SafeSense: Real-time Safety Alerts for Construction workers

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Abstract

Our research presents a cutting-edge solution for enhancing safety in construction sites: the Smart Helmet-based Wearable Personnel Proximity Warning System, specifically designed to prevent collisions & zone-based alerts in hazardous areas. Through the use of Bluetooth beacons strategically placed on heavy machinery and hazardous areas, the system communicates with a smart helmet worn by workers. Featuring an ESP32 module and Radio Frequency Identification (RFID) technology, the helmet provides real-time alerts with minimal effort from the user. When unsafe zone is notified by the safety manager in the safety command center, smart helmet receives this signal and turns the Light Emitting Diode (LED) indicators flash red and are accompanied by both auditory alerts and Heads Up Display (HUD) based directions. The inclusion of Bluetooth Low Energy (BLE) technology also increases the accuracy of proximity detection, ensuring reliability even in dynamic work settings. To ensure ease of use, the system incorporates a lithium polymer battery for portability. Laboratory based controlled environment is chosen for study of the Proof of Concept (PoC) to validate the functionality with 2 mock-up workers. Dynamic alerts, Communication to workers in real time, Low cost, High utility & Easy ergonomics are the five parameters experimented. The proposed model has the potential to be widely adopted in the construction industry and reduce the accidents using dynamic alerts to the workers in the real time. Present study also highlights the associated limitations of the smart helmet where future study can happen to overcome these limitations.

Keywords –

Smart Helmet, Personnel Proximity Warning System, Safety sign indications, Collision Prevention, Bluetooth Beacons, HUD

1 Introduction

The construction work force constitutes only 29 % to total industry workforce, but the contribution of accidents is 40% to the total industry. This clearly indicates accident exposure is so high in construction industry and it tops the list of all industries [1]. This is due to the dynamic nature of construction activities and exposure to open areas. Big equipment like cranes, dozers, moving vehicles & the need to work on higher elevations make construction site highly accident prone. Fall from height, struck by, caught between, electrical shock are the fatal four categories of construction accidents. In such a hazardous work environment, safety helmets, part of Personal Protective Equipment (PPE), are crucial in the construction industry. Other popular safety precautions are use of sign boards to display specific field conditions like Safe zone/ unsafe zone / Use ear protectors etc., Designated work areas are marked using signboards, to indicate area which are not safe to work. This approach of making an area based on geographical co-ordinates is known as Geo-fencing. This geo-fencing will not remain the same, it will change with time and location in the construction industry. For example, activities like electrical cabling or plumbing or excavation demands different kinds of geo fencing and depend on the construction stages.

Though PPE monitoring and sign boards work effectively in other industries, they are not so effective in the construction industry because of dynamic changes happening in the field. One approach to address both the issues is to embed the warning messages into the safety helmet itself [2][3][4].

Another critical difference of construction industry is difficulty involved in making a uniform risk level. Consider the case where multiple activities masonry and carpentry works on going, they are exposed to different risk levels, though they operate in same area. For example, mason and electrician may be having different risk exposure. While making a generalized risk exposure and associated safety rules is possible in other industries, this is not possible in the construction industry. In short, workers are dynamic, conditions are dynamic, geographical co-ordinates are dynamic. This forces big challenge to build any safety alert system for construction industry.

Considering the advancements in mobile communication, use of mobile phones could be an approach, however construction work nature and ergonomics requirements of this industry prohibits use of mobile phones which is widely accepted in other industries.

Lastly any proposed safety approach has to be cost effective and able to use current infrastructure than green field approach of making new PPE

All the above-mentioned safety challenges posed the following research question:

“Is it possible to build safety helmet which can take care of highly dynamic and unsafe conditions of construction field maintaining the cost, utility and ergonomics demands using advancements in the electronics and computer science filed to reduce the accident counts in the construction?”

2 Literature Survey

To address the research question, literature review is carried out to critically examine the studies, comparing methodologies, outcomes, and implications. A comprehensive understanding of the evolving landscape of safety helmets that use Personal Proximity Warning Systems (PWS) in other industrial settings is studied.

One study[2] proposed use of smart glasses and BLE signals from beacons in a mining site. The study demonstrates that the smart glasses based PWS effectively provided visual proximity alerts with accompanying images of approaching equipment. The average BLE signal recognition distances were reported for different scenarios, and the workload analysis using NASA-TLX criteria indicated lower mental efforts and improved work efficiency when using smart glasses compared to a smartphone-based PWS.

Another study [3] explores indoor localization solutions for safety applications, with a focus on meeting system requirements and adhering to existing standards and regulations. This study discusses various technologies for worker localization and emphasizes the potential of RFID, particularly passive UHF-RFID technology, in ensuring worker safety. The study considers the properties required for an indoor localization system, considering safety directives and machinery assemblies.

Another study[4] used personal PWS with visual and tactile proximity warnings using an AI smart helmet equipped with a camera module. The system analyzes image data on a cloud server to evaluate recognition distance and hazard warning accuracy. The study demonstrates that the AI smart helmet achieved recognition distances varying with the input minimum diagonal length and maintained high hazard warning accuracy at different face angles between the camera module and mining equipment. The proposed smart helmet based PWS focuses on preventing collision accidents with moving equipment and suggests future extensions, including the integration of additional sensors for worker health monitoring and environment sensing.

AI Based safety helmet [7], Long Range Radio (LoRA) based communication[8], beacon based alarm[9][10], Situation aware PPE [11], smart PPE [12], proximality warning [13] are the other few state of the art possibilities in this area. In below table 1, present study compares the features available towards construction safety and established new solution to address all the gaps.

Present study extends this exploration by proposing a new safety helmet module integrating an ESP32 microcontroller, BLE receiver, LEDs and buzzers offering unique perspective on hazard detection and communication.

The study investigated three proposed solutions [2], [3], [4] for providing visual alerts in various environments, including construction sites, mining sites, and machinery assemblies and summarized the features and gaps in the Table 1.

Table 1: Comparison of Technologies

Communication techniques	BLE	RFID	WiFi	Present Study
Dynamic alert	✓	X	✓	Yes
Realtime notification	✓	X	✓	Yes
Ergonomic comfort	✓	✓	X	Yes
Less Work obstruction	X	✓	X	Yes
Low Cost	X	X	✓	Yes
Profile based notification	X	X	X	Yes
Large coverage area	X	X	✓	Yes
Brown Field approach	✓	✓	✓	Yes

3 Methodology & Experimentation setup

The proposed system utilizes BLE technology for data transmission and communication between a network of helmets worn by workers and central control unit. Each helmet is equipped with a receiver module comprising an ESP32 microcontroller for data collection and analysis, as well as a wave-shaped acrylic sheet housing LEDs for visual alert. The central control unit serves as safety command center. This will be operated by the safety manager, who manages the network of helmets and transmits hazard information through color changes and blink patterns of the LEDs. Front end application- a web interface - enables the safety manager to monitor and update the status of different areas in real-time, facilitating him to send prompt alerts to the workers in the detected hazard zones.

3.1 System Architecture

The proposed smart helmet system is depicted in Figure 1. It has two components: One is hardware helmet worn by all workers and other one is centralized control unit. Helmet is ergonomically designed so that worker will still feel comfortable. Alerts are sent via wave shaped LEDs using color codes so that his work is not impacted, and alerts are seen clearly. In addition to the visual alerts, tiny buzzers are added in the hardware which will serve as speakers to alert the workers. The components of the hardware are a) Blue tooth module b) TP4056 Battery management system c) Wave shaped acrylic LED Holder d) LED e) ESP Module f) Battery

The safety command center will be operated by the safety manager, who manages the network of helmets and communicates hazard information to the helmets via BLE signals.

Each helmet will have designated unique identifier - Media Access Control Identifier (MAC ID). The MAC ID is registered on the ESP32 module when it is created in the factory, it is permanent for each helmet. Authorization is carried out based on MAC ID. Only registered MAC IDs will be authorized to get the alerts from the safety command center. This MAC ID is attached with the worker's employee identification number. There by analytics data about the worker can be collected using the MAC ID of the helmet. This MAC ID also plays crucial role in sending the profile based alerts. Present study used Electronic Design Automation (EDA) tool - a software application to create design, simulation, and testing of electronic circuits and systems. Detailed circuit designing is carried out using EDA to show schematic capture, layout, routing, and 3D visualization.

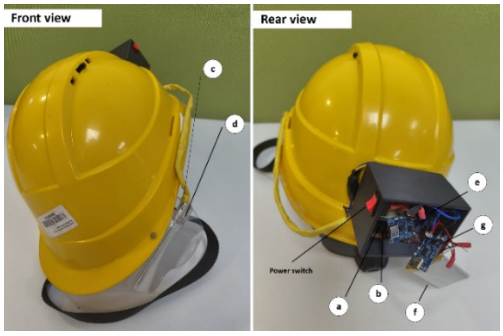

Figure 1: Safety helmet front view and rear view

3.2 Data Transmission and Communication

The BLE technology is utilized for establishing a communication network between the helmets and the central control unit. This enables efficient and low-power data transmission, ensuring minimal impact on the battery life of the helmets. The central control unit is responsible for transmitting hazard information to the helmets, which is then displayed to the worker wearing the helmet through color changes and blink patterns of the LEDs.

3.3 Real-time Hazard Monitoring

Real-time hazard monitoring is addressed using a web interface which safety command centre (Figure 2.1 & 2.2). The interface allows the safety manager to map different areas within the environment with BLE transmitter information. When a hazard is detected in a specific area, workers will notify the safety manager, then he can update the status of that area through the web interface easily as the system allows use of easy drawing and marking tools. This information is then transmitted to the corresponding helmets, prompting immediate visual alert to the workers.

An experimental setup was constructed within the laboratory environment to assess the performance of the PoC. The software aspect of the system was intricately designed to simulate three distinct zones: Room_1, Room_2, Room_3. Safety managers were granted the functionality to dynamically modify the status of each room in real-time. This feature allowed for the designation of specific areas as " unsafe zone" and all unmarked area is considered as "safe zone"

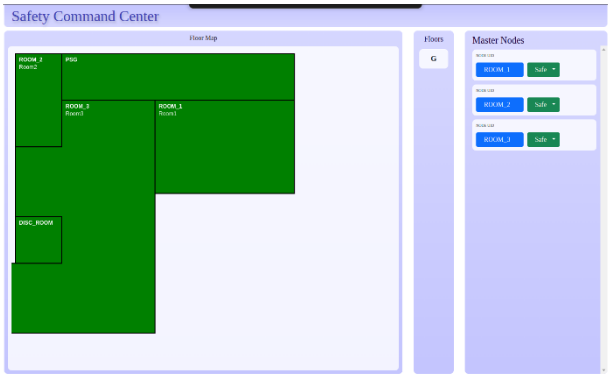

Figure 2.1: Safety command center software safe zone marking

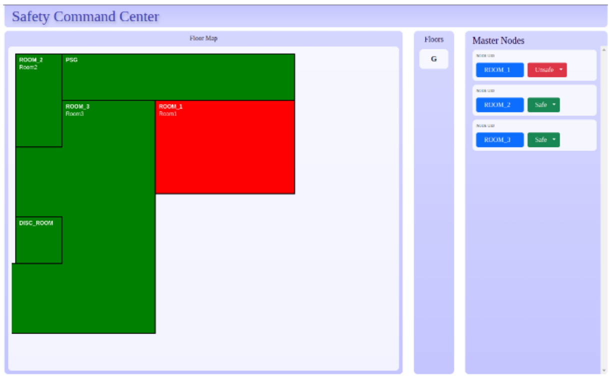

Figure 2.2: Safety command center software unsafe zone marking

When workers enter into such designated zones, workers would observe an immediate change in the LED color within their wave shaped shield of their helmets, transitioning to red to signify the hazardous nature of the environment.

In Figure 2.1, All the three rooms, Room_1, Room_2 and Room_3 are marked as safe and indicated with green color in the UI. In Figure 2.2, the Room_1 marked as unsafe using the controls. That specific room (Room_1) is changed to red color in the UI. Whenever the worker enters to that room the color of the LED will change to red for indicating the unsafe area. Figure 3(Left part) shows the worker wearing the helmet and located in a safe area and Figure 3(Right part) shows the worker wearing the helmet located in unsafe area. Helmet showing different LED color signals – green and red respectively for safe and unsafe zones.

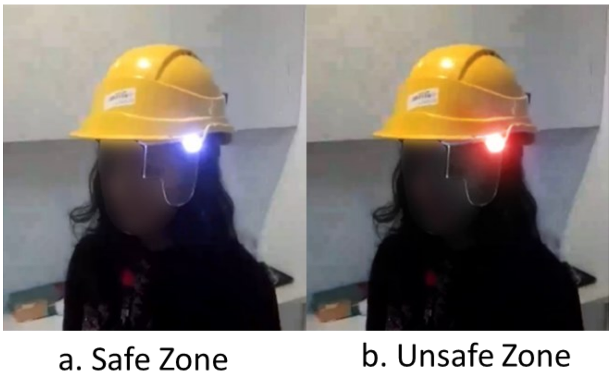

Figure 3: Worker wearing helmet in safe zone (a) and unsafe zone (b)

4 Solution

The safety helmet designed for hazardous environments operates seamlessly and efficiently to detect and communicate potential hazards in a timely manner.

The following steps outline the key functionalities of the system (Figure 4):

- Workers wear the safety helmet, which serves as the primary interface for hazard detection and communication.
- The safety helmet is outfitted with BLE receiver (B), responsible for collecting the information related to the environment.
- BLE transmitters (A) are strategically positioned throughout the workplace to establish a comprehensive network, particularly in areas marked as potential hazard zones.
- A central control unit (D) continuously monitors the workplace for potential hazards. This task is done by safety manager who gets inputs from all the workers and management about the safe zones of construction. Based on this input, safety manager sets the alert in the system, the server promptly sends this real-time hazard information to active BLE receivers within the identified hazard area remotely through internet/intranet
- Upon receiving hazard information, the safety helmet communicates with the user through red LED lights / blinking lights to visually alert the user about the presence of a hazard.

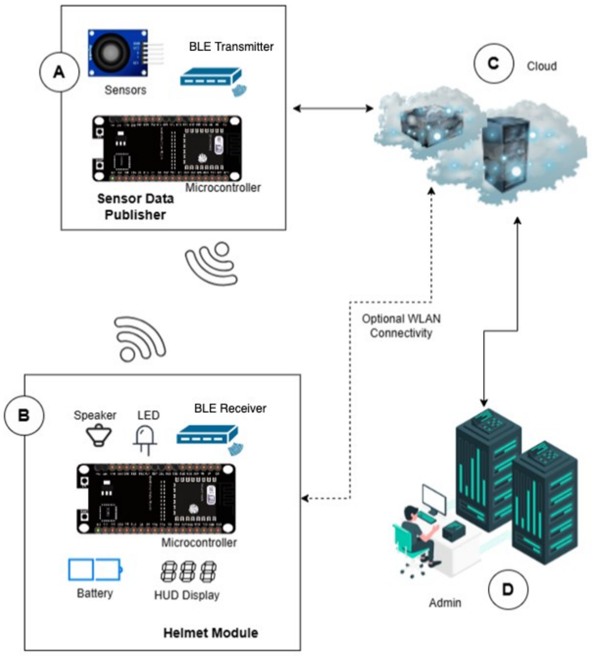

Figure 4: Solution architecture

The system architecture comprises two primary components: hardware and software. The hardware segment primarily focuses on data transmission and visualization utilizing BLE technology and LED indicators, respectively. The software part is dedicated to controlling the system overall and marking hazardous environments by the safety manager.

The entire flow of the working principle of smart helmet is depicted in the Figure 5. The steps involved are

- Deploy BLE transmitters across site
- Smart helmet receives the signal from transmitter
- MAC ID is sent to server for verification
- Server responds validity
- Server sends alerts – Location, Battery, Profile Risk
- Alert signal received
- Alert signal notifies using LED and Buzzer

3.7V 500mA Lithium Polymer Battery is the critical component of entire system. The LiPo battery is a rechargeable battery makes the helmet a lightweight and demands only compact power source. The compact size of the battery makes the system design thin, light weight and easy to deployable.

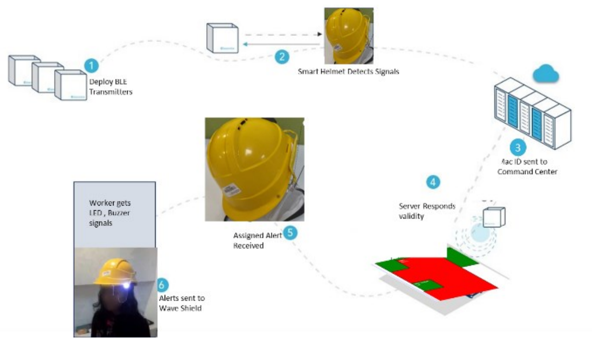

Figure 5: Solution workflow

4.1 Hardware Design

The hardware system comprises of two components: the transmitter and the receiver. The transmitter component is affixed in each hazardous environment, establishing a connection with Wi-Fi or Ethernet to gather information from the safety command center. Subsequently, it transmits the data via BLE signals to the smart helmets. The smart helmet is equipped with a receiver module, responsible for capturing the BLE signals and translating them into LED indications, which are then presented to the laborers.

4.1.1 Transmitter

The transmitter circuit comprises an ESP32, Bluetooth HC-05 module, and a Battery Management System (BMS) circuit. In the schematic (Figure 6), the ESP32 is connected to the Bluetooth module via the RX and TX pins. The BMS circuit includes a TP4056, which interfaces with the ESP32 through the GND and VIN pins, establishing connections with the positive and negative terminals of the BMS circuit. The battery is linked to the BMS circuit through the BAT+ and BAT- pins on the TP4056, completing the entire transmitter circuit.

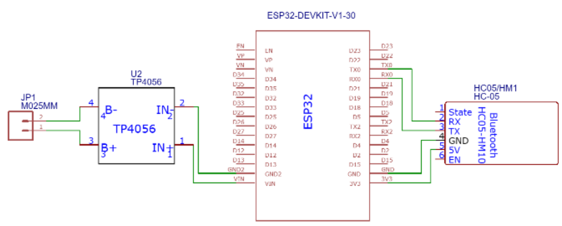

Figure 6: Transmitter circuit diagram

4.1.2 Receiver

The receiver circuit includes an ESP32, Bluetooth HC-05 module, BMS circuit, OLED display, WS2812B addressable LED, and a buzzer. In the schematic (Figure 7), the ESP32 is linked to the Bluetooth module via the RX and TX pins. The TP4056 serves as the battery management system, connecting to the ESP32 through the GND and VIN pins, establishing connections with the positive and negative terminals of the BMS circuit. The battery is interfaced with the BMS circuit through the BAT+ and BAT- pins on the TP4056.

For functional components, the OLED display (optional) is connected to the ESP32 using the SCL and SDA pins, while the WS2812B addressable LED and buzzer are linked to the ESP32's I/O pins for actuation.

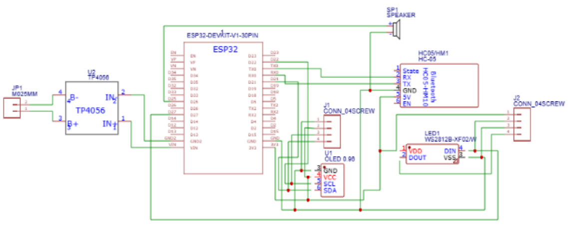

Figure 7: Received circuit diagram

4.2 Software Design

The software aspect of the system is designed using React.js which offers a seamless experience for users to visualize the entirety of the designated area, facilitating the clear demarcation of safe and unsafe zones. Moreover, an administrative dashboard has been implemented to provide real-time monitoring of the status of connected helmets.

In addition to its user interface capabilities, the system boasts a robust control panel (Refer Figure 2.1 in section 3.3) positioned conveniently on the right-hand side. This feature empowers safety managers with the functionality to swiftly designate areas as either safe or unsafe, thereby enhancing overall operational efficiency. Subsequently, this critical information is seamlessly relayed over the internet to the BLE transmitter.

Furthermore, the system is enriched with an array of analytical tools (Figure 8) designed to provide comprehensive insights into helmet utilization patterns. These analytics not only afford administrators the ability to gauge the frequency and duration of helmet usage but also enable them to identify potential areas for optimization and improvement.

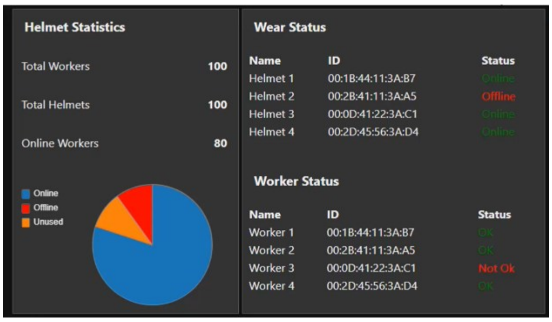

Figure 8: Software Dashboard

When an unauthorized MAC ID is registered in the system, verification fails and that MAC ID will not get any alerts. Further details about such MAC ID will be logged in the system to find the trespasser and security hacker

5 Results

When the PoC was carried out in our lab setup, below results were observed.

When the worker was loaded with other tasks, suddenly alert was sent by setting that zone as unsafe. Immediately red LED was powered and red light was shown and since it was easily noticeable, worker was able to understand the alert and moved out of the area till the LED warning sign turns back into normal color.

Secondly when the battery was used for more than 5 hours and then checked the safety command center to observe the battery condition of this worker. As expected in the UI, alert was triggered to safety manager and helmet condition changed to Red

Third condition, two different workers are observed in two regions. Worker 1 – Room_1, Worker 2 – Room_2 is the initial setup. When Room_1 was set us unsafe zone, checked whether worker 1's helmet is giving red signal, and when he moved to Room_2 (safe zone) his helmet signboard turned into green. Again, from the safety command center, Room_2 is marked as unsafe and turned Room_1 to safe zone, expected behavior of both signboards of helmets are turning into red is observed correctly. While asking only Worker 1 to move into Room_1 (safe zone now), Keeping the worker 2 in unsafe zone Room_2. It is observed that additional triggers are being sent to the safety manager after 3 minutes as worker 2 has not acted upon the signal warning.

Profile based alert or person-based alert was also tested. Though a worker is in safe zone, due to his higher risk exposure, sent an alert to worker 2 from the system, then helmet of the worker 2 received the alert and warning red LED was on.

Continuous monitoring over long duration is carried out to know the battery capability. It is observed that helmet battery can work for 5 hours in continuous manner.

We asked workers about ergonomic comfort like weight and disturbance caused by electronic signal. Both the workers responded that additional weight is negligible which is around 150 grams and electronic signal and LED signboard are not causing any trouble to their regular activities. However, there is a concern over charging the helmet on regular basis which is a new additional task to them.

6 Discussions & Future scope

Five major challenges that affect building any safety system in construction work force- Dynamic nature, communication, cost, utility & ergonomics, ability to collect data. The present study proposes BLE powered smart helmet which can overcome all the specified challenges to some extent. Because of connectivity established, any area in the construction site can be marked as safe or unsafe zones easily within minutes of time. By using BLE beacons and BLE receivers inside the helmet communication gap related challenges can be addressed. The present study is carried out on experimental study on lab setup, so detailed cost comparison is not yet made. However considering the huge number of accidents in this sector, it justifies the investment on new technology-based safety helmet. Still our calculations show that this helmet will be comparable enough costing 1500 Rupees (INR-Indian currency). Present study carefully designed the safety warning using color-based alert using tricolor LEDs. Transparent acrylic board with LED is ergonomically positioned in such a way that it will not affect the works being carried out, at the same time able to alert the worker quickly to get full attention. A major advantage of the proposed study is its ability to collect the data from all the construction workers and helps in forming safety analytics dashboard like how many workers entered into unsafe zone and how long they were inside unsafe zone. Data collection helps to provide reasonable Rewards and Recognition to the safety compliant workers. Experimental results showed that all the critical challenges can be addressed by this proposed study, however the same need to be validated with field implementation in the future work.

Though there are lot of benefits in the proposed approach, there are also few limitations. Those issues are privacy, battery charging and dependency of zone data entry. Present study assumes safety manager will be knowing all the data about safe and unsafe zones and able to enter them into safety command center instantly. This assumption may not be practically possible. Hence auto detection of safety zones will be studied in the future study. Location data about workers' movement is continuously recorded in the system, so privacy consent must be collected from workers to adhere to Global data privacy and regulation (GDPR). In the future study, data purging, consent collection and other requirements of GDPR will be built. Battery powered helmets are having inherent issue of battery charging regularly. Though there is an alert sent to workers whenever battery charge goes below 20% and there is data collection about the workers' devices which are having drained batteries, charging still has to be done. Since construction work is of open nature, in the future study possibility of using solar Photo Voltaic (PV) will be studied to overcome this critical challenge. Installing beacons and Wi-Fi routers across the construction site could be a tedious task and may not even be possible in some extreme scenarios. Profile based alerts opens up the possibility of handling various risk exposure which also changes with time. Constant wear of BLE powered helmet may expose Specific Absorption Rate (SAR) which is a measure of the rate at which RF energy is absorbed by the human body when exposed to a wireless signal from devices. IoT devices are exposed to high software security threats and attacks, the present study follows just MAC address-based approach. In the future, detailed white listing approach can be studied.

7 Conclusions

Considering the research question, the study's objective was to develop a proof-of-concept smart helmet and measure its ability to address the critical challenges faced by construction industry. A BLE beacon-based communication was adopted, and an ergonomically designed warning board with tri-color LED was adopted. Results demonstrated that dynamic zone can be indicated to workers instantly using both software and hardware. Using front end GUI, whenever safety manager marks any zone as safe or unsafe and helmet hardware instantly gets this alert. However, at this stage, the contraption is just a proof-of-concept to demonstrate the capability of IoT based smart helmet to understand the possibilities and limitations associated with it. Nevertheless, this study is a step closer to realizing the potential of such smart helmets in making highly unsafe construction field into a safe area to work.

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