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Development of an IoT-Based Smart Vest for Occupational Safety Monitoring of Traffic Enforcers

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ABSTRACT

Traffic enforcers are frequently exposed to hazardous working conditions such as extreme heat, air pollution, prolonged standing, and physically demanding roadside operations. Existing wearable monitoring devices are often limited to fitness tracking and lack automatic emergency detection, environmental monitoring, and cloud-based communication capabilities. This study proposes the development of an IoT-based Smart Vest designed to support the occupational safety of traffic enforcers through real-time health and environmental monitoring. The system integrates multiple sensors, including heart rate, body temperature, motion, air quality, humidity, and GPS modules connected to an ESP32 microcontroller. Threshold-based monitoring logic is utilized to evaluate sensor readings and classify conditions into normal, warning, and critical states. The system also employs Internet of Things (IoT) technologies to transmit monitoring data to a Firebase Realtime Database and a Flutter-based mobile application for monitoring and emergency response purposes. When abnormal conditions are detected, the system automatically triggers SOS alerts and transmits GPS location data to authorized users and emergency contacts through Firebase Cloud Messaging.

The study utilized a developmental research design and followed the Agile Scrum methodology in designing, developing, testing, and refining the prototype system. Preliminary testing demonstrated that the Smart Vest prototype was capable of collecting monitoring data, displaying monitoring conditions within the mobile application, transmitting information through cloud-based synchronization, and generating emergency alert notifications during simulated abnormal conditions. The developed prototype demonstrates the feasibility of integrating wearable sensing, IoT communication, and mobile monitoring technologies within a single occupational safety monitoring platform intended for traffic enforcers during roadside operations.

Keywords: Internet of Things (IoT), Smart Vest, Occupational Safety Monitoring, Wearable Monitoring System, Emergency Alert System

INTRODUCTION

Internet of Things (IoT) technologies and wearable monitoring systems have significantly influenced modern occupational health and safety applications through the development of smart wearable devices capable of continuous monitoring and automated emergency-notification functionalities. Recent advancements in wearable computing have enabled safety devices to evolve beyond traditional fitness tracking by integrating physiological monitoring, environmental sensing, wireless communication, and cloud-based data synchronization. These technologies create opportunities for improved monitoring accessibility and monitoring-state awareness through continuous collection and synchronization of physiological and environmental information within hazardous work environments.

Traffic enforcers are among the public safety personnel regularly exposed to physically demanding and high-risk working conditions. Daily roadside operations require prolonged exposure to vehicle emissions, elevated temperatures, humidity, and heavy traffic environments that may negatively affect both physical health and occupational safety. In addition to environmental hazards, traffic enforcers are vulnerable to fatigue, heat stress, abnormal physiological conditions, sudden falls, and delayed emergency communication during critical roadside incidents. Despite these risks, many commercially available wearable devices remain limited to general fitness monitoring and often require manual interaction during emergencies, reducing their applicability within occupational monitoring environments.

Existing wearable monitoring systems primarily focus on industrial workers, construction personnel, or general health-tracking applications. Many systems lack integrated environmental monitoring, automated alert generation, and GPS-based monitoring synchronization within a single wearable platform. Furthermore, limited studies have explored IoT-enabled wearable monitoring systems specifically designed for traffic enforcers operating in roadside environments. This research gap highlights the need for a wearable monitoring prototype capable of simultaneously supporting physiological monitoring, environmental sensing, GPS synchronization, and emergency-notification workflows within a unified occupational safety platform.

To address these limitations, this study proposes the development of an IoT-based Smart Vest (SmartVest) prototype for traffic enforcers that integrates physiological, environmental, and location-based monitoring within a single wearable monitoring system. The proposed SmartVest prototype incorporates multiple sensors, including MAX30102 for heart rate monitoring, MLX90614 for body temperature detection, MPU-6050 for motion and fall-detection monitoring, MQ-135 for air-quality monitoring, DHT22 for humidity and ambient-temperature sensing, and NEO-6M for GPS tracking. These sensors are connected to an ESP32 DevKit V1 microcontroller responsible for sensor-data acquisition, filtering, threshold-based monitoring evaluation, and cloud-based data synchronization.

The system applies predefined physiological and environmental monitoring thresholds to categorize detected conditions into Normal, Warning, and Critical monitoring states. Monitoring readings are transmitted through Wi-Fi connectivity to Firebase synchronized Database and displayed through a Flutter-based mobile monitoring application that provides dashboard visualization, alert-history accessibility, and GPS monitoring functionalities. During simulated Critical monitoring-state scenarios, the system automatically activates a local buzzer-warning mechanism and transmits emergency notifications with GPS monitoring information to registered emergency contacts using Firebase Cloud Messaging (FCM).

This study aims to develop an IoT-based wearable monitoring prototype capable of supporting occupational safety monitoring among traffic enforcers through physiological, environmental, and location-based monitoring functionalities. Specifically, the study aims to:

1. Develop a smart vest prototype capable of monitoring physiological and environmental conditions through wearable sensing technologies.
2. Implement IoT-based emergency-notification and GPS-monitoring functionalities for abnormal monitoring scenarios.
3. Provide a mobile monitoring platform that allows authorized users to access synchronized monitoring information and alert-history records remotely.

The study focuses on the design and preliminary prototype development of a wearable occupational monitoring system intended for traffic enforcers assigned to roadside and field operations. The proposed system is limited to monitoring, synchronization, and early-warning functionalities and does not provide direct medical diagnosis, clinical-grade physiological evaluation, or emergency-response validation. Preliminary evaluation procedures primarily utilized simulated monitoring scenarios and controlled prototype testing conditions due to ongoing hardware integration activities. Additionally, communication and synchronization functionalities depended on the availability of stable internet connectivity, which may affect monitoring-data transmission behavior in areas with limited network coverage.

REVIEW OF RELATED LITERATURE AND STUDIES

Wearable Occupational Safety Systems

The development of wearable technology has significantly influenced modern occupational health and safety management systems. Recent advancements in smart personal protective equipment (PPE) have enabled wearable devices to evolve from passive safety tools into intelligent monitoring systems capable of real-time data collection and hazard detection. Rasouli and Alipouri (2024) explained that modern smart PPE integrates sensors, wireless communication modules, and data processing capabilities that continuously monitor workplace conditions and worker health status. Through these technologies, conventional safety equipment can provide early warning mechanisms and improve occupational risk management.

Several studies have demonstrated the effectiveness of wearable safety systems in hazardous work environments. Rajendran, Wahab, and Yeap (2020) developed a smart safety vest capable of detecting nearby hazards and generating warning alerts for workers operating in dangerous environments. Similarly, Abainza, Aguilar, and Edmondson (2020) developed a Philippine-based smart construction vest integrating physiological monitoring sensors and wireless communication technologies for continuous worker monitoring. Their findings demonstrated that wearable monitoring systems improve workplace safety by enabling supervisors to identify worker fatigue and abnormal health conditions at earlier stages.

Other studies highlighted the growing importance of wearable systems in improving occupational safety management. Zhang, Chen, and Wang (2021), Li, Chan, and Luo (2022), and Lee et al. (2023) emphasized that wearable monitoring devices equipped with wireless communication technologies enhance situational awareness and allow organizations to respond more effectively to hazardous conditions. These systems contribute to proactive safety management by continuously monitoring worker conditions and transmitting data to remote monitoring platforms.

IOT and Emergency Communication Systems

The integration of Internet of Things technologies has enabled wearable safety systems to support real-time communication, cloud-based monitoring, and emergency response functionalities. Xu et al. (2020) explained that IoT systems allow interconnected sensors to transmit data continuously to centralized monitoring platforms, improving safety management in complex working environments. These systems enable organizations to collect and analyse large volumes of real-time data while supporting rapid response during emergencies.

Several studies highlighted the importance of IoT-enabled communication systems in occupational safety applications. Mehata and Shankar (2022) proposed an IoT-based smart vest capable of transmitting physiological and environmental data to remote monitoring systems for continuous worker observation. Edirisinghe (2025) developed an IoT-based smart vest designed to monitor heat stress among outdoor workers through continuous environmental and physiological monitoring.

The Federal Highway Administration (2022) developed a Connected Smart Vest designed for highway work zones that utilized real-time connectivity and warning systems to improve worker awareness of incoming vehicular threats. Similarly, Guo et al. (2024) presented an IoT-integrated rescue vest featuring rapid emergency response mechanisms and fall detection functionalities. These studies demonstrate the growing role of IoT communication technologies in enhancing worker safety and improving emergency response efficiency.

Environmental And Physiological Monitoring Technologies

Environmental and physiological monitoring technologies play a significant role in wearable occupational safety systems. Chen et al. (2023) examined wearable monitoring devices capable of tracking environmental conditions such as temperature, humidity, and hazardous gas levels while simultaneously monitoring physiological conditions including heart rate and fatigue. Their findings highlighted the importance of integrated monitoring systems in reducing workplace accidents caused by delayed hazard recognition.

Aghimien et al. (2024) also emphasized that wearable physiological monitoring systems improve occupational safety by enabling early detection of heat stress, exhaustion, and abnormal physical conditions. Gautam et al. (2024) further demonstrated that continuous monitoring systems capable of analysing environmental hazards and physiological conditions support proactive workplace safety management and improve organizational response during critical situations.

In the Philippine context, Llamas et al. (2024) explored wearable health monitoring systems integrated with web-based monitoring platforms for real-time medical tracking applications. Reyes et al. (2024) also demonstrated the feasibility of locally developed IoT-based wearable safety devices integrating GPS tracking and emergency communication technologies. These studies support the applicability of wearable monitoring technologies in local occupational safety environments.

Research Gap and Study Relevance

The reviewed literature and studies demonstrate the increasing importance of wearable technologies, automated monitoring systems, and IoT-enabled communication platforms in improving occupational safety management. Existing studies have shown that wearable systems can effectively monitor physiological conditions, environmental hazards, and emergency situations through integrated sensing and communication technologies.

However, most existing wearable monitoring systems are primarily designed for industrial workers, construction personnel, or general workplace environments. Limited studies have focused specifically on traffic enforcers who are continuously exposed to vehicle emissions, heat, humidity, prolonged standing, and roadside operational hazards. Furthermore, many existing systems do not fully integrate physiological monitoring, environmental sensing, GPS tracking, emergency notification, cloud-based monitoring, and mobile accessibility within a single wearable platform.

Therefore, this study addresses these identified gaps through the development of an IoT-based Smart Vest specifically designed for traffic enforcers. The proposed system integrates physiological monitoring, environmental sensing, threshold-based monitoring logic, IoT communication, and emergency notification functionalities to support real-time occupational safety monitoring in roadside operational environments.

METHODOLOGY

Research Design

This study utilized a developmental and experimental research approach for the design, implementation, and preliminary evaluation of the proposed IoT-based Smart Vest (Smart Vest) prototype system. The research focused on integrating wearable sensing technologies, IoT communication, cloud-based monitoring, and threshold-based monitoring logic within a unified occupational safety platform intended for traffic enforcers.

The study involved the collection and analysis of physiological, environmental, and location-based monitoring data obtained from the developed hardware prototype during controlled prototype testing procedures. Physiological monitoring data included heart rate readings obtained from the MAX30102 sensor and body temperature readings collected using the MLX90614 infrared temperature sensor. Motion and fall detection data were acquired through the MPU-6050 accelerometer and gyroscope module, while environmental monitoring data included air quality measurements from the MQ-135 sensor and humidity and ambient temperature readings from the DHT22 sensor. synchronized location information was obtained using the NEO-6M GPS module.

The system applied predefined physiological and environmental thresholds to categorize detected conditions into Normal, Warning, and Critical monitoring states. These classifications were used to determine whether the system should continue standard monitoring operations or activate emergency alert mechanisms. Preliminary testing primarily utilized simulated monitoring scenarios and prototype-based evaluation procedures intended to assess system functionality, cloud synchronization behavior, and emergency notification workflows.

To support iterative development and continuous system refinement, the study adopted the Agile Software Development Life Cycle (SDLC) methodology using the Scrum framework. Agile methodology was selected due to its flexibility in handling simultaneous hardware and software development activities, including sensor integration, firmware development, database connectivity, and mobile application implementation. The Scrum framework enabled the researchers to divide the development process into manageable sprint cycles for testing, evaluation, and refinement.

Agile Development Phases

Figure 1. Agile Scrum Software Development Life Cycle (SDLC) Model

SPRINT 1–Requirement Analysis

The functional and technical requirements of the Smart Vest prototype system were identified during the initial planning stage. Required hardware components, including sensors, communication modules, and the ESP32 microcontroller, were selected based on the intended monitoring and emergency notification functionalities of the system. Software tools such as Flutter, Firebase, and Arduino IDE were also identified. User requirements and expected monitoring functionalities were organized through a product backlog to guide subsequent development activities.

SPRINT 2–System Design

The overall architecture of the Smart Vest system was designed using the Input-Process-Output (IPO) framework. Data flow between system components was modeled using a Data Flow Diagram (DFD), while database relationships were structured using an Entity-Relationship Diagram (ERD). Mobile application wireframes and hardware wiring layouts were also prepared to guide implementation and prototype integration activities.

SPRINT 3–Hardware Integration and Firmware Development

The hardware components were assembled and integrated using the ESP32 DevKit V1 microcontroller as the central processing unit. Sensor modules were programmed using the Arduino IDE to perform live data acquisition, filtering, and threshold-based monitoring evaluation. Wi-Fi communication functionality was implemented to enable transmission of sensor readings to Firebase Realtime Database. The buzzer module was also configured to activate during simulated critical monitoring conditions.

SPRINT 4–Mobile Application Development

A Flutter-based Android companion application was developed to provide continuous monitoring and remote accessibility. Firebase Authentication was implemented for secure user access, while Firebase Realtime Database was integrated to display live sensor readings and alert history records. Firebase Cloud Messaging (FCM) was also configured to deliver emergency notifications and GPS coordinates to registered emergency contacts during simulated abnormal monitoring conditions.

SPRINT 5–Testing and Preliminary Evaluation

The developed Smart Vest prototype underwent preliminary functionality and performance testing to evaluate system responsiveness and communication behavior. Individual sensors underwent controlled prototype testing procedures to observe monitoring consistency and system integration performance. Data transmission behavior, dashboard synchronization, GPS tracking functionality, and emergency alert workflows were also evaluated to assess continuous monitoring capabilities. Simulated emergency scenarios were conducted to evaluate the effectiveness of the threshold-based monitoring and emergency notification mechanisms.

SPRINT 6–Evaluation And Refinement

The final phase involved evaluating the integrated prototype system based on testing outcomes and identified performance limitations. Necessary refinements were applied to improve sensor stability, data transmission reliability, dashboard synchronization, and alert responsiveness. The final SmartVest prototype was then prepared for documentation and preliminary system assessment.

Proposed System Architecture

The proposed SmartVest system follows an Input-Process-Output (IPO) architecture to support continuous occupational safety monitoring for traffic enforcers. The system integrates physiological, environmental, and location-based monitoring technologies within a unified wearable prototype platform connected to cloud-based and mobile monitoring services.

The input layer consists of integrated sensor modules responsible for collecting physiological and environmental monitoring data from the wearer and surrounding environment. These include the MAX30102 heart rate sensor, MLX90614 body temperature sensor, MPU-6050 motion and fall detection sensor, MQ-135 air quality sensor, DHT22 humidity and ambient temperature sensor, and NEO-6M GPS module.

The process layer is handled by the ESP32 DevKit V1 microcontroller, which performs sensor data acquisition, filtering, and threshold-based monitoring evaluation. The system categorizes detected conditions into Normal, Warning, and Critical monitoring states based on predefined physiological and environmental thresholds. Processed monitoring data are transmitted through Wi-Fi connectivity to Firebase Realtime Database for cloud-based storage and dashboard synchronization.

The output layer includes the Flutter-based mobile monitoring application, emergency notification system, and local alert mechanisms. Authorized users can access synchronized monitoring data, alert history, and GPS tracking information through the mobile application. During simulated critical situations, the system automatically activates a buzzer alarm and sends emergency notifications with location coordinates to registered emergency contacts using Firebase Cloud Messaging (FCM).

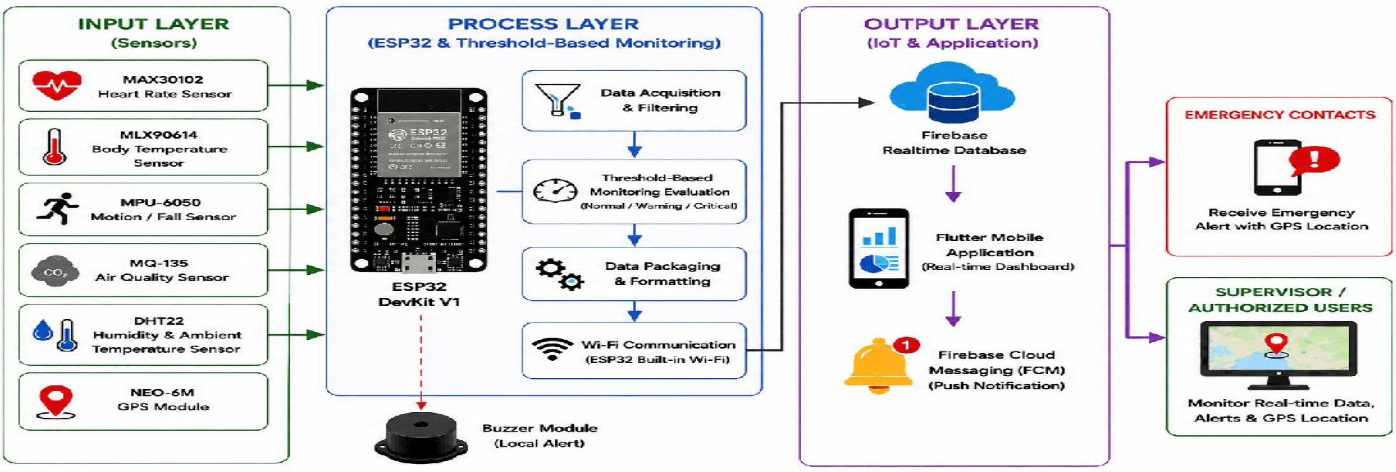

Figure 2. Proposed Smart Vest System Architecture Using Input-Process-Output (IPO) Framework

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System Workflow

The Smart Vest system operates through continuous acquisition of physiological, environmental, and location-based monitoring data from integrated sensors connected to the ESP32 microcontroller. Collected data undergo filtering and threshold-based monitoring evaluation before transmission to Firebase Realtime Database through Wi-Fi communication. The processed monitoring information is displayed within the Flutter-based mobile application for continuous dashboard monitoring. During simulated critical monitoring conditions, the system automatically activates local buzzer alerts and transmits emergency notifications with GPS coordinates to registered emergency contacts.

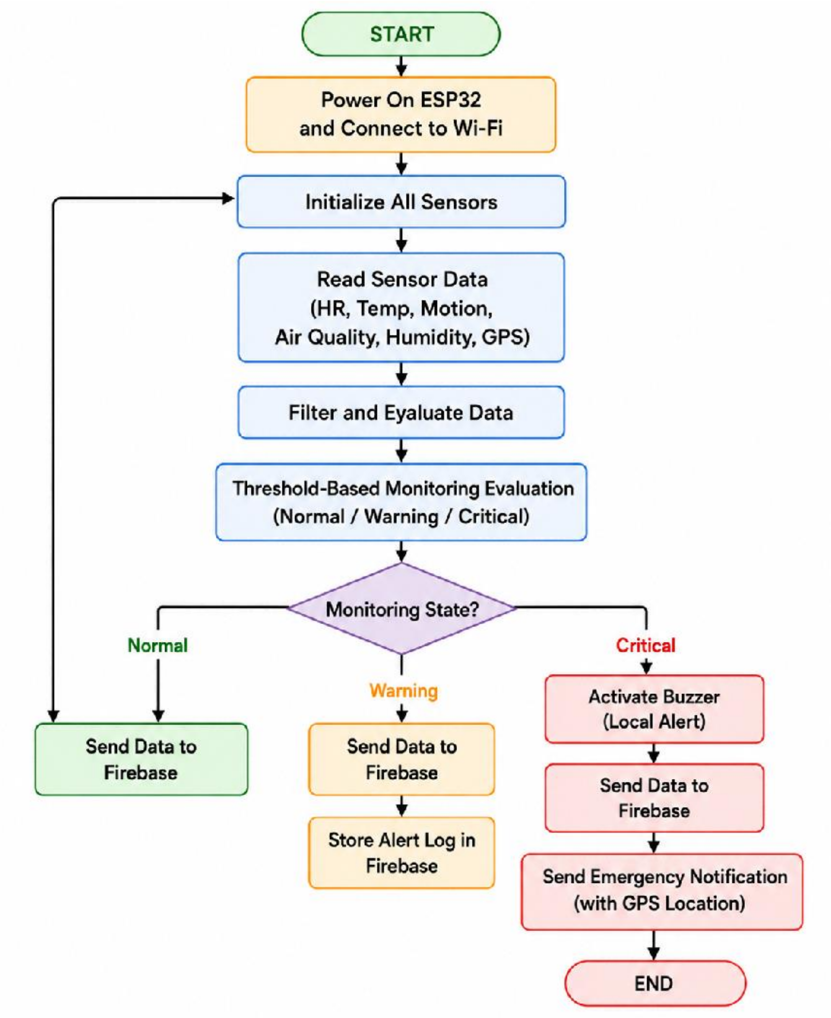

Figure 3. Flowchart of the proposed Smart Vest system.

Database And Communication Structure

The SmartVest system utilizes cloud-based communication and Firebase Realtime Database technologies to support remote monitoring and emergency notification functionalities. Sensor readings collected from the ESP32 microcontroller are transmitted through Wi-Fi connectivity to Firebase Realtime Database, where monitoring data are stored and synchronized with the Flutter-based mobile application. The system also supports communication between authorized users, emergency contacts, and monitoring interfaces through Firebase Cloud Messaging (FCM) services.

The communication structure enables continuous monitoring of physiological, environmental, and location-based information while maintaining synchronization between the wearable prototype hardware, cloud database, and mobile monitoring platform. During simulated abnormal monitoring conditions, the system supports automatic dashboard updating, alert logging, GPS location synchronization, and emergency notification transmission for prototype evaluation purposes.

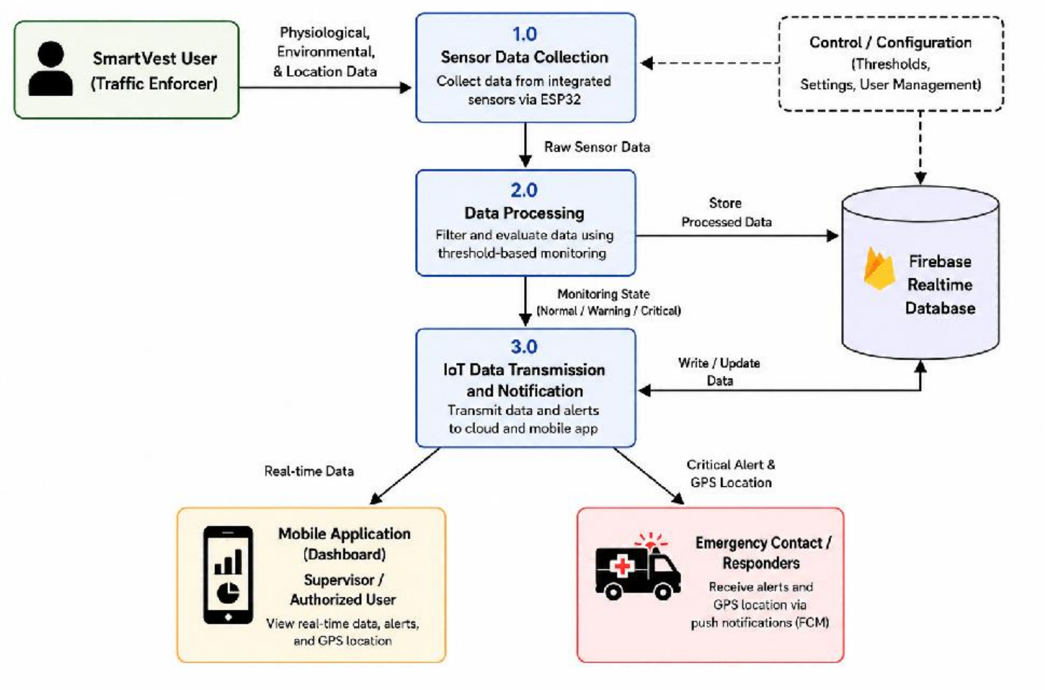

Figure 4. Data flow diagram of the Smart Vest system.

Database Design

The Smart Vest database structure was designed to organize user information, sensor readings, emergency notifications, and monitoring records within Firebase Realtime Database. The database supports live synchronization between the wearable prototype hardware and the Flutter-based mobile monitoring application while maintaining structured relationships among system entities.

The database design includes user account records, physiological and environmental monitoring data, GPS location records, and emergency alert logs generated during prototype operation. These relationships enable authorized users to access monitoring history, view recorded alerts, and support continuous safety monitoring functionalities during preliminary system evaluation.

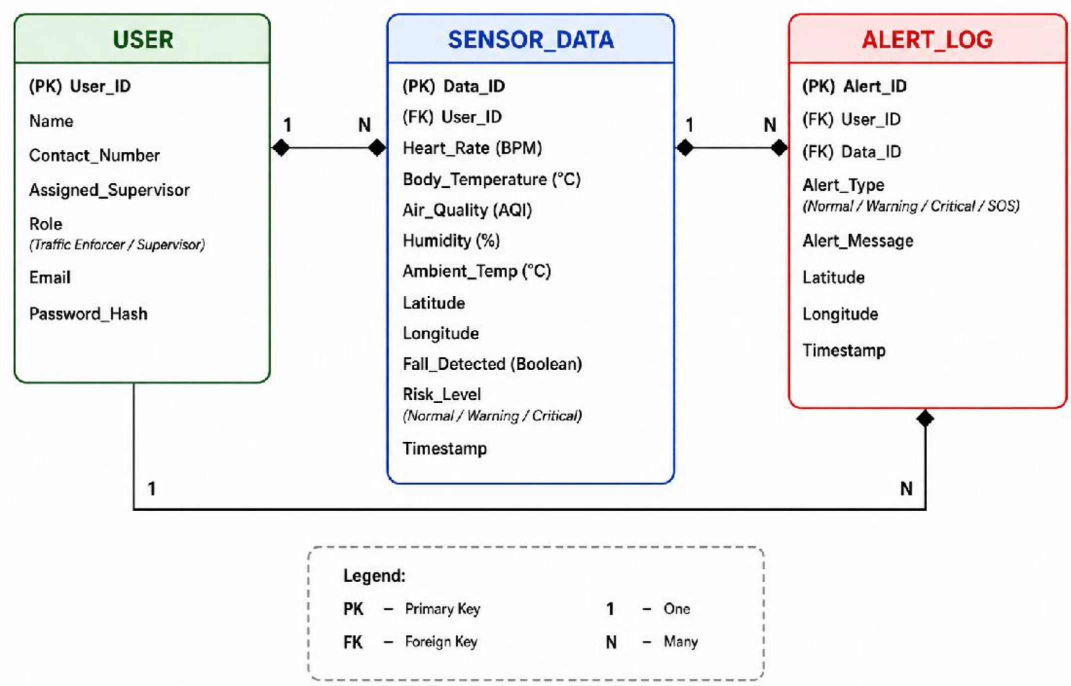

Figure 5. Entity-relationship diagram of the Smart Vest database.

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System Functional Interaction

The Smart Vest system supports interaction among multiple users and monitoring components through the mobile application and cloud-based services. Traffic enforcers serve as the primary users of the wearable prototype device, while supervisors and emergency contacts interact with the monitoring platform to receive alerts and access monitoring information.

The system enables authorized users to monitor sensor readings, receive emergency notifications, review alert history, and track GPS location information during simulated critical monitoring conditions. These functionalities support efficient communication, monitoring accessibility, and emergency notification workflows during preliminary prototype evaluation procedures.

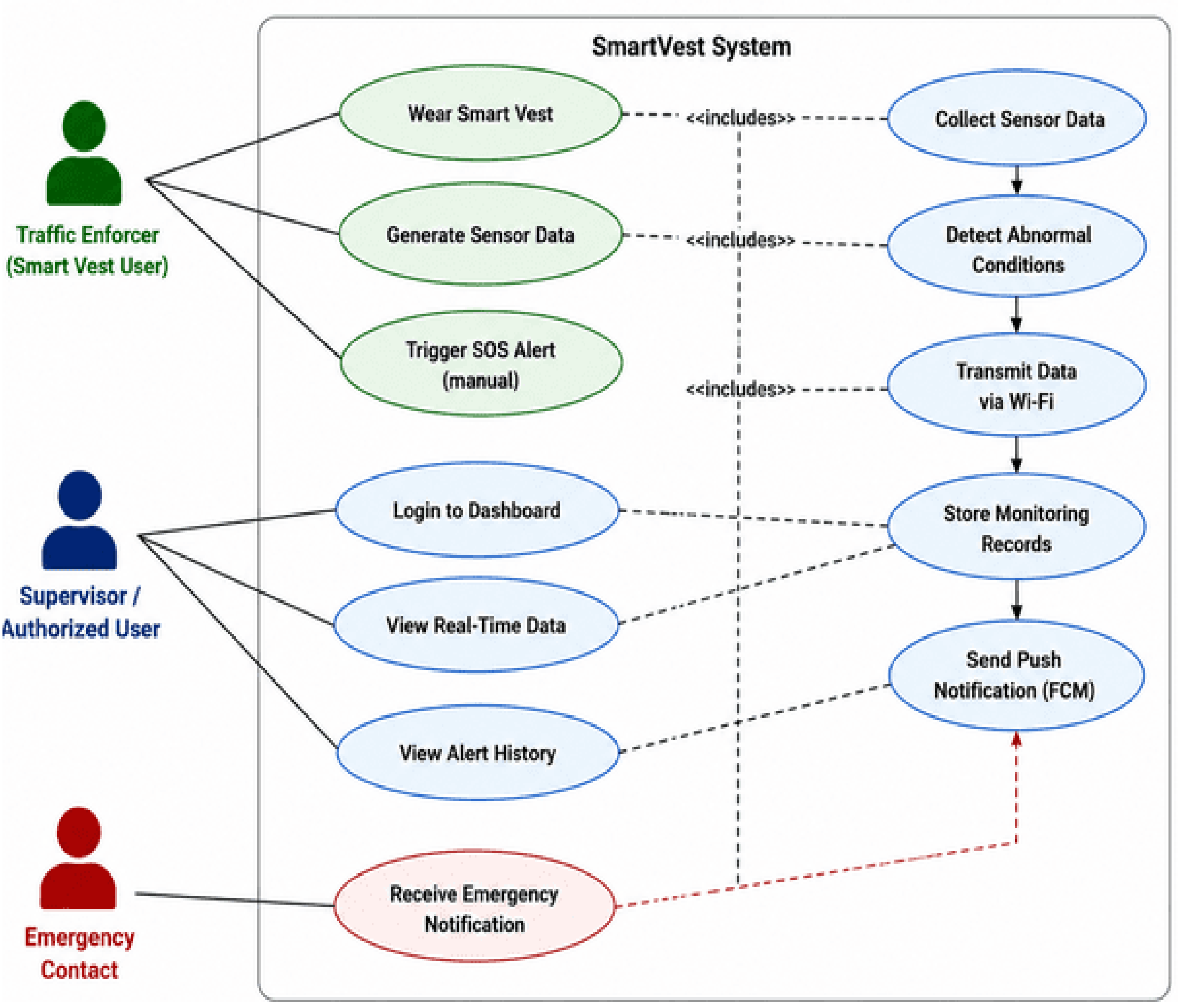

Figure 6. Use case diagram of the Smart Vest system.

Use Case Descriptions

The SmartVest system supports interaction among traffic enforcers, supervisors, authorized users, and emergency contacts through integrated wearable prototype hardware, cloud-based services, and mobile monitoring technologies. The following use cases summarize the primary monitoring, notification, and communication functionalities implemented within the proposed SmartVest prototype platform during preliminary system evaluation.

Table 1. Summary of Smart Vest System Use Cases

Actor	Use Case	Description
Traffic Enforcer (Smart Vest User)	Wear Smart Vest	The traffic enforcer wears the vest during duty, which automatically initiates sensor data collection without requiring manual interaction.
Traffic Enforcer (Smart Vest User)	Generate Sensor Data	The vest continuously generates physiological and environmental monitoring readings, including heart rate, body temperature, motion, air quality, humidity, and GPS location information.
Traffic Enforcer (Smart Vest User)	Trigger SOS Alert (manual)	The traffic enforcer may manually trigger an SOS alert through a physical button on the vest during emergency situations not automatically detected by the system.
System (ESP32 Prototype Module)	Collect Sensor Data	The ESP32 microcontroller collects data from connected sensors and applies filtering procedures before data transmission and monitoring evaluation.
System (ESP32 Prototype Module)	Detect Abnormal Conditions	The system evaluates sensor readings using predefined physiological and environmental thresholds to classify monitoring conditions as Normal, Warning, or Critical.
System (ESP32 Prototype Module)	Transmit Data via Wi-Fi	Processed monitoring information and alert statuses are transmitted to Firebase Realtime Database using the ESP32 built-in Wi-Fi module.
System (Firebase)	Store Monitoring Records	Firebase Realtime Database stores sensor readings, timestamps, alert logs, and GPS coordinates for monitoring history and preliminary system evaluation purposes.
System (Firebase)	Send Push Notification (FCM)	Firebase Cloud Messaging sends emergency notifications to registered emergency contacts during simulated critical monitoring conditions.
Supervisor / Authorized User	Login to Dashboard	The supervisor authenticates through Firebase Authentication to securely access the SmartVest monitoring dashboard.
Supervisor / Authorized User	View Monitoring Data	The supervisor accesses monitoring information, including heart rate, body temperature, GPS location, humidity, and air quality readings.
Supervisor / Authorized User	View Alert History	The supervisor reviews recorded alert logs and monitoring history generated during prototype operation.
Emergency Contact	Receive Emergency Notification	The emergency contact receives an emergency notification containing alert information and GPS coordinates through the mobile application notification system.

Monitoring Threshold Configuration

To support threshold-based monitoring-state evaluation, predefined physiological and environmental monitoring thresholds were configured within the Smart Vest prototype during preliminary prototype development. The configured thresholds were based on publicly available physiological, environmental, and occupational monitoring references commonly used in wearable monitoring applications. These thresholds were intended solely for prototype-level monitoring evaluation and were not intended to represent medical-grade diagnostic standards.

Table 2. Monitoring Threshold Configuration

Parameter	Threshold Basis	Monitoring State
Heart Rate	Resting adult heart-rate references (60–100 BPM)	Warning/Critical when exceeding configured range
Body Temperature	Fever-monitoring references (>37.5°C)	Warning/Critical when elevated
Air Quality	Air-quality exposure monitoring guidelines	Warning/Critical during poor air conditions
Humidity	Environmental comfort and heat-stress references	Warning during elevated humidity
Fall Detection	MPU-6050 abnormal motion-change detection	Critical during abnormal movement

The configured monitoring thresholds were utilized solely for preliminary prototype evaluation and wearable monitoring workflow demonstration during simulated monitoring scenarios. The Smart Vest prototype was not intended to provide medical-grade physiological diagnosis or certified occupational health assessment.

Smart Vest Hardware Configuration

The Smart Vest prototype was designed to integrate multiple physiological, environmental, and location-monitoring sensors within a wearable safety vest intended for traffic enforcers and field personnel. The placement of each sensor and hardware component was carefully planned to support monitoring accessibility, wearer comfort, environmental exposure, and synchronized data acquisition during prototype operation.

Physiological sensors, including the MAX30102 heart rate sensor and MLX90614 body temperature sensor, were positioned near the upper chest area to support consistent physiological monitoring measurements. Environmental sensors such as the MQ-135 air quality sensor and DHT22 temperature and humidity sensor were placed near exposed lower sections of the vest to support environmental monitoring and surrounding air exposure evaluation.

Meanwhile, the ESP32 microcontroller, GPS module, and buzzer module were strategically positioned within accessible pockets and protected sections of the vest to support stable data processing, wireless communication, emergency notification transmission, and overall prototype portability. Figure 6 illustrates the proposed hardware placement configuration of the SmartVest prototype.

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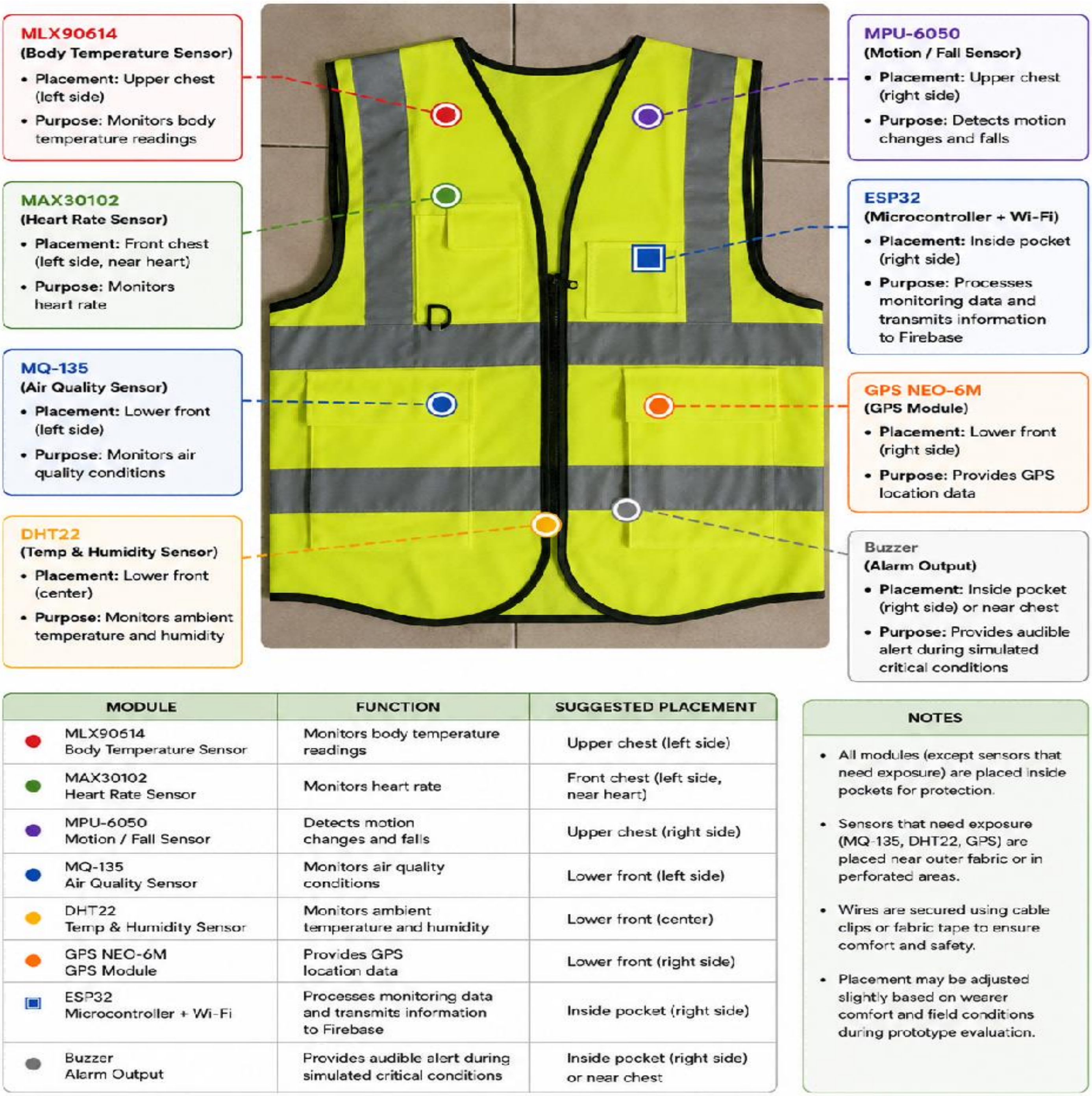

MODULE	FUNCTION	SUGGESTED PLACEMENT
MLX90614 Body Temperature Sensor	Monitors body temperature readings	Upper chest (left side)
MAX30102 Heart Rate Sensor	Monitors heart rate	Front chest (left side, near heart)
MPU-6050 Motion / Fall Sensor	Detects motion changes and falls	Upper chest (right side)
MQ-135 Air Quality Sensor	Monitors air quality conditions	Lower front (left side)
DHT22 Temp & Humidity Sensor	Monitors ambient temperature and humidity	Lower front (center)
GPS NEO-6M GPS Module	Provides GPS location data	Lower front (right side)
ESP32 Microcontroller + Wi-Fi	Processes monitoring data and transmits information to Firebase	Inside pocket (right side)
Buzzer Alarm Output	Provides audible alert during simulated critical conditions	Inside pocket (right side) or near chest

Figure 7. Proposed Sensor and Module Placement Configuration of the SmartVest Prototype

RESULTS AND DISCUSSION

The Results and Discussion section presents the preliminary prototype demonstration and functional evaluation of the SmartVest system. Since selected hardware modules were still undergoing acquisition, assembly, and integration during the development phase, simulated monitoring values were utilized for selected physiological and environmental monitoring components during controlled prototype testing procedures.

The evaluation procedures primarily focused on assessing the wearable monitoring workflow, Firebase Realtime Database synchronization, mobile dashboard visualization, threshold-based monitoring behavior, GPS data synchronization, alert logging functionality, and emergency notification workflows of the proposed SmartVest prototype system. The conducted evaluation was intended to demonstrate the feasibility of integrating wearable monitoring, cloud-based communication, and mobile monitoring functionalities within a unified occupational safety prototype platform.

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Prototype Sensor Functionality Testing

The SmartVest prototype was designed to collect physiological, environmental, and location-based monitoring information using integrated wearable sensing technologies connected to the ESP32 processing module. Preliminary prototype testing demonstrated the ability of the system to acquire, process, and display monitoring information within the Flutter-based mobile application dashboard during controlled monitoring scenarios.

The conducted testing procedures primarily focused on observing sensor integration behavior, dashboard synchronization, monitoring-state visualization, and cloud-based data transmission functionalities of the SmartVest prototype system. Selected physiological and environmental monitoring components utilized simulated monitoring values during preliminary evaluation procedures due to ongoing hardware acquisition and integration activities.

Figure 8. Preliminary SmartVest Prototype Integration and Sensor Configuration

The successful integration of the wearable prototype components demonstrated the feasibility of combining physiological monitoring, environmental sensing, wireless communication, and cloud-based monitoring technologies within a unified occupational safety prototype platform. The developed prototype maintained portability while supporting synchronized monitoring and dashboard visualization functionalities during preliminary prototype evaluation procedures.

The conducted prototype testing demonstrated the capability of the SmartVest system to support wearable monitoring workflows intended for traffic enforcers performing prolonged roadside duties under continuously changing environmental conditions. However, the preliminary evaluation primarily focused on system integration behavior, monitoring-state visualization, and communication workflow demonstration under controlled testing scenarios.

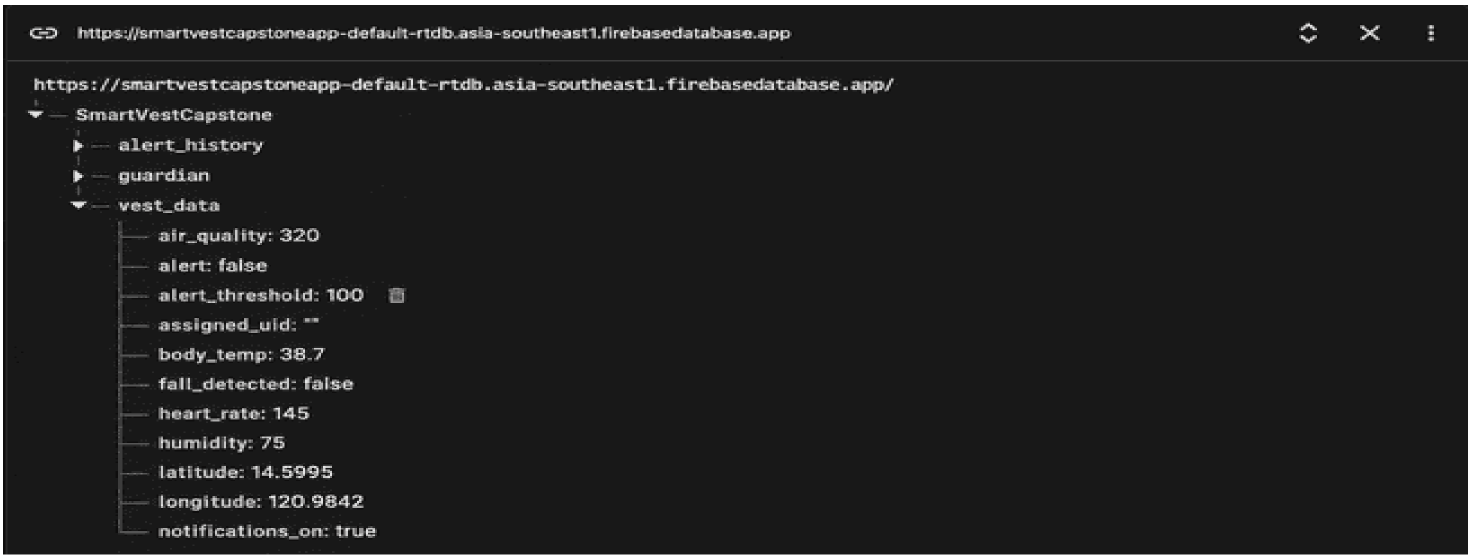

Figure 9. Firebase Realtime Database Containing SmartVest Monitoring Data

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The SmartVest system successfully synchronized monitoring information with Firebase Realtime Database through Wi-Fi communication during preliminary prototype testing procedures. Firebase Realtime Database served as the centralized cloud-based platform responsible for handling monitoring records, alert logs, GPS synchronization, and mobile dashboard updating functionalities within the SmartVest prototype system.

The successful synchronization between the ESP32 module and Firebase Realtime Database demonstrated the feasibility of supporting cloud-based wearable monitoring and remote dashboard accessibility within a unified occupational safety prototype platform. The implemented communication workflow enabled supervisors and authorized users to remotely observe monitoring information, alert conditions, and GPS location data during simulated abnormal monitoring scenarios.

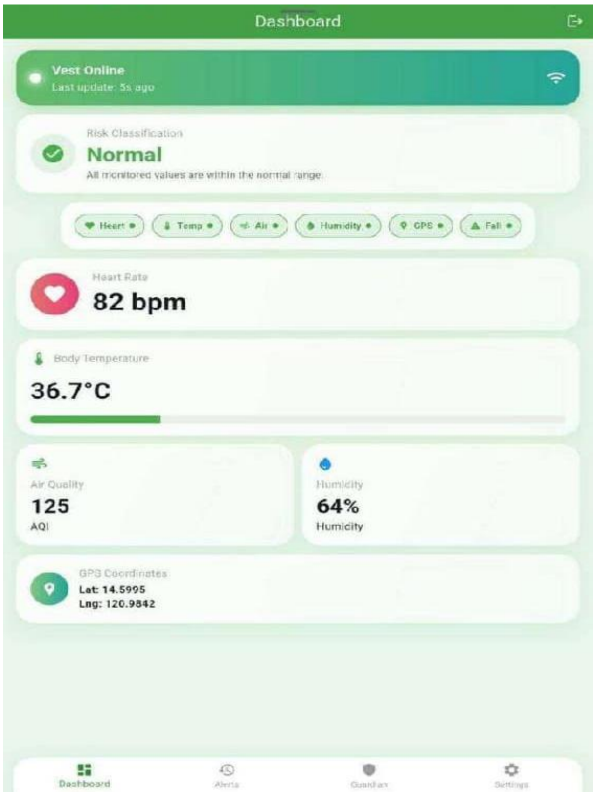

Figure 10. Firebase Realtime Database Synchronization During Preliminary Prototype Testing

Under simulated normal monitoring conditions, the SmartVest prototype displayed physiological and environmental monitoring readings within predefined threshold ranges. The Flutter-based dashboard interface successfully visualized synchronized monitoring information while maintaining continuous synchronization with Firebase Realtime Database during preliminary prototype testing procedures.

The conducted evaluation demonstrated the capability of the SmartVest prototype to support cloud-based monitoring workflows, dashboard updating, and monitoring-state visualization under controlled testing scenarios. The synchronized monitoring interface allowed authorized users to remotely access physiological, environmental, and GPS monitoring information through the mobile application platform.

Table 3. Sample Normal Condition Monitoring Output

Parameter	Sample Monitoring Reading
Heart Rate (bpm)	78
Body Temperature (°C)	36.7
Air Quality (AQI)	82

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Humidity (%)	67
GPS Coordinates	14.5995, 120.9842
Fall Detection Status	False
Monitoring State	Normal

The preliminary evaluation results demonstrated that the SmartVest prototype was capable of supporting continuous monitoring visualization and wearable monitoring information synchronization during simulated safe monitoring conditions. The Normal monitoring-state evaluation demonstrated that the SmartVest prototype was capable of maintaining stable monitoring workflows under predefined physiological and environmental threshold ranges during controlled prototype testing procedures.

Continuous synchronization and dashboard visualization functionalities indicated the feasibility of integrating wearable monitoring, cloud-based communication, and mobile dashboard accessibility within a unified occupational safety prototype platform. The conducted evaluation primarily demonstrated monitoring workflow behavior, dashboard updating, and data synchronization functionalities intended for prolonged monitoring activities during traffic enforcement operations.

Threshold-Based Monitoring Evaluation

The SmartVest prototype implemented a threshold-based monitoring evaluation mechanism designed to categorize monitoring information into Normal, Warning, and Critical monitoring states. The monitoring-state logic was configured within the ESP32 firmware and mobile monitoring workflow to support wearable monitoring visualization, alert-state generation, and emergency notification functionalities during preliminary prototype testing procedures.

The implemented threshold-based evaluation mechanism utilized predefined physiological and environmental monitoring thresholds to determine whether the system should maintain standard monitoring workflows or activate warning and emergency notification functions under simulated abnormal monitoring conditions. The conducted evaluation primarily focused on observing monitoring-state transitions, dashboard alert visualization, and notification workflow behavior during controlled prototype testing scenarios.

Figure 11. Warning Condition Displayed in the Mobile Dashboard

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The Warning monitoring state was triggered when physiological or environmental monitoring readings exceeded predefined threshold ranges while remaining below Critical monitoring-state thresholds during simulated prototype testing procedures. During controlled monitoring scenarios, the Flutter-based dashboard interface successfully displayed elevated monitoring readings and corresponding Warning monitoring-state visualizations within the mobile monitoring platform.

The conducted evaluation demonstrated the capability of the SmartVest prototype to support threshold-based monitoring-state transitions, dashboard synchronization, and alert-state visualization during simulated abnormal monitoring conditions. The Warning monitoring-state workflow allowed authorized users to observe elevated monitoring readings and corresponding dashboard updates through the cloud-based monitoring interface.

Table 4. Sample Warning Condition Monitoring Output

Parameter	Sample Reading
Heart Rate (bpm)	124
Body Temperature (°C)	37.9
Air Quality (AQI)	168
Humidity (%)	72
GPS Coordinates	14.5995, 120.9842
Fall Detection Status	False
Monitoring State	Warning

The Warning monitoring-state mechanism demonstrated the capability of the SmartVest prototype to identify elevated physiological and environmental monitoring readings before reaching predefined Critical monitoring-state thresholds during simulated prototype evaluation procedures. The implemented threshold-based monitoring workflow supported early-warning visualization and alert-state synchronization within the mobile monitoring platform.

The conducted evaluation demonstrated the feasibility of using threshold-based monitoring mechanisms to support wearable monitoring awareness and cloud-based dashboard accessibility during abnormal monitoring scenarios. The Warning monitoring-state workflow enabled authorized users to observe elevated monitoring readings and corresponding dashboard updates before activation of Critical monitoring-state notifications.

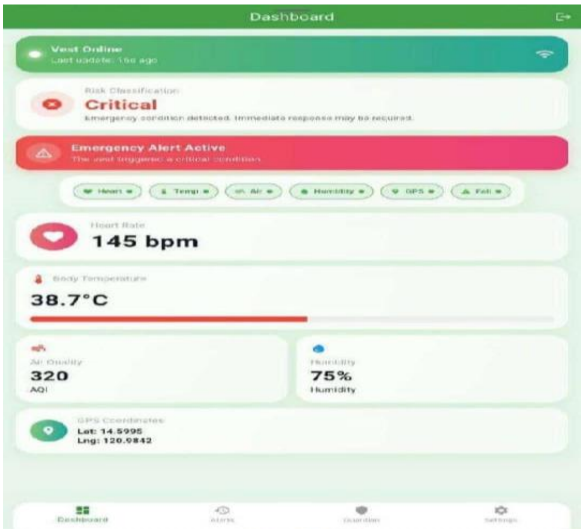

Figure 12. Critical Condition Alert Displayed in the Mobile Dashboard

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Critical monitoring states were triggered during simulated abnormal monitoring scenarios involving elevated physiological or environmental monitoring readings and abnormal motion-detection events during controlled prototype testing procedures. The SmartVest prototype successfully displayed Critical monitoring-state indicators, dashboard alert visualizations, and emergency notification workflows during simulated Critical monitoring-state evaluation scenarios.

The conducted evaluation demonstrated the capability of the SmartVest prototype to support threshold-based monitoring-state transitions, cloud-based dashboard synchronization, and emergency alert visualization functionalities during simulated abnormal monitoring conditions. The Critical monitoring-state workflow enabled authorized users and registered emergency contacts to receive synchronized alert notifications and GPS monitoring information through the mobile monitoring platform.

Table 5. Sample Critical Condition Monitoring Output

Parameter	**Sample Reading**
Heart Rate (bpm)	145
Body Temperature (°C)	38.7
Air Quality (AQI)	320
Humidity (%)	75
GPS Coordinates	14.5995, 120.9842
Fall Detection Status	True
Monitoring State	Critical

During simulated Critical monitoring-state scenarios, the SmartVest prototype successfully activated the intended monitoring and emergency-notification workflow, including dashboard warning visualization, alert logging, GPS synchronization, and emergency notification transmission during controlled prototype testing procedures. The implemented workflow demonstrated the capability of the SmartVest prototype to support monitoring-state awareness, dashboard accessibility, and cloud-based alert synchronization during simulated abnormal monitoring conditions.

The conducted preliminary evaluation demonstrated the feasibility of integrating wearable monitoring, threshold-based alert mechanisms, and cloud-based communication functionalities within a unified occupational safety prototype platform. However, the conducted testing procedures primarily focused on monitoring workflow behavior, synchronization functionality, and dashboard alert visualization under controlled prototype evaluation scenarios.

Firebase Communication and Data Transmission Testing

The communication functionalities of the SmartVest prototype were evaluated through preliminary synchronization testing between the ESP32 processing module, Firebase Realtime Database, and Flutter-based mobile application during controlled prototype testing procedures. The conducted evaluation focused on assessing cloud-based monitoring synchronization, dashboard updating behavior, GPS data synchronization, and emergency notification transmission workflows within the proposed SmartVest prototype system.

The preliminary synchronization evaluation demonstrated the capability of the SmartVest prototype to transmit monitoring information from the wearable sensing components to Firebase Realtime Database through Wi-Fi communication. The synchronized monitoring information was successfully reflected within the Flutter-based mobile dashboard interface during simulated monitoring scenarios. The conducted evaluation primarily focused on synchronization behavior, monitoring workflow continuity, and cloud-based communication functionality during preliminary prototype testing conditions.

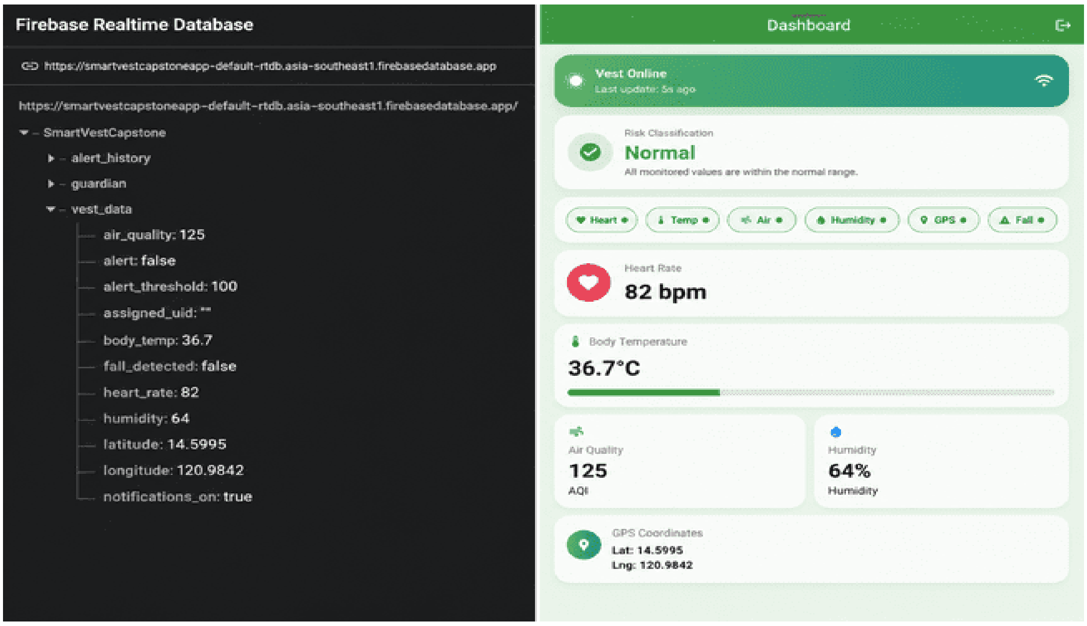

Figure 13. Dashboard Synchronization Using Firebase Realtime Database

The communication and synchronization evaluation demonstrated that the SmartVest prototype architecture was capable of supporting cloud-based wearable monitoring workflows during preliminary prototype testing procedures. Functional Wi-Fi communication and Firebase Realtime Database synchronization enabled continuous dashboard updating and monitoring-information transmission between the wearable prototype hardware and the Flutter-based mobile monitoring application.

The conducted evaluation demonstrated the feasibility of integrating IoT-based communication technologies, wearable monitoring functionalities, and cloud-based dashboard synchronization within a unified occupational safety prototype platform. The synchronization workflow allowed authorized users to remotely observe physiological, environmental, and GPS monitoring information during simulated monitoring scenarios under controlled prototype evaluation conditions.

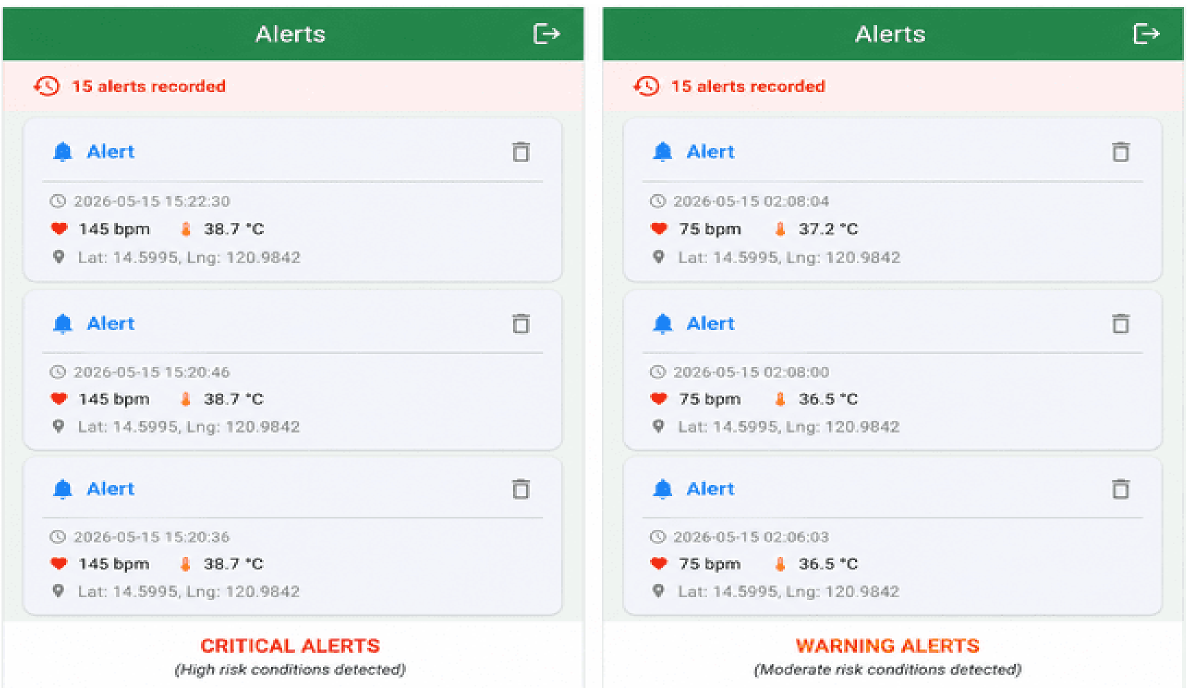

Figure 14. Alert Logging and Monitoring History Interface

The emergency-notification workflow demonstrated the integration of threshold-based monitoring, cloud-based synchronization, GPS monitoring, and notification services within a unified wearable occupational safety prototype platform. The SmartVest prototype successfully generated dashboard alerts, synchronized GPS monitoring information, and transmitted emergency notifications during simulated Critical monitoring-state scenarios under controlled prototype testing procedures.

The conducted evaluation demonstrated the feasibility of integrating wearable monitoring workflows, cloud-based communication functionalities, and emergency-notification synchronization within the proposed SmartVest prototype system. The implemented workflow enabled authorized users and registered emergency contacts to receive synchronized monitoring alerts and GPS monitoring information through the Flutter-based mobile monitoring platform during simulated abnormal monitoring conditions.

Table 6. Preliminary Communication and Synchronization Testing Results

Feature Tested	**Observed Outcome**
Wi-Fi Connectivity	The ESP32 processing module successfully established wireless communication with the local Wi-Fi network during preliminary testing.
Firebase Synchronization	Monitoring data from the SmartVest prototype was successfully synchronized and stored within Firebase Realtime Database during preliminary testing
Dashboard Updating	The Flutter-based mobile application successfully reflected updated monitoring information without requiring manual refresh operations.
Alert Logging	Simulated warning and critical monitoring conditions successfully generated alert records within the alert history interface.
GPS Data Display	GPS coordinate information was successfully displayed within the dashboard monitoring interface during synchronization testing.
Notification Workflow	The system successfully executed the intended emergency monitoring workflow during simulated abnormal monitoring conditions.

The preliminary prototype evaluation results demonstrated the capability of the SmartVest prototype system to support cloud-based wearable monitoring workflows through synchronization between the wearable prototype architecture and the Flutter-based mobile monitoring application during controlled prototype testing procedures.

The conducted synchronization evaluation demonstrated the feasibility of integrating wearable sensing technologies, Wi-Fi communication, Firebase Realtime Database synchronization, and mobile dashboard accessibility within a unified occupational safety prototype platform. The synchronized monitoring workflow enabled authorized users to remotely access physiological, environmental, and GPS monitoring information during simulated monitoring scenarios.

Emergency Alert and Notification Testing

Emergency-notification functionality was evaluated through simulated abnormal monitoring conditions and alert-activation scenarios during controlled prototype testing procedures. The SmartVest prototype was designed to generate monitoring alerts, activate local buzzer-warning mechanisms, and initiate notification workflows for authorized users and registered emergency contacts through the cloud-based mobile monitoring platform.

The conducted evaluation focused on observing dashboard alert visualization, GPS monitoring-information synchronization, emergency-notification transmission behavior, and alert logging functionalities during simulated Critical monitoring-state scenarios. The implemented workflow demonstrated the feasibility of integrating wearable monitoring, threshold-based alert mechanisms, and cloud-based communication services within a unified occupational safety prototype platform.

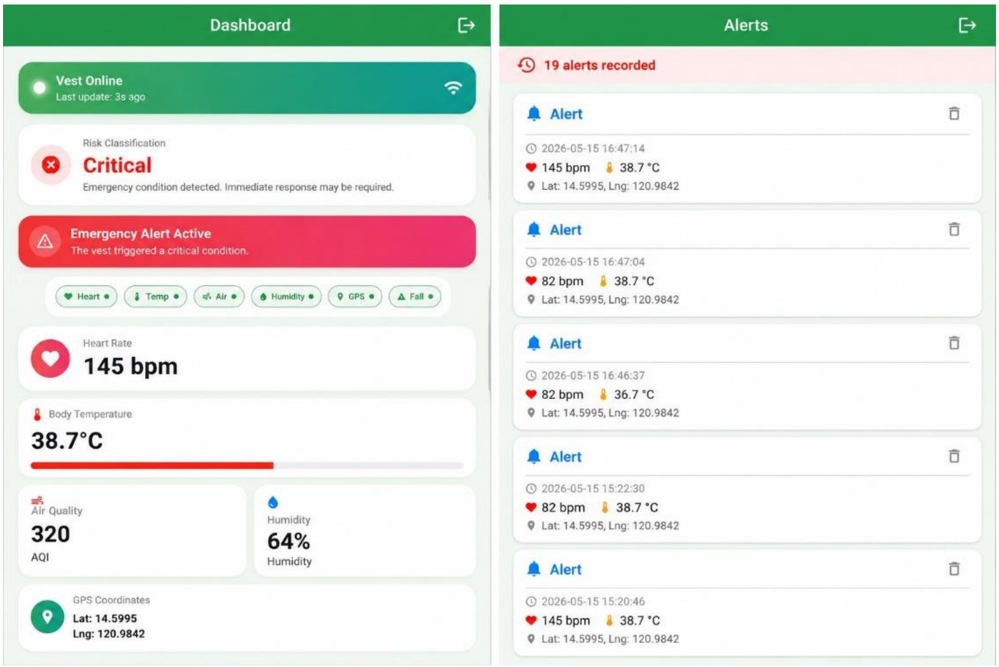

Figure 15. Simulated Emergency Alert Activation

The SmartVest prototype demonstrated the intended emergency-notification workflow during simulated Critical monitoring-state scenarios under controlled prototype testing procedures. Emergency notifications, dashboard warning visualizations, and alert-log records were successfully reflected within the Flutter-based mobile monitoring application and cloud-based alert logging interface.

The conducted evaluation demonstrated the capability of the SmartVest prototype to support threshold-based monitoring-state transitions, notification synchronization, and dashboard alert visualization during simulated abnormal monitoring conditions. The synchronized alert workflow enabled authorized users and registered emergency contacts to receive monitoring alerts and GPS monitoring information through the mobile monitoring platform.

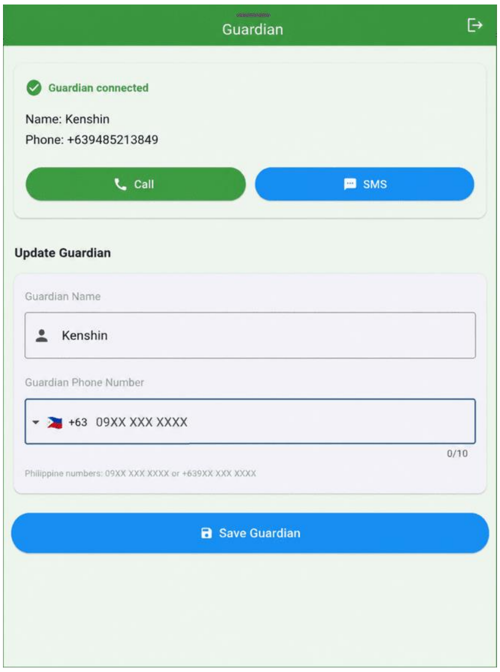

Figure 16. Emergency Contact and Notification Interface

The guardian and emergency-contact interface enabled authorized users to observe emergency-notification behavior, dashboard alert visualization, and simulated GPS monitoring-information synchronization workflows during controlled prototype testing procedures. The implemented communication workflow supported cloud-based alert synchronization and monitoring-state accessibility within the Flutter-based mobile monitoring platform during simulated abnormal monitoring scenarios.

Table 7. Emergency Notification Functionality Testing

Emergency Feature	**Observed Outcome**
Emergency Alert Activation	The SmartVest prototype successfully generated monitoring-alert responses during simulated Critical monitoring-state scenarios under controlled prototype testing procedures.
Alert History Logging	Simulated abnormal monitoring events were successfully synchronized and recorded within the alert-history interface of the Flutter-based mobile monitoring application.
GPS Coordinate Display	GPS monitoring information was successfully displayed and synchronized within the emergency-notification monitoring interface during preliminary prototype evaluation procedures.
Dashboard Warning Display	The Flutter-based dashboard interface successfully reflected Warning and Critical monitoring-state visualizations during simulated monitoring scenarios.
Notification Workflow	The SmartVest prototype successfully executed the intended monitoring-alert and emergency-notification synchronization workflow for authorized users and registered emergency contacts during controlled prototype testing conditions.

The SmartVest prototype successfully demonstrated the proposed emergency-notification workflow through simulated monitoring-alert activation, dashboard visualization, GPS monitoring-information synchronization, and cloud-based notification transmission during controlled prototype testing procedures.

The conducted preliminary evaluation demonstrated the feasibility of integrating threshold-based monitoring workflows, wearable sensing technologies, cloud-based communication services, and mobile dashboard synchronization within a unified occupational safety prototype platform. The implemented workflow enabled authorized users and registered emergency contacts to receive synchronized monitoring alerts and GPS monitoring information during simulated Critical monitoring-state scenarios.

Overall System Evaluation

The preliminary prototype evaluation demonstrated that the SmartVest prototype was capable of integrating physiological monitoring, environmental sensing, cloud-based synchronization, threshold-based monitoring-state evaluation, and emergency-notification functionalities within a unified wearable occupational safety prototype platform. The developed prototype successfully demonstrated wearable monitoring workflows intended for traffic enforcers operating within simulated roadside monitoring scenarios during controlled prototype testing procedures.

The integration of threshold-based monitoring logic and IoT communication technologies supported automated monitoring-state transitions, dashboard synchronization, and cloud-based monitoring accessibility within the proposed SmartVest prototype system. Furthermore, Firebase Realtime Database and the Flutter-based mobile monitoring platform enabled continuous synchronization and accessibility of monitoring information for authorized users and registered emergency contacts during simulated monitoring scenarios.

Although selected monitoring readings utilized simulated monitoring scenarios and partial sensor integration during preliminary prototype evaluation procedures, the SmartVest prototype successfully demonstrated the feasibility of integrating wearable sensing technologies, cloud-based monitoring services, and emergency-notification workflows within a unified occupational safety monitoring platform intended for prototype-level occupational monitoring applications.

The developed SmartVest prototype should be interpreted as a preliminary prototype feasibility study intended to demonstrate the integration of wearable sensing technologies, cloud-based monitoring synchronization, threshold-based monitoring-state visualization, and emergency-notification functionalities.

The current implementation utilized predefined physiological and environmental monitoring thresholds and simulated monitoring scenarios during controlled prototype evaluation procedures. Full medical-grade validation, sensor calibration against certified reference devices, communication latency evaluation, long-term field deployment, battery endurance analysis, and occupational health validation procedures remain outside the scope of the present study and are recommended for future development and evaluation.

CONCLUSION

The study successfully developed a preliminary prototype of an IoT-based SmartVest system intended to support wearable physiological, environmental, and location-based monitoring for occupational safety applications. The proposed SmartVest prototype integrated wearable sensing technologies, ESP32 microcontroller processing, Firebase Realtime Database communication, and a Flutter-based mobile monitoring application within a unified occupational safety prototype platform. The developed prototype was designed to support cloud-based monitoring synchronization, dashboard visualization, and emergency-notification workflows during simulated monitoring scenarios.

Preliminary prototype evaluation demonstrated that the SmartVest prototype was capable of supporting wearable monitoring workflows and synchronization functionalities between the wearable prototype architecture and the mobile monitoring application during controlled prototype testing procedures. Simulated monitoring scenarios successfully reflected corresponding monitoring readings within Firebase Realtime Database and the Flutter-based dashboard interface. The implemented threshold-based monitoring mechanism also demonstrated the capability of the system to display Normal, Warning, and Critical monitoring states based on predefined physiological and environmental monitoring thresholds.

The conducted evaluation further demonstrated the capability of the proposed SmartVest prototype to support emergency-notification workflows during simulated abnormal monitoring scenarios. The SmartVest prototype successfully generated dashboard warning visualizations, alert-history records, GPS monitoring-information synchronization, and emergency-notification interfaces intended for authorized users and registered emergency contacts. Cloud-based synchronization through Firebase Realtime Database enabled continuous accessibility of monitoring information within the mobile monitoring environment during preliminary prototype evaluation procedures.

The findings of the study demonstrated the feasibility of integrating wearable monitoring technologies, environmental sensing, cloud-based communication services, and mobile dashboard synchronization within a unified occupational safety prototype platform intended for traffic enforcers and field personnel operating in hazardous roadside environments. The implemented monitoring workflow demonstrated the potential of IoT-based wearable monitoring systems to support monitoring accessibility, dashboard awareness, and emergency-notification synchronization during simulated abnormal monitoring conditions.

Although the study successfully demonstrated the feasibility of the proposed SmartVest prototype architecture, several limitations were identified during the development process. Preliminary evaluation procedures primarily utilized simulated monitoring scenarios and partial sensor integration due to hardware availability constraints. The conducted evaluation focused mainly on synchronization workflows, dashboard visualization, threshold-based monitoring-state behavior, and emergency-notification functionalities under controlled prototype testing conditions.

The study did not include long-term field deployment, reference-device comparison, sensor calibration validation, communication latency evaluation, battery endurance analysis, or real-user occupational testing procedures. Battery endurance evaluation and quantitative communication-performance measurements, including latency and packet-loss analysis, remained outside the scope of the preliminary prototype evaluation procedures.

Future researchers may further improve the proposed SmartVest prototype by implementing complete hardware integration, sensor calibration procedures, communication latency analysis, battery optimization, miniaturization of wearable components, long-term field deployment, and expanded emergency-notification functionalities. Additional studies may also explore advanced monitoring analytics, broader IoT communication architectures, and integration with larger occupational safety and emergency-monitoring infrastructures.

Overall, the study successfully demonstrated the feasibility of developing an IoT-based wearable monitoring prototype capable of supporting wearable monitoring workflows, cloud-based synchronization, threshold-based monitoring-state visualization, emergency-notification transmission, and mobile monitoring accessibility for occupational safety applications under simulated prototype evaluation conditions.

RECOMMENDATIONS

Based on the findings and limitations of the study, the researchers recommend further enhancement and evaluation of the proposed SmartVest prototype through complete hardware integration, sensor calibration procedures, and expanded field-based prototype testing. Future studies may improve the wearable monitoring prototype by integrating additional sensing technologies, improving monitoring stability, implementing reference-device comparison procedures, and conducting long-term operational evaluation within actual roadside and occupational monitoring environments.

Future researchers may also enhance the communication functionalities of the proposed system by integrating automated SMS notification services, expanded cloud-based communication workflows, communication latency evaluation procedures, and improved dashboard synchronization mechanisms. Additional improvements may include battery optimization, wearable component miniaturization, waterproof hardware protection, and extended prototype deployment testing under varying environmental monitoring conditions.

Furthermore, future implementations may explore advanced monitoring analytics, threshold-optimization techniques, anomaly-monitoring workflows, and interoperability with broader occupational safety and monitoring infrastructures. Additional studies involving real-user occupational testing, communication reliability analysis, and long-term synchronization evaluation may further improve the development of wearable occupational monitoring technologies.

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