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Smart Geofence: An Intelligent Location-Based Boundary Monitoring System

Vishwajit Virkar, Prasad Mandi, Mayur Chaudhari, Mansi Bhandari, Shreya Sidnale, Gajanan Gambhire
Department of B.Tech CSE(AIML), Vishwakarma Institute Of Technology, Pune ,India

Abstract - This research discusses an embedded real-time geofencing system for industrial and construction workplace safety . Using ESP32, GPS, and RFID technologies, it tracks worker movement, initiates local alarms on boundary violations, and provides a light-weight, robust, and scalable solution for low-infrastructure contexts.

Keywords - Geo-fencing System, Location Monitoring, Neo-6M GPS, Arduino, Boundary Detection, Real-Time Alert, Buzzer Notification, NMEA Parsing.

I. INTRODUCTION

Worker safety is a significant issue in industrial and construction settings. Heavy machinery and dangerous conditions raise the risk of accidents. Traditional safety measures often depend on analyzing incidents after they happen and do not include real-time monitoring. This leads to delayed responses and injuries that could be avoided. To solve these problems, this study suggests an IoT-based geofencing system for monitoring employees in real time. The system uses GPS tracking and virtual boundaries to create safe zones around the worksite. If a worker crosses the boundary, an immediate alert goes off, letting supervisors know to prevent possible accidents.

The proposed solution enhances safety and operational efficiency by offering real-time information about the movement and activities of workers. It is affordable, easy to expand, and does not require an internet connection, which makes it ideal for remote or low-connectivity environments. Constructed with low-cost components such as Neo-6M GPS and ESP32 microcontrollers, it maintains continuous safety assistance without needing internet connectivity. Such a system can be extended to other sectors like logistics, warehouses, and fleet tracking, and it opens up the foundation for an overarching real-time safety management system.

II. LITERATURE REVIEW

During the recent years, geofencing technology that has been integrated with Internet of Things (IoT) systems attracted much attention towards enhancing workplace safety, particularly in dangerous environments such as construction and factory workplaces. Sharma and Patel [1] presented an IoT-based geofencing system which made use of intelligent helmets, proximity sensors, and on-board controllers such as Raspberry Pi and Arduino to define virtual safety boundaries. Their findings indicated sensational reductions in hazard prevention and tracking in real-time. Nevertheless, reported were implementation cost issues and employee adaptability.

Thompson and Nguyen [2] also examined how geofencing is capable of improve workplace safety by combining artificial intelligence (AI), augmented reality (AR), virtual reality (VR), and telematics. Their solution was offering immersive hazard training and real-time risk evaluation, which considerably decreased workplace accidents. Still, scalability challenges and deployment cost issues were reported. In yet another contribution, Mehta, Desai, and Roy [3] proposed a low-cost GPS-based geofencing system using the Point-in-Polygon algorithm with Neo-6M GPS and ESP8266 Wi-Fi modules. Their system reliably validated real-time tracking and boundary monitoring, affirming that accurate geofencing solutions can be implemented using cost-effective embedded hardware in dynamic industrial environments. Cumulatively, these works form a sound basis for further research that seeks to create an embedded, offline-supporting, and energy-efficient geofencing system for real-time worker safety in far-flung or low-connectivity industrial environments.

Geofencing is a generic and dynamic location-tracking technology that employs GPS or Radio Frequency Identification (RFID) to mark virtual perimeters called geofences [4]. These digital perimeters enable systems to deliver context-aware services that respond to real-world user movements, supporting applications such as electronic billing, targeted marketing, and tourism assistance [4].

Initially adopted for simpler purposes like anti-theft systems and home surveillance, geofencing has since evolved into a sophisticated technology with far-reaching applications [4]. Normally, a geofence selects a particular area with coordinates (latitude and longitude) and a defined radius, and it starts performing actions like sending notifications or alerts when a device leaves or enters that area [4]. In commercial settings, this concept has turned into a new marketing strategy where businesses offer customized offers or notifications to customers within a predetermined proximity to their store or event [5].

Scientists have also created adaptive, affinity-based geofences that automatically adapt according to user taste and behavioral patterns, enabling more effective and tailored engagement [5]. Apart from commercial use, geofencing has been an essential tool in enhancing individual safety—especially for women in urban and rural settings—by creating safety zones around workplaces or residences that initiate warning alerts when a user exits or enters the designated zone [6]. This allows quicker response and greater awareness of safety in emergency situations.

With ongoing technological advancements, geofencing has expanded its capability by adding the use of Bluetooth technology for added positioning precision and enabling the use of low-cost security solutions [10]. For example, a domestic security system can be implemented using an ESP32-CAM module that records real-time video and sends real-time alerts via a Telegram bot whenever motion is sensed, providing a real-life illustration of premise security driven by IoT [10]. Overcoming the spatial constraints of conventional GPS-based geofencing in complicated environments, scientists have introduced GEM (Geofencing with network EMbedding) [11], a semi-supervised technique that utilizes ambient radio frequency (RF) signals and represents them as a weighted bipartite graph. GEM makes use of a new embedding algorithm, BiSAGE, to learn between-node associations and train a one-class classification model for precise in-out detection. This strategy has been found to be effective in uses like care of the elderly and wandering prevention in patients with dementia [11].

Apart from its industrial and security use, geofencing is becoming more identified in academic studies as a low-invasive and battery-conserving strategy for carrying out location-based behavioral research [12]. In research, virtual limits are established to initiate smartphone-driven activity—like polls—only when participants move into or out of a specified area [12]. A major benefit of this system is that participants can choose their own significant locations, such as their office or house, so that no sensitive location information is transmitted to researchers. Not only does this maintain participant privacy and anonymity, but it also allows real-world behavioral and cognitive research to be conducted without perpetual monitoring or excessive power expenditure [12].

In totality, the transformation of geofencing from workplace protection systems and intelligent marketing applications to complex research and security applications shows the flexibility and increasing relevance in the greater IoT system. The studies reviewed here collectively portray the promise of coupling geofencing with intelligent embedded chips, communication modules, and AI-powered analytics in creating safer, more intelligent, and responsive systems for contemporary use.

III. METHODOLOGY

This system uses an embedded geofencing setup for real-time monitoring. It aims to boost worker safety in those risky hazardous zones. Basically, it pulls together GPS tracking, some microcontroller processing, and IoT communication to spot locations and fire off alerts right away.

The ESP32 microcontroller handles the main controlling duties. You know, it sips power without much fuss and comes with built-in Wi-Fi right there. They use the Arduino IDE as the development spot. That means libraries like TinyGPS++ to parse the GPS data, PubSubClient for the MQTT side of things, and Wi-Fi setup for getting connected. The NEO-6M GPS module feeds in real-time latitude and longitude via serial communication. Then TinyGPS++ pulls out the usable bits from that. Oh and, they throw in a Kalman Filter to sharpen up the location accuracy. It helps cut down on that annoying GPS drift too.

Once the coordinates get processed, the system checks them against these predefined geofence boundaries. Those boundaries sit stored inside the microcontroller. If a worker steps over that virtual line, a buzzer kicks in along with a red LED for a local alert. Right at the same time, an MQTT message goes out to a central server. That message packs in the worker's ID, the location details, and the breach status. They integrate it with the Telegram Bot API too. So supervisors get instant alerts on their mobile devices. That gives them remote monitoring without much hassle. Plus, there's an RFID module tossed in for identifying workers and keeping track of who's where. For the visualization part, a server built on Express.js and Node.js talks to the MQTT broker. It pushes live updates over to a web dashboard made with Leaflet.js.

They test the whole setup under different real-world conditions. That covers GPS accuracy, response times, and how reliable the alerts turn out. After that validation, it rolls out in some selected industrial areas. There they check durability, battery life, and signal stability more. Overall, the system comes across as scalable and affordable. Pretty dependable too for real-time worker safety monitoring. It ties in those embedded IoT components with cloud visualization in an effective way

System Architecture

The functioning of GPS based realtime worker's safety monitoring system and geofencing model is shown in following figure (1). This is designed in the way that it will real-time monitor the working areas and transfer the effective data, so that the actionable alarm movement can be performed. The system's backbone is the ESP8266 NodeMCU, which is a Wi-Fi microcontroller capable of taking GPS coordinates from the GY-NEO6MV2 module and sending the data to a remote server using HTTP requests.

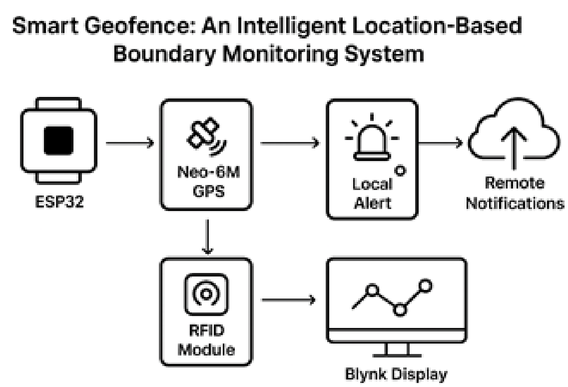

Figure 1: System architecture for Geo-fencing

The circuit diagram as shown in the following figure (2) is the real-time connections of the circuit and the execution process is based on it. This setup is basically a small, easy to carry GPS tracker. It runs on a rechargeable 18650 lithium ion battery. The TP4056 module handles the charging to keep things steady. The whole thing uses a NodeMCU microcontroller hooked up with a GPS module and an outside antenna. That way it gets pretty accurate location info.The GPS spits out NMEA data. The NodeMCU grabs that and uses the TinyGPS plus plus library to pull out the latitude, longitude, and time stamp. Not bad for something so compact. Every few seconds it sends the location data over Wi Fi to a backend server built with Node.js. Over there the data gets stored and shown live on a web dashboard made with Leaflet.js. To add geofencing using Leaflet realtime and leaflet pip libraries.

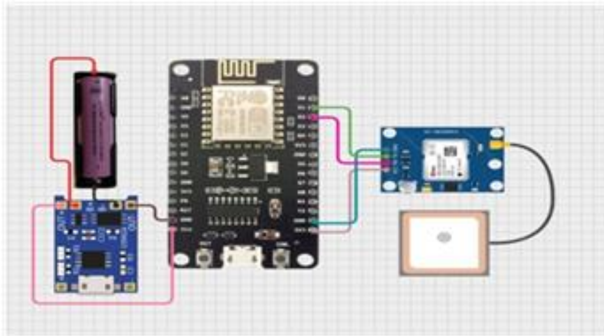

Figure 2: Geo-fencing Prototype

Results

The GPS tracker we put together, with that geo-fencing feature, really showed off real-time location tracking. And boundary monitoring too as shown in the result figure (3). It picked up GPS data using the Neo-6M module. Then sent everything over Wi-Fi via the NodeMCU. You got to see the main stuff like latitude, longitude, altitude, speed, signal strength. All through a command interface. Plus a Google Maps link. Things ran steady, with good connectivity and accuracy. Makes it right for safety checks or keeping track of assets.

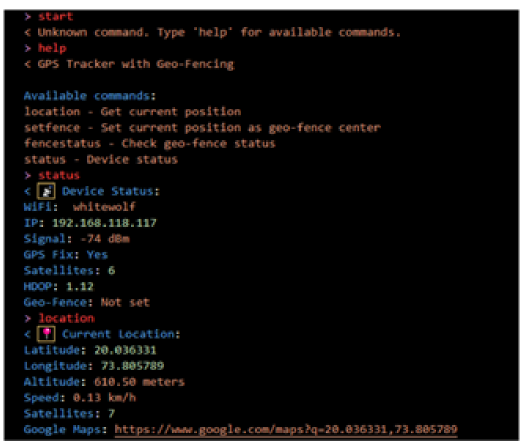

Figure 3: Geofencing Result

IV. CONCLUSION

The increasing incidence of workplace injuries and safety infractions in industrial and construction environments is an indicator of the necessity for newer technology-driven measures in this aspect. Traditional safety measures, based primarily on human vigilance and post-event analysis, are discovered to be inadequate in providing cover against real-time hazards. The current research bridges such critical limitations by developing a GPS-based real-time tracking and geofencing of laborers system ensuring active safety monitoring.

With the incorporation of GPS tracking modules, geofencing techniques, and wireless data transfer, the system described here is an interactive framework for real-time tracking of employee locations. Through the application of static and dynamic geofencing, site managers can identify hazardous or restricted areas and be alerted instantaneously when an employee enters or exits such an area. This aspect supports prompt response, minimizes risk exposure, and provides compliance with safety procedures.

In addition to that, the system promotes precision and dependability through utilization of filtering techniques like the Kalman filter for diminishing location mistakes occasioned by external conditions. There is live information transmission to a web application featuring live mapping of locations, alarm generation, and geofencing configuration. It facilitates safe action enforcement to prevent accidents, enabling real-time provision of actionable intelligence to managers for decreased incident response time.

The modularity and scalability of the system allow it to be used in many industrial applications, whether it is in construction, mining, logistics, or manufacturing. The real-time operating feature of the system not only gives assurance that the workers are at all times being monitored but also that they are being protected through smart boundary enforcement. The system can also store and process data in the long term, and therefore organizations can audit safety compliance as well as plan the workforce optimally based on history.

In conclusion, the proposed system of real-time worker safety and geofencing bridges the important gap between enforcement of safety and technology. The system grants managers easy access on-site to ensure the enforcement of safety rules, removes the risk of injury and death, and ensures a culture of safety first. With the redefinition of monitoring and managing safety, this system has the potential to significantly improve the health of workers and the success of projects in high-risk industries.

Limitations

Apart from the good performance and good real-time monitoring capabilities, the proposed GPS-based worker safety and geofencing system also has some limitations that need to be mentioned. The most serious issue is dependency on the quality of the GPS signal, which can be significantly affected by environmental factors like the presence of tall buildings, underground tunnels, dense forests, or working underground. In such situations, the GPS module will fail to capture or retain satellite signals and therefore lose data.

The system also uses Wi-Fi for communication of data to the server. Where there is no constant Wi-Fi or internet connection, the real-time sending of location information can be compromised. Buffering this in the form of short-term storage on the device may be beneficial, but this adds to system complexity and yet doesn't solve the issue of real-time monitoring and alerting while offline.

On the software side, while geofencing using polygons is versatile, it is also expensive to compute, especially when large numbers of workers simultaneously are being monitored against large or multi-sided boundaries. It can lead to slow processing and response times for geofence violations unless the server is well-optimized or scaled. Dynamic geofencing also requires human effort to establish the boundaries, which can be man-intensive. Scalability of Cost Effectiveness: While cost-effectiveness is imaginable from the project in commercial or small-sized situations, the total cost can be a considerable aspect for consideration on a large scale. Cost control and preserving the assets will be critical in order to make it larger.

Literature Adaptation: Certain parts of the project might need further adaptation with new and latest literature. There needs to be a careful review of contemporary studies and practice integrated into forthcoming work for development of the project's theoretical background. Lack of Industry-Level Validation: There is no direct input taken from large-scale businesses in this present study. Detailed surveys and interviews with industry players would yield relevant information about actual issues and needs, enabling the project to be sharpened and made more practically viable. Scalability of Cost Effectiveness: While cost-effectiveness is imaginable from the project in commercial or small-sized situations, the total cost can be a considerable aspect for consideration on a large scale. Cost control and preserving the assets will be critical in order to make it larger.

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Lastly, data privacy and security issues also place constraints. Tracking workers' locations and storing their location data also has ethical and legal implications regarding surveillance and consent. Protecting data transmission and sensitive worker data from unauthorized access is critical. In the absence of proper encryption, user authentication, and access control, the system can be vulnerable to abuse or intrusion.

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