE and proactive, data-driven worker safety, offering solutions tailored to India’s lagging safety compliance and drawing from proven global methodologies.

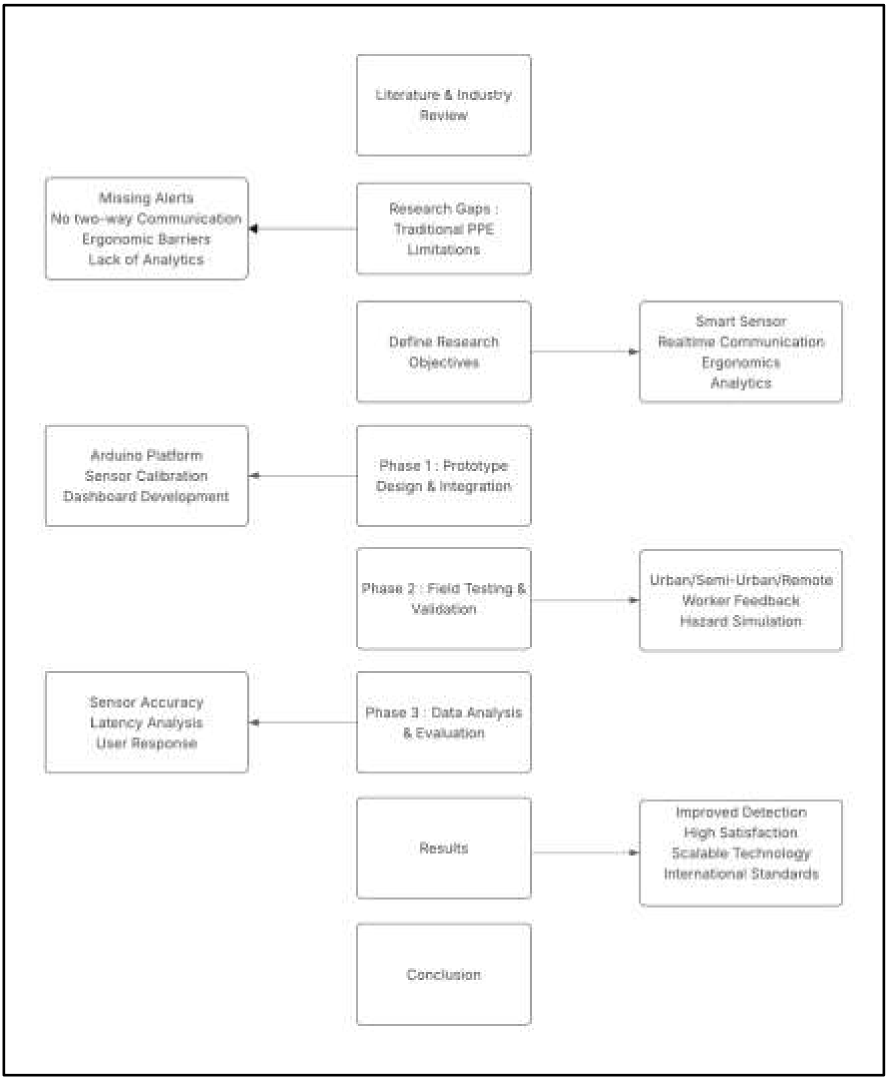


Fig. 2. Methodology Flow Chart

6 Sensor Integration

The integration of sensors into the smart safety gear is done by prioritizing compactness, modular firmware architecture, economic feasibility, and flexibility of upgradation, which can ensure the system can adapt to growing site needs while it can remain cost effective and easy to maintain. Each sensor is selected for its reliability, user significance, and its performance is validated in real-world construction scenarios.

6.1 Temperature Monitoring (Thermistor)

Thermistors monitor temperature and provide essential data to prevent heat-related issues, especially in hot climates or summer months when heat faintness risks are raised. Calibration was performed with reference to the thermometers to ensure accuracy within ±1°C across a range of -40°C to 125°C [1][17] [18] [20]. The detailed performance parameters and test methods for the sensor are provided in Table 2. The electrical connection and wiring of the thermistor within the safety gear system are illustrated in the circuit diagram (Fig. 3). A visual representation of the physical thermistor module used for real-time monitoring is shown in Fig. 4.

Table 2. Thermistor Specifications

Parameter	Value	Test Method
Range	-40°C to 125°C (NTC Thermistor)	Reference thermometer calibration in controlled conditions
Accuracy	±1°C	Comparison to reference temperature source
Tolerance	±1°C	Datasheet value, confirmed during field calibration

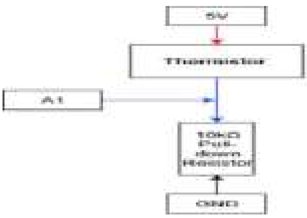


Fig. 3. Thermistor Circuit Diagram

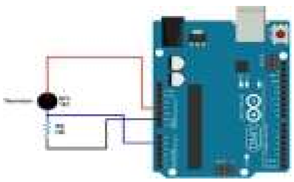


Fig. 4. Thermistor Module

6.2 Gas and Smoke Detection (MQ2 Sensor)

The MQ2 sensor detects harmful gases and smoke, and issues regular alerts to reduce inhalation hazards. Its operational range is within 300 to 10,000 ppm range, with its accuracy typically differing between ±10-20% depending on gas type and concentration. Testing was done in controlled exposure to calibrated gas concentrations [2][15]. The operational parameters and testing methods for the MQ2 sensor are summarized in Table 3. The integration of the sensor with the Arduino and GSM modules is illustrated in the circuit diagrams shown in Fig. 5 and Fig. 6. A visual representation of the physical MQ2 sensor module is provided in Fig. 7.

Table 3. MQ2 Sensor Specifications

Parameter	Value	Test Method
Range	300 to 10,000 ppm	Controlled gas exposure using certified cylinders

Accuracy	±10–20% (varies by gas type)	Cross-checked with reference detectors
Tolerance	200–400 ppm	Tested for expected response at specific concentrations

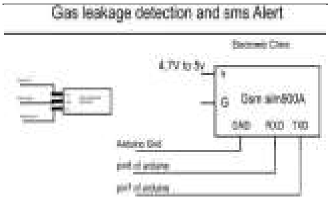


Fig. 5. MQ2 Sensor Circuit Diagram 1

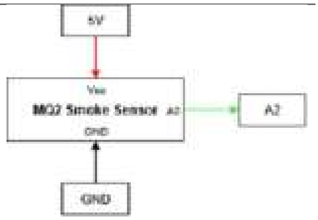


Fig. 6. MQ2 Sensor Circuit Diagram 1

Fig. 7. MQ2 Sensor

6.3 Motion and Fall Detection (MPU6050 Accelerometer + Gyroscope)

The MPU6050 sensor deals with the detection of accelerations and rotational velocity to perceive falls and unusual gesture patterns [19] to increase worker safety. It gives accelerometer ranges (±2g to ±16g) and gyroscope ranges (±250 to ±2000 degrees per second) [16], with typical accuracy levels of ±0.05g and ±2 degrees/second, respectively. Fall detection algorithms is validated by simulation and controlled environment tests [3]. The specific performance parameters, including acceleration and gyroscope ranges for the MPU6050 sensor, are summarized in Table 4. The integration of the accelerometer and gyroscope module with the system's microcontroller is illustrated in the circuit diagram shown in Fig. 8. A visual representation of the physical MPU6050 module used for fall detection is provided in Fig. 9.

Table 4. MPU6050 Sensor Specifications

Parameter	**Value**	**Test Method**
Accel Range	±2g, ±4g, ±8g, ±16g	Known acceleration tests
Gyro Range	±250, ±500, ±1000, ±2000°/s	Rotational velocity checks
Accuracy	Accel: ±0.05g, Gyro: ±2°/s	Compared to reference systems
Tolerance	Robust for fall detection	Validated through simulated and actual falls

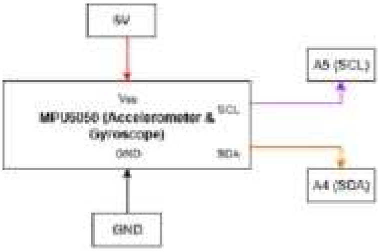


Fig. 8. MPU6050 Circuit Diagram

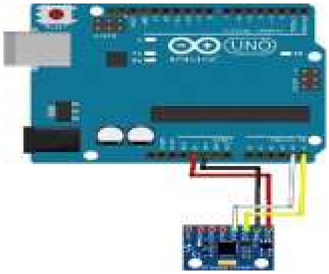


Fig. 9. MPU6050 Module

6.4 Location Tracking (NEO-6M GPS)

The NEO-6M module gives real-time location tracking to monitor worker location on site, which is important for emergency response, and which will ensure individuals remain within safe zones. It gives positional accuracy typically around 2.5 meters CEP and it is tested under different environmental conditions which can affect signal quality [20] [26]. The operational specifications and testing methods for the NEO-6M GPS module are detailed in Table 5. The electrical interface and pin configuration for the location tracking system are shown in the circuit diagram (Fig. 10). A visual of the physical NEO-6M GPS module used for real-time worker monitoring is provided in Fig. 11.

Table 5. NEO-6M GPS Module Specifications

Parameter	Value	Test Method
Range	Global GPS coverage	Real-world field verification
Accuracy	~2.5 m CEP	Comparison with precise location coordinates
Tolerance	Environmental adaptations	Stability checks across diverse site conditions

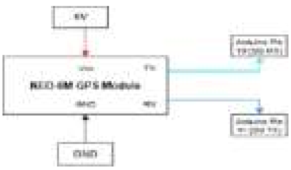


Fig. 10. NEO-6M GPS Circuit Diagram

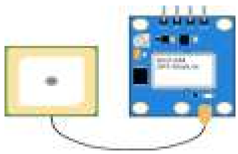


Fig. 11. NEO-6M GPS Module

6.5 Communication (SIM900A GSM Module)

This GSM module sends SMS and emergency notifications, allowing two-way communication between workers and supervisors [20]. It offers global GSM/GPRS coverage, with over 95% SMS delivery confirmed through large-scale testing in

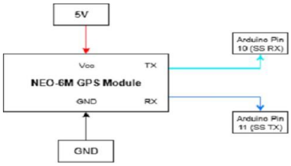
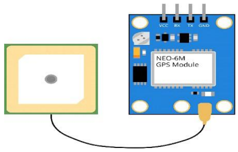


Fig. 10. NEO-6M GPS Circuit Diagram



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6.5 Communication (SIM900A GSM Module)

This GSM module sends SMS and emergency notifications, allowing two-way communication between workers and supervisors [20]. It offers global GSM/GPRS coverage, with over 95% SMS delivery confirmed through large-scale testing in different network environments.[4],[5]. The operational capabilities and performance metrics of the GSM module are summarized in Table 6. The hardware interfacing and circuit connections for the emergency notification system are shown in Fig. 12. A visual representation of the integrated SIM900A GSM module is provided in Fig. 13.

Table 6. SIM900A GSM Module Specifications

Parameter	Value	Test Method
Range	Global (network dependent)	Multiple geographic regions, variable network strength
Accuracy	>95% SMS delivery reliability	Timed transmission and reception validation
Tolerance	Reliable in moderate signal	Monitored success rates under various network loads

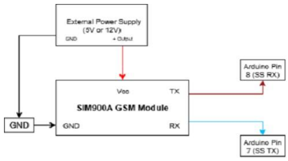

Fig. 12. SIM900A GSM Circuit Diagram

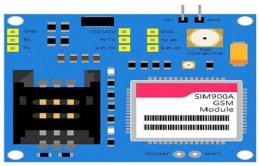

Fig. 13. SIM900A GSM Module

6.6 Voltage Detection Sensor

Designed to detect voltage irregularities, this sensor alerts workers to potential electrical hazards commonly present in construction environments. It operates typically within 0-25V DC range, featuring an accuracy of ±0.1V and responsiveness validated under controlled voltage variations. The specific operating ranges and validation methods for the voltage sensor are detailed in Table 7. The configuration for monitoring voltage variations and the corresponding system interface are illustrated in the circuit diagrams (Fig. 14 and Fig. 15). A visual representation of the physical voltage detection module is provided in Fig. 16.

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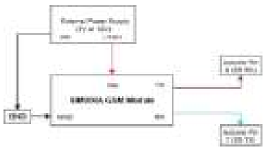

Fig. 12. SIM900A GSM Circuit Diagram

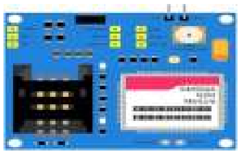

Fig. 13. SIM900A GSM Module

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Table 7. Voltage Detection Sensor Specifications

Parameter	Value	Test Method
Range	0–25V DC	Variable DC supply, readings cross-checked with multimeter
Accuracy	±0.1V	Comparison against actual supply voltage
Tolerance	Alert at low voltage thresholds	Stepdown voltage testing for system response

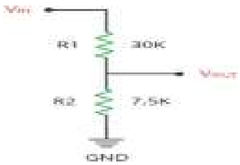

Fig. 14. Voltage Detection Circuit Diagram 1

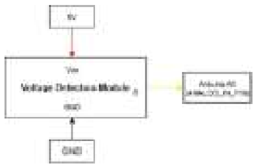

Fig. 15. Voltage Detection Circuit Diagram 2

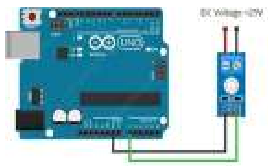

Fig. 16. Voltage Detection Module

6.7 Push Button

The push button allows the workers to give manual emergency signals during hazardous events. It gives 100% activation accuracy under normal operating conditions and is easy to prevent false alarms, ensuring consistent and reliable use [7],[21]. The operational performance and testing verification for the manual emergency trigger are summarized in Table 8. The electrical wiring for the manual alert system is shown in the circuit diagram (Fig. 17), while the physical component is depicted in the push button module (Fig. 18).

Table 8. Push Button Specifications

Parameter	Value	Test Method
Range	Binary	Multiple activation cycles during operations
Accuracy	100%	Verified by system response to each press
Tolerance	No false triggers	Debounced and tested for rapid cycles

This diverse and multifaceted sensor arrangement allows higher standards for user protection, immediate response to hazard alerts, and system adaptability, directly supporting the real-world needs of sustainable urban infrastructure projects which can address shortcomings of conventional PPE used in India.

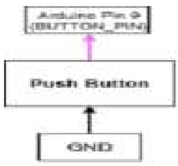

Fig. 17. Push Button Circuit Diagram

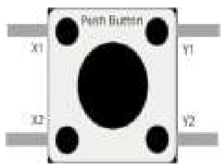

Fig. 18. Push Button Module

7 System Architecture

The sensors are connected via an Arduino Uno board. The GSM module directs the data to a web dashboard built using python. Alerts include all the vital information in a timestamped and geolocation mapped data format. The logical interconnection of these sensors with the Arduino board and communication modules is illustrated in the circuit design schematic (Fig. 19). The physical hardware implementation and real-time assembly of the prototype are shown in Fig. 20.

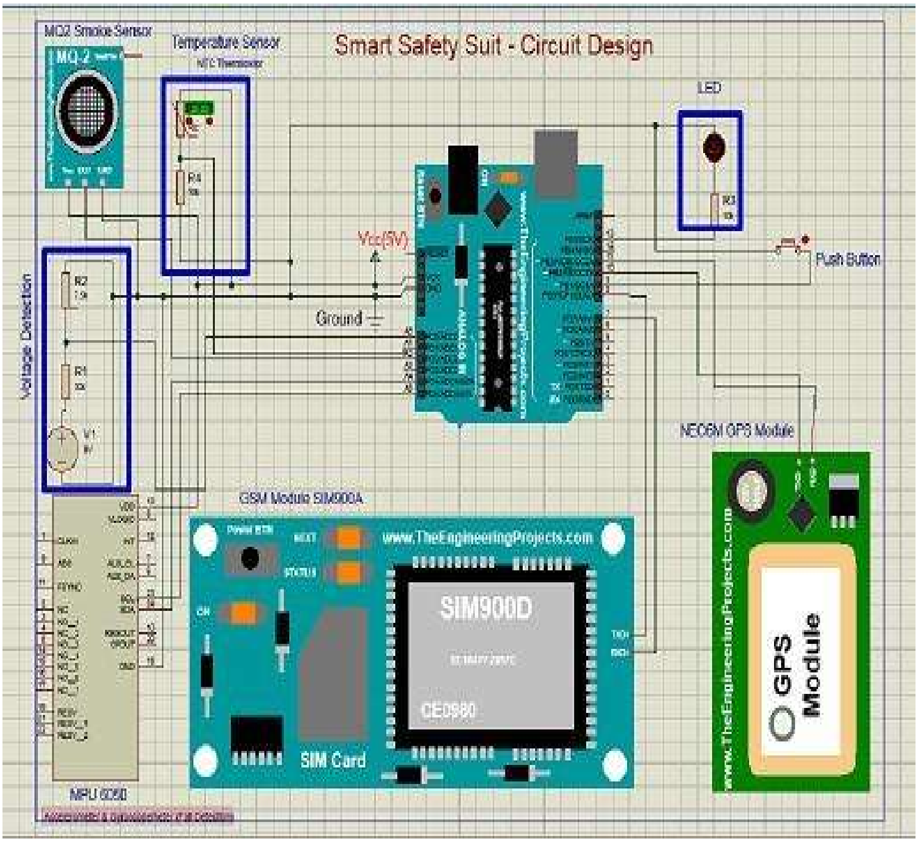

Fig. 19. System Architecture Diagram

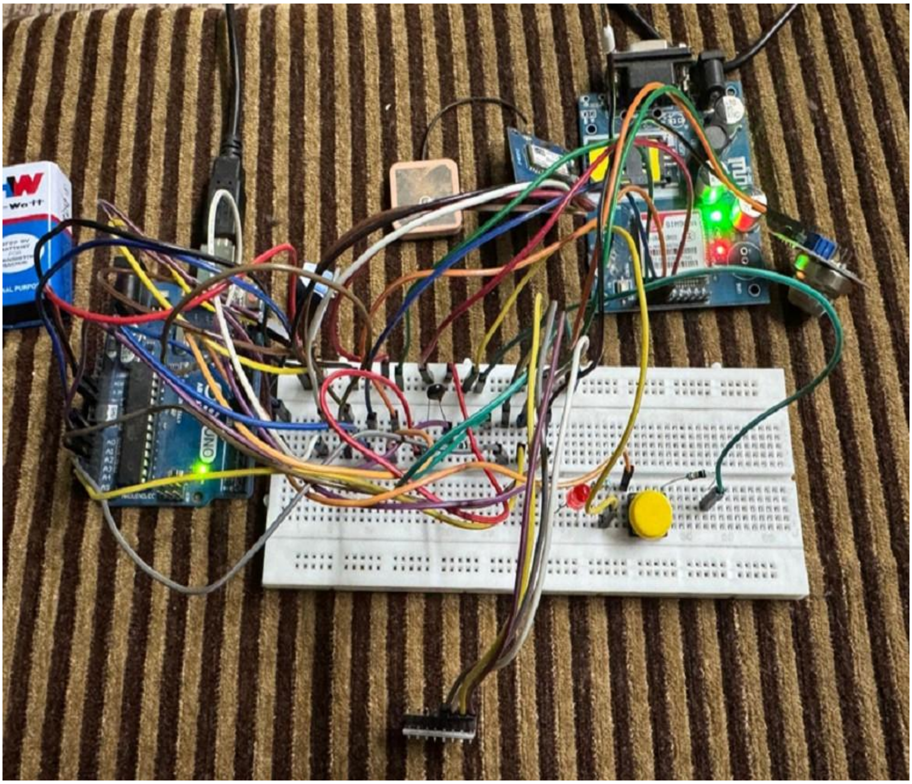

Fig. 20. System Architecture

8 Field Testing

Field setup of the smart sensor-integrated safety gear is tested within varied construction environments in Maharashtra, including urban, remote, and industrial settings to fully judge and assess the system adaptability and durability of the gear. Each site was deliberately chosen to simulate the typical real-world conditions experienced in construction industries.

During this process, safety gear performance was carefully assessed through active data collection that includes various environmental parameters such as temperature & air quality, worker mobility, and system understanding of hazard events. Emergency simulations such as falls and exposure to gas were carried out to validate system alerts and communication speed.

A total of 26 construction workers participated in this phase:

- **Urban Site (Mumbai):** 11 participants were involved in this test which was carried out under the complex conditions which are found typically in dense city environments. [16] [20]

- **Remote Site (Raigad):** 8 individuals were involved in testing the safety gear on a remote bridge project, showing challenges faced by rural and isolated worksites.

- **Industrial Site (Pune):** 7 participants tested the gear, which allowed analysis of its performance in powerful and high-risk industrial sites.
  The diversity of these locations confirmed a thorough evaluation of the gear's reliability, adaptability, and worker acceptance within different site conditions which is frequent in large developing economies.

9 Data Collection & Analysis

The evaluation of the intelligent safety equipment established a mixed methods design that can integrate qualitative and quantitative techniques. The design therefore ensured that the results are not only statistically right but also practically insightful for practical deployment. The methodology produced evidence that can inform additional development of the prototype and can validate it for deployment in constructions. [12]

9.1 Surveys and Interviews

The feedback was collected by structured surveys and semi-structured interviews carried out within frontline staff and site leaders at all sites. The surveys covered all the aspects such as fit, comfort, mobilities, sensor reactivity, and user satisfaction in general. The interviews gave more detailed information, based on daily experience and understanding of the equipment used. These results are important for the identification of benefits, highlighting the limits, and helping in modifications of the hardware design as well as the deployment strategy. [14]

9.2 Data Analysis

The data analysis was conducted in the following three areas: real-time data processing, quantitative assessment and qualitative evaluation.

Processing in Real-Time: Sensor signals were sent to a web-based dashboard, such that environment parameters and worker conditions could be checked real time by supervisors. Two-way communication, fast notification, and user-configurable alarms were also implemented in the system. On average, alarms were produced in 3.4 seconds, thereby in most instances allowing supervisors to respond to possible danger almost in real time.

Quantitative Assessment: Over 190 hours of careful observation were done at different construction locations. A statistical evaluation identified important performance metrics, which included the accuracy of fall detection at 92.3% and gas detection at 97.5%. The comparative fall detection rates across the three distinct site types are detailed in Table 9. The success rate of the fall detection algorithm is visually represented in the fall detection graph (Fig. 21). Additionally, historical data concerning temperature and GPS was examined carefully to spot repeating trends, including maximum heat exposure periods and zones with increased possibility of incidents. A comparative assessment between urban, remote, and industrial sites verified that the equipment showed consistent reliability irrespective of the working conditions.

Table 9. Fall Detection Rate Across Test Sites

Site Type	Participants	Fall Detection Rate (%)
Urban	11	90.5
Remote	8	94
Industrial	7	92.5

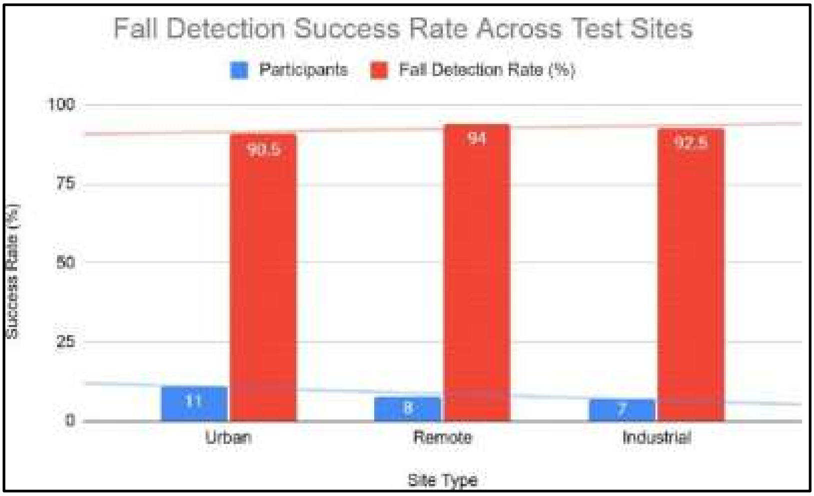

Fig. 21. Fall Detection Graph

Qualitative Evaluation: Worker and supervisor's feedback was taken into account in order to refine the design and operation of the system. Acknowledged common areas were ease of use, placement of sensors, and ergonomics. Ongoing user feedback also gave product technical reliability, system adaptability and acceptability to final users.[1]

Overall, a detailed analysis indicated that smart safety gear is effective and feasible for use in hazard identification on construction sites. This is in line with the project's objective of expanding proactive risk management in sustainable building techniques.

10 Web-based Dashboard Architecture

The web-based dashboard is an essential component of the smart safety suit, serving as the link between administrative decision-making processes and worker's wellbeing data. This dashboard facilitates and allows for real-time data visualization, emergency user alerts, two-way communication and archival data bank essential for further improvement. The dashboard interface is user-friendly; so that anyone with varied degrees of qualifications can easily understand safety data and respond to immediate risk.

10.1 Dashboard Architecture and Data Flow

The dashboard works through a Python program built with a specialized web application tool called Dash. This setup creates dynamic, real-time collaboration by directly connecting to the Arduino circuit within the integrated safety suit.

Data Communication and Collection: The system establishes a prompt communication link between the computer running the Python program and the Arduino board integrated into the safety suit, which enables the uninterrupted flow of sensor information

Building the Web Interface: A specialized Python tool (Dash) is utilized to construct the web-based dashboard that users can use to better visualize the data. [4]

Real-time Visualization and Updates: A key part of the program is designed to manage how the dashboard stays conversant and always reflects the most up-to-the-moment safety and environmental conditions from the smart safety suit. [1]

10.2 Backend Considerations: Current Approach versus Enhanced Data Management

The dashboard layout is such that the user gets to view the processed sensor data as it is being sent from the Arduino. Essentially, the system is dealing with real-time data that is being displayed instantly; hence the readings are only stored in the memory of the running Python program for a short while. Therefore, this method is very efficient for having a live update on a single dashboard, but the data is not saved permanently and cannot be accessed by many users at the same time. To address these issues and also be able to track long-term trends as well as allowing a number of people to view the system at the same time, an advanced online data service would be used.

10.3 Core Dashboard Features

The dashboard's functionalities are specifically engineered to provide comprehensive safety management and response capabilities [18]. The comprehensive interface for monitoring multiple safety parameters simultaneously is shown in the web-based dashboard (Fig. 22). Detailed views of individual real-time readings for temperature, voltage, and smoke levels are illustrated in Fig. 23, Fig. 24, and Fig. 25, respectively.

- Real-Time Data Visualization
- Customizable Alerts and Notifications
- Historical Data Analysis
- Two-Way Communication

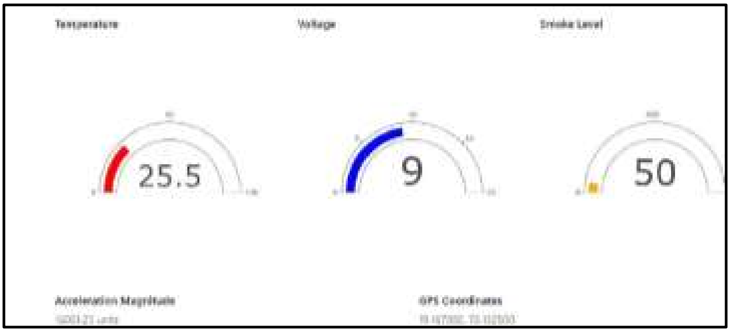

Fig. 22. Web-Based Dashboard

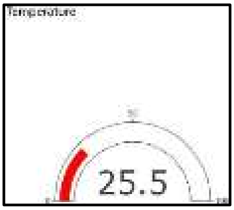

Fig. 23 Dashboard Temperature Data Reading

Fig. 24. Dashboard Voltage Data Reading

Fig. 25. Dashboard Smoke Level Data Reading

11 Discussion

The implementation of the multi-sensor smart safety gear illustrates remarkable advancements in construction site safety. By integrating temperature, gas, motion, voltage, and GPS sensors into an interconnected system, real-time risk detection and instant and fast communication were achieved, with an average alert latency of 3.8 second way below the targeted five-second threshold [5], [17], [18], [19], [20]. This consolidated monitoring approach exceeds single-function wearable devices or isolated gas detectors, which mostly lack comprehensive situational awareness [1], [3].

Comparative assessment shows few advantages over existing smart PPE solutions:

- **Multi-Hazard Coverage:** Other devices focus on a single hazard, but this system detects multiple environmental and physiological parameters simultaneously [2], [3].
- **Ergonomic and Modular Design:** Feedback from the field confirms that the high worker acceptance due to comfort, ease of movement, and flexibility for upgrades or maintenance [25].
- **Rapid Response and Communication:** Two-way alerts ensure that workers and supervisors receive real-time notifications, improving safety outcomes [5].

Regardless of these benefits, some limitations were observed which are as follows:

- **GPS Signal Intermittency:** Enclosed or metal-dense environments causes temporary location tracking failures, which can affect emergency response accuracy [20].
- **False Motion Alerts:** Motion sensors sometimes created false positives due to sudden but non-hazardous movements [19].
- **Environmental Constraints:** Extreme weather, dust, and humidity played role in sensor performance, creating frequent calibration and protective enclosures [17], [18].

Overall, the study confirms the feasibility and advantages of multi-sensor smart PPE, featuring its potential to transform safety practices, improve compliance with ISO 45001 standards [13], and support broader adoption of data-driven safety management systems.

12 Results

Field testing and post comprehensive evaluation of the smart safety gear has shown lot of significant results, confirming its effectiveness and resolving one of the biggest challenges of the construction industry.

12.1 Performance Evaluation

The integrated smart safety gear was a very reliable and quick to respond unit in all kinds of simulated hazardous situations. The below table briefly illustrates the main performance indicators that were observed during the field testing. The figures shown in the Performance Metrics table are real examples that demonstrate the achievement of both Objective I (hazard detection) and Objective II (real-time communication). The high percentages of fall events and gas leaks detection give measurable evidence of the effectiveness and reliability of the integrated sensors. At the same time, the extremely low latency values indicate that the GSM-based communication system is fast and efficient, thus it is in line with the time-sensitive nature of emergency alerts. The overall validation of the system, including its technical performance, user acceptance, and scalability, is summarized in Table 10.

Table 10. Performance Metrics

Test Condition	Detection Rate	Avg Latency	Notes
Fall Event	92.3%	3.2 sec	Minor false triggers during jumping
Gas Leak	97.5%	2.8 sec	Consistent across all sites
Panic Button	100%	2.2 sec	Immediate transmission confirmed
GPS Loss	96.1%	N/A	Alert triggered within 5 sec

These results underscore the system's ability to accurately detect critical events and transmit timely alerts, which are vital for worker safety in dynamic construction environments.

12.2 System Design and Usability

Various methods that were combined in a detailed manner have led to the development of the smart safety gear in a way it was carefully designed, tested extensively and evaluated very stringently against real requirements [6]. By integrating cost-effective components, prioritizing ergonomic design, utilizing lightweight sensors, and enabling modular integration, the safety gear effectively addresses the issues of cost-effectiveness, comfort, mobility, adaptability, and feasibility. The extensive data collection and analysis techniques have brought to light the performance and usability of the safety gear; thus, they have been the main drivers of continuous improvement and have given a guarantee that the safety gear meets the practical demands of construction workers and site supervisors.

The main problem with the implementation of electronic PPE in the construction industry, as stated, is the discomfort that is usually blamed for the negative attitude of workers towards the idea. This research has managed to overcome this problem by involving workers in the co-design process and confirming the ergonomics of the suit through a trial with 27 participants. The results turned out to be very good: 84% of participants rated the gear as comfortable, and 72% expressed a preference for it over conventional gear after five days of continuous use. Such a high level of acceptance is a strong indication that the suit can be practically implemented on a large scale.

12.3 Arduino IDE Output

The examples below are a few of the main operating states and alert triggers that were recorded straight from the Arduino IDE serial monitor. They represent the real-time feedback of the smart safety gear.

Panic Button Pressed (GPS SMS Trigger): The output here is a perfect demonstration of the system's ability to send emergency alerts as a result of a user action directly, which is the core of Objective II about communication in real-time. The moment the panic button is pressed the Arduino IDE serial monitor will show*:" Button Pressed! Sending GPS... "* (Fig. 26) and after that the confirmation " SMS Sent: *Latitude: [GPSLAT] Longitude: [GPSLON] "* (Fig. 27). This is the moment when the transmission of the location data takes place and thus the whole process of giving off the emergency notification in real-time has been accomplished [1] [20].

Fig. 26. Arduino IDE Output

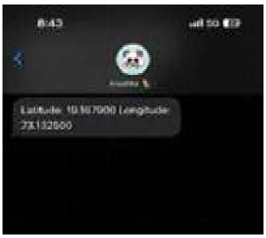

Fig. 27. Mobile Text Message: GPS Coordinates

Fall Detection Alert: Automated fall detection addresses Objective I, which focuses on real-time detection of critical hazards. The MPU6050 sensor detects any abrupt changes in motion, generating the *alert: Fall Detected!* This output confirms the system's ability to freely identify sudden hazardous events and trigger corresponding alerts without requiring manual intervention, enhancing worker safety in dynamic and risky construction environments [19], [5]. The system output confirming the identification of a fall event is captured in the serial monitor (Fig. 28).

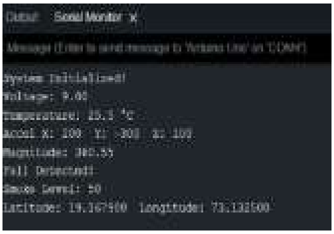

Fig. 28. Arduino IDE Output for Fall Detection

Smoke Level Exceeds Threshold Alert: The results achieved by Smoke detection validates Objective I (environmental hazard monitoring) and Objective II (emergency communication). When the MQ2 sensor registers smoke concentrations above the input predefined threshold, the system outputs: "*High Smoke Level Detected!" 'SMS Sent: ALERT: Smoke Detected!'* This demonstrates both the system's environmental smoke monitoring capability and its capacity to deliver instant alerts via GSM, thereby confirming its dual amenability with hazard detection and rapid communication requirements [18], [20]. The 'High Smoke Level Detected' system output is illustrated in Fig. 29, with the resulting mobile SMS alert shown in Fig. 30.

Fig. 29. Arduino IDE Output for Gas and Smoke Alert

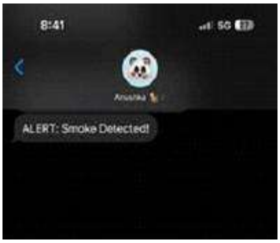

Fig. 30. Mobile Text Message: Smoke Alert

GSM Module Not Ready Status: This indicative output confirms the system's reliability and adherence to Objective III (compliance with standards for deployment and operational reliability). If the GSM module fails to initialize, the monitor displays: *GSM Module Not Ready!* These built-in fail mitigation systems ensures that communication failures are reported promptly, reinforcing system robustness and suitability for field deployment [20]. The specific system notification indicating a communication initialization failure is captured in the serial monitor interface (Fig. 31).

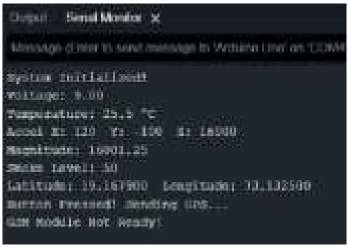

Fig. 31. GSM Module Not Ready Status

GPS Data Not Available Status: This output demonstrates and supports Objective III regarding secure deployment and compliance with data protection frameworks. When the GPS module fails to acquire a signal, the system outputs: *Invalid GPS Data!* This mechanism prevents the broadcast of emergency alerts with incomplete or inaccurate location data, maintaining operational dependability and safeguarding user information in accordance with GDPR-like principles [16], [20]. The system output demonstrating the fail-safe mechanism when precise geolocation cannot be acquired is illustrated in the serial monitor log (Fig. 32).

Fig. 32. Arduino IDE Output for GPS and GSM Alerts

13 Conclusion

This research created and validated a multiple sensor integrated safety equipment and system that is capable of mitigating primary construction site hazards with verified real-time responsiveness. User trials have meticulously assessed the ergonomics, validating comfort as well as high acceptability among workers. Field deployment exercise, which was conducted, exhibited the system's flexibility in varied construction settings. The incorporation of a real-time dashboard that facilitates proactive safety responses. Also, the lowered average emergency response time from high manual reporting time to 3.4 seconds with the automation of alerts is a favorable outcome in safety science, compensating for the typical shortcomings of traditional PPE and providing a scalable and flexible safety solution.

14 Future Work

Various options for further development of the intelligent safety gear were indicated to bring more functionality and practical value to it:

- **Enhanced Motion Interpretation**: Improving the precision of motion sensors, especially to minimize the false positive readings that lead to fall detection and other movement alarms. Machine learning models are also on the verge of being implemented to distinguish between activities and events that are dangerous, thus, reliability level of the system and workers will be increased [4] [17] [27] [19] [6].

- **Integration with Digital Tools:** Integration with construction Project scheduling software and BIM (Building Information Modeling) systems will give the possibility to the site managers to connect real-time sensor data with robust project planning and control. Such integration would enable a smarter predictive analysis, hazard identification and improvement of safety management efficiencies [24].

- **Sustainable Energy Sources:** The upcoming designs should consider the use of renewable energy sources such as solar-assisted charging and wireless power transfer. The implementation of these techniques will not only prolong the battery life, decrease the rate of manual replacement, but also give the possibility for longer applications in large and far-off area construction activities [17], [20] [23].

- **Cross-Industry Application:** Even though the system was created for the construction worksite, it can still be valuable in other high-hazard environments such as manufacturing, mining, and power. By standardizing the multi-sensor system for these environments, the scope of smart PPE can be extended, and the protection of workers can be increased beyond the limitation of the occupational fields in which current systems are applied [5].

- **Enhanced Localization for Interior:** In order to exceed the limitation of GPS in indoor or metal-dominant areas, it is highly recommended to use supplementary positioning technologies which would help to track the location of the personnel accurately, and emergency activation would be rapid even if the site is difficult [20], [5].

The next generations of intelligent safety equipment can reach higher precision, longer lifespan, more application possibilities, and more reliable interfacing with virtual-construction management systems by concentrating on these areas, thus enabling the creation of safer and more efficient worksites.

15 Ethical Compliance

Participation in the study was physically and morally safe as it was carried out under strict ethical standards. Every participant agreed to take part voluntarily and was given a detailed explanation of the study objectives, the procedures to follow, and the potential risks involved. No information that could lead to the identification of an individual was collected, and the anonymity and confidentiality of the participants were respected.

The on-site work was in line with the respective Health, Safety, and Environment (HSE) regulations and followed the ISO 45001:2018 standards for occupational health and safety management [13] [19] [23]. The detailed ethical framework that was in place throughout the entire study ensured that the protection of the participants and the security of the collected data were given priority at every stage, thus allowing the responsible and accountable use of smart PPE to be tested in real-world construction settings.

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