FIREFIGHTER HEALTH MONITORING NETWORK

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Abstract

The Firefighter Health Monitoring Network addresses the challenges of real-time health monitoring for firefighters operating in hazardous environments. The system integrates wearable sensor units into firefighter gear to continuously monitor vital signs, including heart rate, motion, ambient temperature, and location tracking. Processed data and alerts are transmitted via a resilient mesh network to a central monitoring hub, providing incident commanders with immediate awareness of the health status of all firefighters on scene. The wearable units achieve 90% accuracy in data collection and can operate for at least 2 hours on a single charge in typical fire fighting conditions above 30°C when housed within firefighter suits. Alerts are generated within 10 seconds of detecting abnormal vital signs or lack of motion. The mesh network maintains connectivity with a minimum range of 250 meters in urban settings and 600 meters in open areas, with a maximum end-to-end transmission time of 15 seconds.

Contents

1. Introduction

1.1 Problem

Firefighters operate in extremely hazardous environments where their health and safety are constantly at risk. Current methods of monitoring firefighter health during active duty are limited, often relying on periodic check-ins or self-reporting. This can lead to delayed responses to health emergencies, such as heat exhaustion, overexertion, or cardiac events. Incident commanders lack real-time, comprehensive health data on their team, making it challenging to make informed decisions about resource allocation and firefighter safety.

Research supports the critical nature of this problem:

- Cardiovascular events: Studies have shown that firefighters are at a significantly higher risk of on-duty cardiovascular events compared to other professions. Kales et al. (2007) found that 45% of on-duty firefighter fatalities were due to sudden cardiac death, highlighting the need for continuous cardiac monitoring [4].
- Heat stress: A study by Horn et al. (2013) demonstrated that core body temperature can rise to dangerous levels during firefighting activities, with some firefighters reaching temperatures above 38.5°C (101.3°F), which is associated with heat exhaustion and cognitive impairment [2].
- Physical exertion: Rodríguez-Marroyo et al. (2012) reported that firefighters routinely work at 60-95% of their maximum heart rate during emergency operations, indicating high levels of physiological stress that require monitoring [6].
- Limitations of current monitoring: Coca et al. (2011) highlighted the inadequacy of periodic vital sign checks, noting that they fail to capture the dynamic nature of physiological responses during firefighting activities [1].
- Decision-making challenges: Smith et al. (2016) emphasized the importance of real-time physiological data for incident commanders to make informed decisions about crew rotation and resource allocation, which current systems do not adequately provide [7].

These research findings underscore the urgent need for a comprehensive, real-time health monitoring system for firefighters that can track vital signs such as heart rate and movement patterns through accelerometry. Such a system would enable early detection of potential health emergencies and support more informed decision-making by incident commanders, ultimately enhancing firefighter safety and operational effectiveness.

1.2 Solution

We propose the development of a "Firefighter Health Monitoring Network" - a system of wearable devices integrated into firefighters' gear that continuously monitors vital signs and environmental conditions. The system uses a mesh network of ESP32-based devices to transmit real-time health data to a central monitoring hub. This allows incident commanders to have immediate, comprehensive awareness of their team's health status, enabling quick decision-making and potentially life-saving interventions.

1.3 High-Level Requirements

1. The system shall continuously monitor and transmit the following data with 90% accuracy and operate on a single charge for at least 2 hours in typical fire fighting conditions above 30°C.
    a. Heart Rate Data
    b. GPS Location
    c. Motion Data
    d. Surrounding Temperature Data
2. The system shall generate buzzer alerts on the wearable unit and central monitor within 10 seconds of abnormal detections based on thresholds on data from sensors:
    a. Heart Rate Data
        i. Heart rates <40 bpm or >150 bpm sustained for >30 seconds.
    b. Motion Data
        i. No significant motion detected for >60 seconds
    c. Surrounding Temperature Data
        i. Temperature exceeds 40°C for more than 3 minutes
3. The mesh network shall maintain connectivity in challenging environments with a minimum range of 250 meters in urban settings and 600 meters in open areas, using LoRa technology. The system shall automatically route data through multiple hops (firefighter-to-firefighter) to reach the central unit when direct communication is not possible. End-to-end data transmission time from any firefighter to the central unit shall not exceed 15 seconds, even when relaying through multiple nodes.

1.4 Subsystem Overview

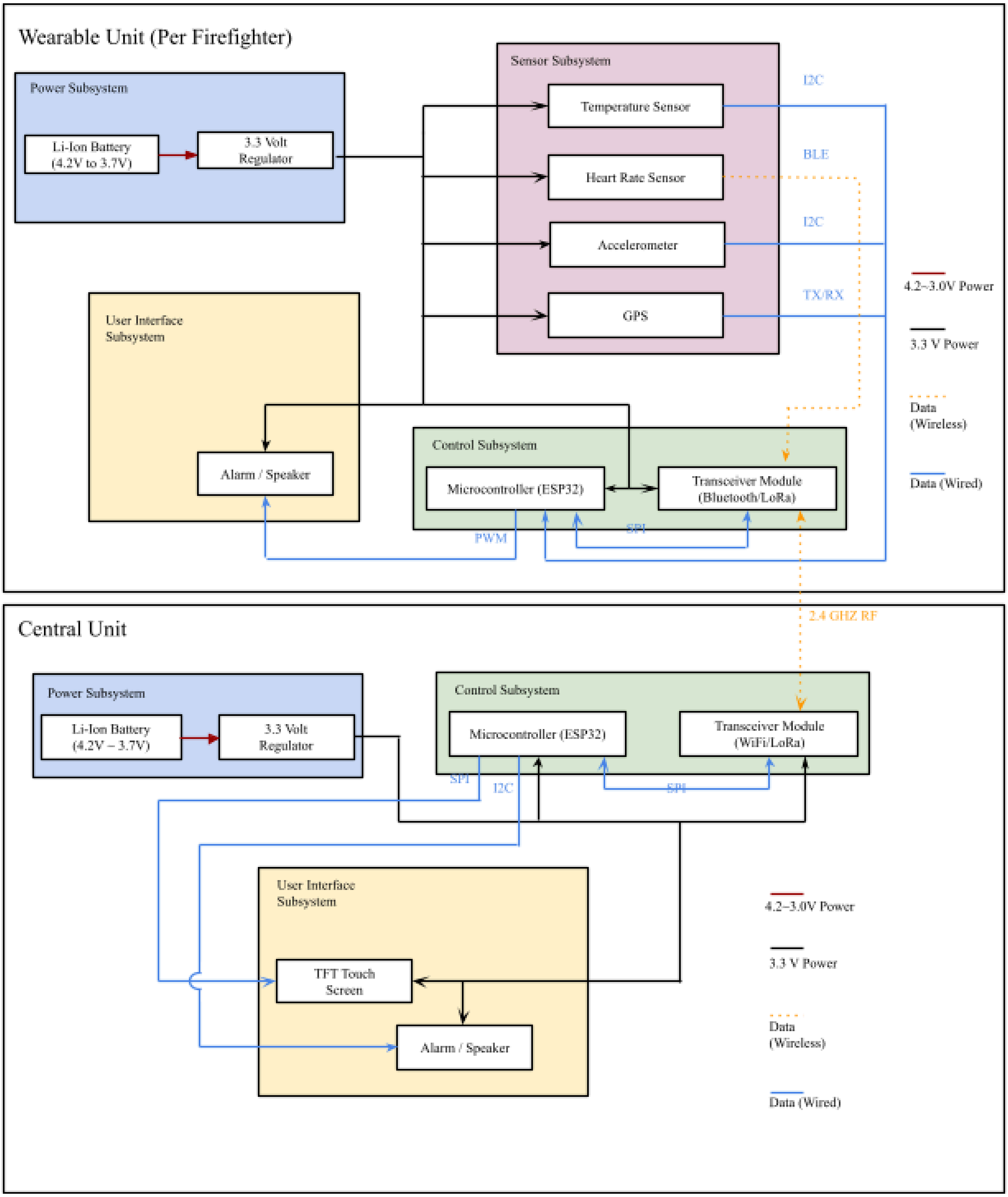

Figure 1. Block Diagram

These subsystems work in concert to provide a comprehensive, real-time health monitoring solution for firefighters. The wearable sensor units play a more significant role in data processing and alert generation. They continuously collect and analyze the sensor data, checking for anomalies and generating alerts when necessary. The processed data and alert status are then transmitted via the mesh network to the central monitoring hub, which serves as a centralized platform for displaying the information and enabling incident commanders to make informed decisions. The power management subsystem and mesh network subsystem support the continuous and reliable operation of the wearable units and the communication between them and the central hub.

2 Design

2.1 Equations and Simulations

The reliability of our Firefighter Health Monitoring Network depends critically on the performance of its LoRa communication system. To validate our design, we analyzed the LoRa link budget using the equation:

$$Link\ Budget\ =\ Transmitter\ Power\ +\ Transmitter\ Antenna\ Gain\ +\ Transmitter\ Antenna\ Gain\ -\ Path\ Loss\ +\ Receiver\ Antenna\ Gain\ -\ Receiver\ Sensitivity \tag{1}$$

Using typical LoRa system values (Transmitter Power: 14 dBm, Antenna Gains: 2 dBi each, Receiver Sensitivity: -137 dBm), we calculated the feasibility of our range requirements. For open areas with a 1 km range requirement, we calculated the Free Space Path Loss (FSPL) using the equation:

$$FSPL\ (dB)\ =\ 20\ *\ log10(d)\ +\ 20\ *\ log10(f)\ -\ 147.55 \tag{2}$$

where d is the distance in meters (1000) and f is the frequency (915 MHz for US LoRa). This calculation yielded an FSPL of 92 dB, resulting in a positive link budget of 63 dB, confirming the feasibility of our open-area range requirement.

For urban environments with a 300-meter requirement, we considered additional path loss factors. The basic path loss at this distance is 81 dB, and we accounted for an additional 25 dB loss due to urban obstacles. This resulted in a total path loss of 106 dB and a positive link budget of 49 dB, validating our urban range requirement.

We also analyzed the mesh network's latency requirements. With a payload size of 400 bytes (3200 bits) and a data rate of 5 kbps, we calculated a transmission time of 0.64 seconds per hop. Given our maximum allowable end-to-end delay of 15 seconds, the system can theoretically support up to 23 hops while maintaining required performance, which is more than adequate for typical firefighting team sizes.

For battery lifetime calculation, we analyzed the power consumption of all components using a 2000mAh lithium-ion battery. The calculation uses the following equation:

$$Battery\ Runtime\ (hours)\ =\ (Battery\ Capacity\ *\ Efficiency)\ /\ Total\ Current\ Draw \tag{3}$$

Where: Battery Capacity = 2000mAh Efficiency = 60% (accounting for temperature and conversion losses)

Total Current Draw = sum of all component currents:

- ESP32 microcontroller: 200mA
- ECG/EKG sensor: 10mA
- Temperature sensor: 0.005mA

- GPS sensor: 25mA
- Accelerometer: 1.5mA
- LoRa module: 13.5mA
- Buzzer: 20mA

$$Total\ Current\ Draw = 200 + 10 + 0.005 + 25 + 1.5 + 13.5 + 20 = 271mA \quad (4)$$
$$Battery\ Runtime = (2000mAh * 0.60) / 271mA = 4.43\ hours \quad (5)$$

This calculation shows that our system can operate for approximately 4.4 hours on a single charge, which exceeds our requirement of 2 hours operation time. The efficiency factor of 60% accounts for real-world conditions including temperature effects on the battery and power conversion losses.

2.2 Design Alternatives, Description and Justification

The Firefighter Health Monitoring Network consists of several interconnected subsystems that work together to collect, transmit, process, and display critical health and environmental data. Each subsystem has been carefully designed and optimized through testing and iteration to ensure reliability in firefighting conditions.

2.2.1 Wearable Unit Subsystem

The wearable sensor subsystem integrates seamlessly into firefighters' gear, featuring carefully selected components for reliability in harsh conditions. Initially, we planned to use an ECG/EKG sensor for heart rate monitoring. However, testing revealed high sensitivity to muscle contractions, which would generate unreliable readings during intense physical activity. We switched to a commercial Bluetooth heart rate strap sensor (the specific model we used is Garmin HRM Dual), which maintains ±5 bpm accuracy even during active movement.

The unit also includes a temperature sensor operating from 0°C to 65°C with ±1.0°C accuracy, an accelerometer with ±2g resolution for motion detection, and a GPS module providing ±20m position accuracy. An ESP32 microcontroller with dual-core 240 MHz processor, 520 KB SRAM, and 4 MB flash memory processes the sensor data locally, enabling quick alert generation when measurements exceed predetermined thresholds.

2.2.2 Central Monitoring Hub Subsystem

The central hub serves as the command center, built around a robust ESP32-based processing unit that handles data aggregation and analysis. A 3.5" TFT touch screen provides real-time data visualization and alert management through a custom-designed interface. The hub processes incoming data streams from multiple wearable units simultaneously, displaying each firefighter's status and location on an intuitive dashboard.

The interface allows incident commanders to quickly assess the situation through color-coded status indicators and detailed data views. Alert conditions are prominently displayed with both visual and auditory notifications, ensuring immediate attention to potential health risks or emergency situations.

2.2.3 Power Management Subsystem

The power subsystem uses 2000mAh lithium-ion batteries, chosen for their high energy density and reliable performance. Our power management circuit optimizes battery life through efficient voltage regulation and smart power distribution. The system operates for 4.4 hours on a single charge (calculated with 60% efficiency factor), exceeding our 2-hour requirement.

Key power-saving features include:

- Dynamic sensor sampling rates based on activity levels
- Low-power modes during periods of inactivity
- Intelligent battery monitoring with low-battery alerts at 10% capacity

2.2.4 Mesh Network Subsystem

The mesh network employs LoRa (Long Range) technology for its superior range and building penetration capabilities. Operating at 915 MHz (North American band), the system maintains connectivity across 600 meters in open areas and 250 meters in urban environments, verified through link budget analysis showing positive margins of 63 dB and 49 dB respectively.

Node Architecture

Each wearable unit functions as both a data source and a relay node within the network, while the central unit functions as the terminal node. The system implements a hierarchical node structure:

1. Node ID 1: Reserved for the central monitoring hub, serving as the terminal node
2. Node IDs 2+: Assigned to individual wearable units

This architecture enables multi-hop message propagation while providing clear message termination criteria when data reaches the central hub.

Message Handling and Routing

Messages in the network contain several key components:

1. Sender ID (1 byte)
2. Hop Count (1 byte)
3. Message ID (4 bytes)
4. Alert Status Flags (4 bytes)
5. Sensor Data Payload (variable length)

To prevent message loops and duplicates, the system implements a robust message tracking mechanism:

```
#define MAX_TRACKED_MESSAGES 50
unsigned long trackedMsgIDs[MAX_TRACKED_MESSAGES];
int trackedIndex = 0;
```

Each node maintains a circular buffer of recently processed message IDs. When a message is received, the node:

1. Checks if the message ID exists in its tracking buffer
2. If new, processes the message and adds its ID to the buffer
3. If duplicate, discards the message to prevent network congestion

The message forwarding logic implements selective retransmission:

```
void sendForwardMessage(int originalSender, int numHop, unsigned long msgID, ...) {
   LoRa.beginPacket();
   LoRa.write(originalSender);    // Preserve original sender ID
   LoRa.write(numHop + 1);        // Increment hop count
   // ... write message data ...
   LoRa.endPacket();
}
```

Hop Management

Messages can traverse up to 23 hops while maintaining end-to-end latency under 15 seconds. This is achieved through:

1. Hop count tracking in each message
2. Minimal processing overhead per hop (~640ms per transmission)
3. Efficient message structure minimizing packet size

The hop limit calculation is based on:

1. Maximum allowed delay = 15000ms
2. Per-hop transmission time ≈ 640ms
3. Maximum hops = 15000/640 ≈ 23 hops

Signal Strength Considerations

To maintain reliable communication, each node monitors the Received Signal Strength Indicator (RSSI) of incoming messages:

```
Serial.print("RSSI ");
Serial.println(LoRa.packetRssi());
```

This information helps validate link quality and can be used to optimize routing paths in future iterations of the system.

2.2.5 Software and Data Processing Subsystem

The software architecture of the wearable unit emphasizes robust health monitoring and reliable alert generation through carefully structured data management and time-based verification systems. This section details the key components and design decisions that enable accurate health status monitoring and emergency detection. The software components are designed with modularity in mind, allowing for easy updates and the addition of new features as requirements evolve.

Alert Status Management

The system utilizes a comprehensive data structure to track various alert conditions and their temporal characteristics. This structure, implemented as the AlertStatus struct, maintains the current state of all monitored parameters and their associated timestamps:

```
struct AlertStatus {
```

```
    bool isHRAlert;           // Current heart rate alert status
    bool isTempAlert;         // Current temperature alert status
    bool isMotionAlert;       // Current motion alert status
    bool lowBattery;          // Current battery alert status

    unsigned long hrAlertStart;     // Timestamp when heart rate alert began
    unsigned long tempAlertStart;   // Timestamp when temperature alert began
    unsigned long motionAlertStart; // Timestamp when motion alert began

    float accX, accY, accZ;       // Last recorded acceleration values

    unsigned long lastUpdate;      // Last data transmission timestamp
    bool inEmergency;             // Overall emergency status
};
```

This structure provides a centralized mechanism for managing alert states while maintaining the temporal context necessary for accurate alert generation. The use of timestamps enables the system to track how long alert conditions have persisted, which is crucial for preventing false alarms.

Alert Generation System

The alert system implements a sophisticated time-based verification approach to ensure the reliability of generated alerts. This is achieved through a combination of threshold definitions and duration requirements:

```
// Health parameter thresholds
const int HR_MAX = 150;             // Maximum heart rate (bpm)
const int HR_MIN = 40;              // Minimum heart rate (bpm)
const float TEMP_MAX = 40.0;        // Maximum temperature (°C)
const float MOVEMENT_THRESHOLD = 0.5;  // Minimum movement detection (G)

// Required duration thresholds
const unsigned long HR_ALERT_TIME = 30000;     // Heart rate (30 seconds)
const unsigned long TEMP_ALERT_TIME = 180000;  // Temperature (3 minutes)
const unsigned long MOTION_ALERT_TIME = 60000; // Motion (1 minute)
```

The alert generation process follows a three-stage verification approach:

1. Initial Detection: When a parameter exceeds its threshold, the system records the timestamp.
2. 2. Duration Verification: The condition must persist for the specified duration before triggering an alert.
3. 3. Status Reset: When parameters return to normal ranges, the system clears both the alert status and associated timestamp.

For example, the heart rate alert verification is implemented as follows:

```
if (heartRate > HR_MAX || heartRate < HR_MIN) {
   if (alertStatus.hrAlertStart == 0) {
      alertStatus.hrAlertStart = currentTime;
   }
   else if (currentTime - alertStatus.hrAlertStart > HR_ALERT_TIME) {
      alertStatus.isHRAlert = true;
   }
}
else {
   alertStatus.isHRAlert = false;
   alertStatus.hrAlertStart = 0;
}
```

Adaptive Update Frequency

The system implements an adaptive update frequency mechanism that adjusts data transmission rates based on the firefighter's status:

```
const unsigned long NORMAL_UPDATE_FREQ = 1000;    // Normal mode: 1 second
const unsigned long EMERGENCY_UPDATE_FREQ = 500;  // Emergency mode: 0.5 seconds

unsigned long updateInterval = wearableAlert.inEmergency ?
   EMERGENCY_UPDATE_FREQ : NORMAL_UPDATE_FREQ;
```

This design ensures more frequent updates during emergency situations while conserving power during normal operation.

Emergency Status Consolidation

The system maintains a consolidated emergency status that combines all individual alert conditions:

```
wearableAlert.inEmergency = wearableAlert.isHRAlert ||
                            wearableAlert.isTempAlert ||
                            wearableAlert.isMotionAlert ||
                            wearableAlert.lowBattery;
```

This consolidated status serves multiple purposes:

1. Triggers the increased update frequency
2. Activates emergency notification systems
3. Enables rapid response to any type of emergency condition

Alert Verification Logic

The alert verification system employs a methodical approach to monitoring various health parameters:

1. Heart Rate Monitoring:
    a. Tracks both high (>150 bpm) and low (<40 bpm) thresholds
    b. Requires 30 seconds of sustained abnormal readings
2. Temperature Monitoring
    a. Monitors for elevated temperatures above 40°C

   b. Requires 3 minutes of sustained elevated readings
3. Motion Detection:
   a. Monitors for lack of movement using accelerometer data
   b. Triggers alert after 1 minute of no significant motion
4. Battery Status:
   a. Monitors battery voltage level
   b. Generates immediate alert when battery level falls below 10%

This comprehensive approach to alert verification ensures reliable emergency detection while minimizing false alarms through appropriate time-based validation of alert conditions.

2.2.6 PCB Design and Iterations

Through the development process, we created four versions of PCBs for both the wearable unit and central unit. Each iteration addressed specific challenges and improvements identified during testing.
One significant challenge we encountered involved the voltage regulator selection. Initially, we used the AZ1117CD-3.3TRG1 3.3V regulator, which has a dropout voltage of 1.2V. This high dropout voltage created critical issues when paired with our lithium-ion battery that operates between 3.7V to 4.2V. Given the battery's voltage range and the regulator's dropout voltage of 1.2V, the maximum output voltage possible would be between 2.5V to 3.0V (battery voltage minus dropout voltage), which is significantly below the required 3.3V for proper operation.
This voltage insufficiency manifested in two major problems:
For the wearable unit, the voltage drop prevented the GPS module from establishing proper satellite connections. The GPS module requires a stable 3.3V supply for optimal performance, but with the battery and high-dropout regulator combination, the actual voltage was consistently below the module's minimum operating voltage, compromising its ability to maintain reliable satellite links.
For the central unit, the same voltage issue manifested in the TFT screen's functionality. The screen failed to operate properly due to insufficient voltage caused by the regulator's high dropout rate. This was particularly problematic as the display is crucial for the central monitoring system's operation.
To resolve the voltage regulator issues, we identified a pin-compatible Low-Dropout (LDO) 3.3V regulator with similar physical dimensions but significantly lower dropout voltage. This drop-in replacement allowed us to maintain the existing PCB design while ensuring proper 3.3V output even when the battery voltage drops to 3.7V.
Another significant issue we discovered during testing was related to the ESP32's GPIO strapping pins. Our initial design included a capacitor connected to a GPIO pin that's used during the boot process. This capacitor was preventing the ESP32 from booting properly on power-up, requiring a manual reset button press each time to start the system. We resolved this by removing the capacitor from the GPIO strapping pin in subsequent PCB versions, allowing the system to boot correctly immediately upon receiving power.
A key improvement in later PCB iterations was the addition of dual power source capability. We implemented a design that supports both 5V and 3.3V power sources simultaneously by adding diodes for power source isolation. This enhancement provides several benefits:

- Allows flexible power source selection without PCB modifications
- Enables seamless switching between power sources if one fails

- Reduces the risk of reverse current flow between power sources
- Maintains stable voltage supply even if one source fluctuates

These iterative improvements resulted in final PCB designs that provide reliable operation while maintaining the compact form factor required for integration into firefighter gear.

2.3 Subsystem Diagrams & Schematics

Reference Appendix B for individual subsystem schematics as well as full PCB schematic

2.3.1 Wearable Unit Subsystem

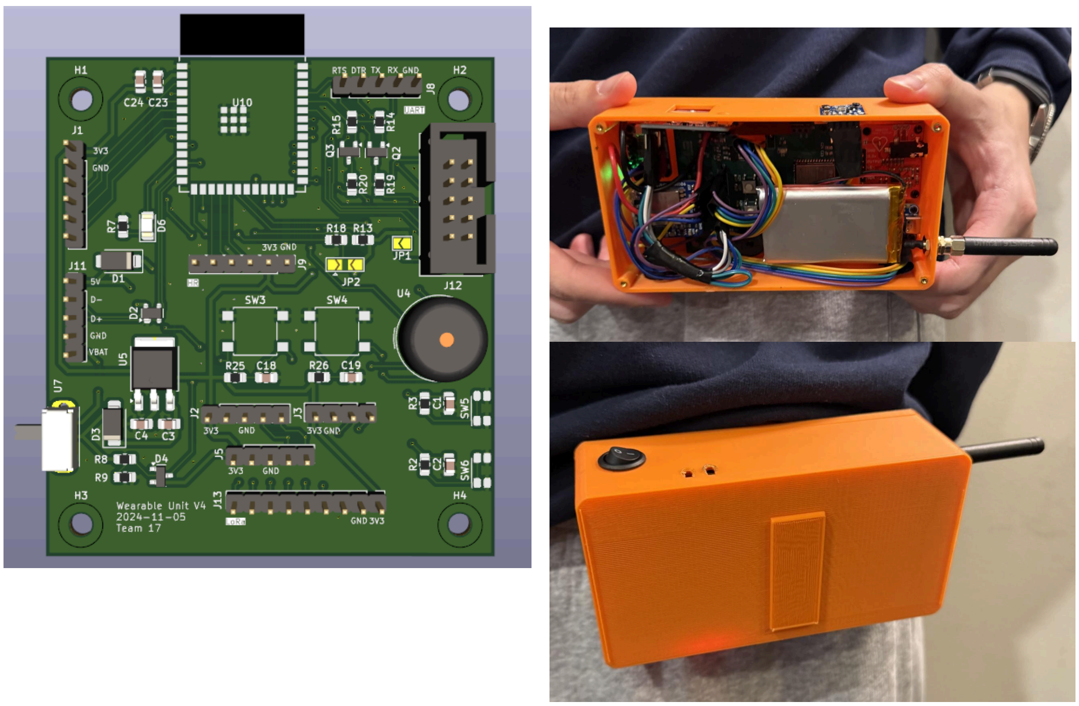

Figure 2. Wearable Unit PCB design and final product

2.3.2 Central Unit Subsystem

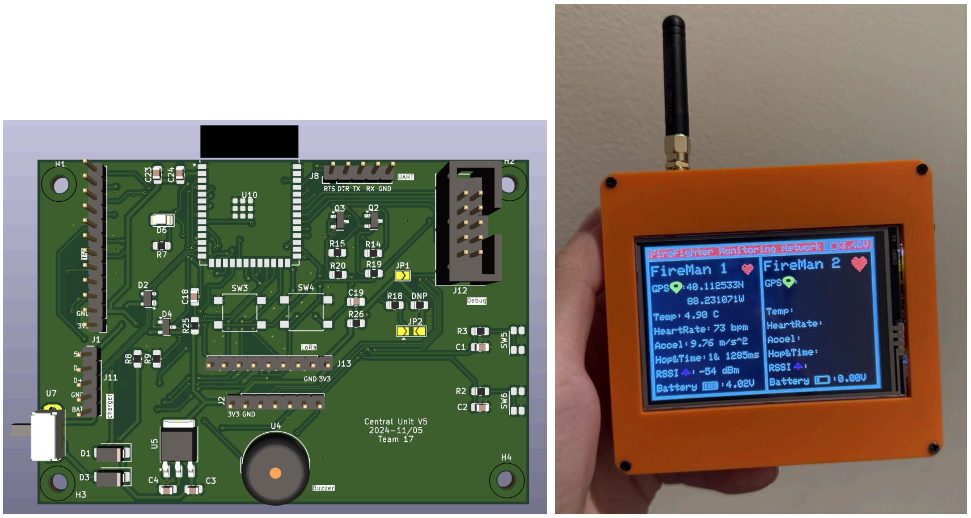

Figure 3. Central Unit PCB design and final product

2.3.2 Power Subsystem

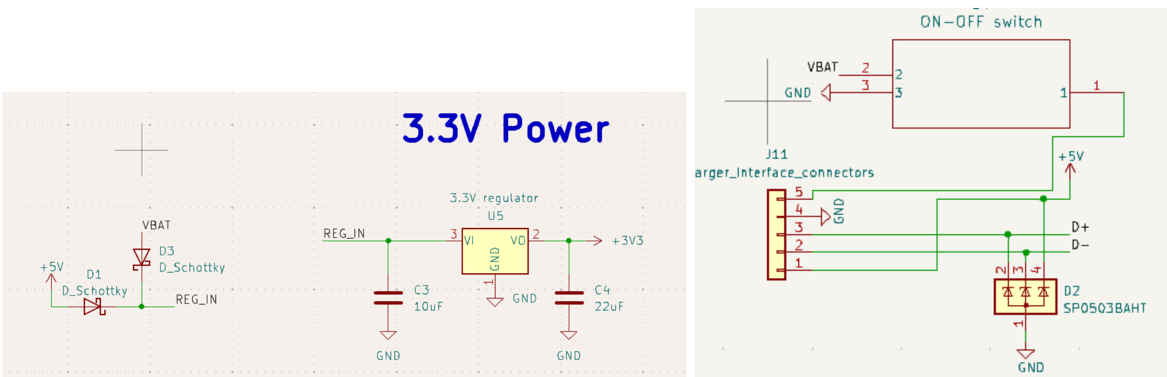

Figure 4. Power Subsystem Schematic

3. Costs

3.1 Parts

To test the functionalities of this project, we assembled one fully-functional wearable unit (with sensors) and one central unit, accompanied by two additional “LoRa unit” consisting of a LoRa transceiver, ESP32 microcontroller, and li-ion battery to test the mesh network.

Description	Manufacturer	Part Number	Quantity	Unit Price	Extended Price	Part Link
GPS	SparkFun	MAX-M10S	1	$44.95	$44.95	Link
LoRa Transceiver	Adafruit	RFM95W	3	$19.95	$59.85	Link
3.5" TFT LCD Display	Adafruit	HX8357D	1	$39.95	$39.95	Link

Single Lead Heart Rate Sensor	Sparkfun	SEN-12650	1	$21.50	$21.50	Link
Temperature Sensor	Adafruit	BMP 180	1	$9.95	$9.95	Link
Accelerometer and Gyroscope	Adafruit	LSM6DS032	1	$12.50	$12.50	Link
Piezo Buzzer	PDK Corporation	PS1240	2	$1.50	$3.00	Link
Lithium Ion Battery	Adafruit	3.7V 2000mAh	3	$12.50	$37.50	Link
Micro-Lipo Charger	Adafruit	Micro-Lipo Charger	3	$4.90	$14.70	Link
ESP32-WROOM	Espressif Systems	DOIT ESP32 DEVKIT V1	3	$15.98	$47.94	Link
Total Purchased Components Price: $291.84						

3.2 Labor

As our team is only composed of Computer Engineering students, we only used the annual salary for Computer Engineering students as a reference. According to the Grainger College of Engineering, the average annual starting salary for Computer Engineering students is $109,176, and number of work days in a year is approximately 365*(5/7) ≈ 261 days. Assume a person works 8 hours a day and 261 days per year, then his or her wage per hour is roughly $109,176 / (261*8hr) ≈ $52/hr. As a result, the labor cost of each student will be $52/hr. Over the course of 2 months, we plan to spend an average of 2 hours per day. Thus, the total labor cost will be $52/hr * 2 hr/day * 60 days * 3 students = $18720. Since there is no cost for other resources, we can estimate the total cost of the entire project to be the sum of purchased part and labor:

$$Cost\ Total\ =\ Cost\ Parts\ +\ Cost\ Labor\ =\ \$291.84\ +\ \$18,720\ =\ \$19,011.84$$

In total, the entire project will cost around $19,011.84

4. Design Verification

Refer to Appendix A for all Tables mentioned below.

4.1 Wearable Sensor Subsystem Requirements and Verification

To determine whether the wearable sensor subsystem can measure each status within the tolerance (Table 4.1, row 1), we conducted four tests to verify the accuracy of each sensor data, including heart rate, temperature, motion, and gps location.

First of all, to verify that the heart rate measurement is within the ±0.5 bpm tolerance, we place the wearable device on a person equipped with an Apple Watch to verify the heart rate. The result is shown in Table 4.6, in which the sensor heartbeat measurements fall within the tolerance.

Furthermore, to verify that the temperature measurement is within the ±5°C tolerance, we place a thermometer in a closed box and see if the values are the same for the device and the thermometer. The result is shown in Figure 4.1, in which the difference falls within the tolerance.

Moreover, to verify that the motion measurement is within the $\pm 2 m/s^2$ tolerance, we place the device on a steady surface and see if the acceleration read is equal to gravity ($9.8 m/s^2$). The result shows that at steady motion, the reading of the motion sensor is about $10.01 m/s^2$ and falls within the tolerance.

Last but not least, to verify that the gps location measurement is within the ±20m tolerance, we measure the current coordinate with the phone and validate the values from the gps sensor in the wearable unit. The result is shown in Figure 4.3 and Table 4.7, in which the gps sensor measurement falls within the tolerance.

To determine whether the alert is generated if a firefighter's heart rate exceeds 150 bpm or falls below 40 bpm for more than 30 seconds (Table 4.1, row 2), we conduct a test to verify. First, we simulate the heart rate of the wearable unit to monitor heart rates while gradually increasing to 160 bpm and decreasing to 35 bpm. Second, we validate that the wearable unit triggers an alert when heart rate exceeds 150 bpm for more than 30 seconds and when it falls below 40 bpm for the same duration. Third, we record response times and ensure alerts are activated correctly. The result of the test shows that the alert is successfully generated when the heart rate is abnormal for 30 seconds, which verifies our requirement.

To determine whether the alert is generated when the temperature exceeds 40°C for more than 3 minutes (Table 4.1, row 3), we conduct a test to verify. First, we place the device near a stove (or controlled heat source) to gradually increase the temperature around the wearable unit. Second, we monitor the wearable unit's temperature sensor and record readings. Third, we validate that the wearable unit triggers an alert when the temperature exceeds 40°C for more than 3 continuous minutes. The result of the test shows that the alert is successfully generated when the temperature exceeds 40°C for more than 3 minutes.

To determine whether the alert is generated if no significant movement is detected on the firefighter for over 60 seconds (Table 4.1, row 4), we conduct a test to verify. First, we secure the wearable unit to a stationary object or user. Second, we ensure that no movement is detected (within a calibrated margin) for a continuous period of 60 seconds, and verify that an alert is triggered at that moment. Third, we test with varying degrees of movement to ensure the threshold for "significant movement" is correctly calibrated. The result of the test shows that the alert is successfully generated when no significant movement is detected on the firefighter for over 60 seconds.

4.2 Central Monitoring Hub Subsystem Requirements and Verification

To determine whether the central unit display should be able to visualize the firefighter data holistically (Table 4.2, row 1), we have two wearable devices sending out simulated information to the central unit to verify it is able to display the firefighters' data holistically. After the test, the central unit can display all the data on the screen, which verifies our requirements.

To determine whether the central unit sends out a critical alert and change of LED color when abnormal activities occur (Table 4.2, row 2), we manually input data with different conditions (normal, abnormal, dangerous) to the subsystem and observe whether the alert is turned on or off. After the test, the central unit can change the text color of those abnormal data from white to red and activate its buzzer, which verifies our requirements.

4.3 Power Subsystem Requirements and Verification

To determine whether wearable and central units can send alerts when the battery is low (below 10%) to the central unit (Table 4.3, row 1), we charge the device to 15% and operate the device until the battery drops down to 10%, which is measured with a multimeter, to verify if the alert is sent. The result shows that the buzzer is activated and an alert is sent to the central unit when the devices have low battery, which verifies our requirement.

To determine whether both the wearable unit and the central unit can last at least 2 hours on a single charge under typical operation conditions (temperatures above 30°C) (Table 4.3, row 2), we use the serial monitor to print out the voltage read from our battery voltage reader to verify both the wearable unit and central unit has battery life longer than 2 hours. The result is shown in Figure 4.2, where both devices have more than 50% voltage after 2.5 hours of operation.

4.4 User Interface Subsystem Requirements and Verification

To determine whether there's a custom-designed graphical user interface (GUI) for the 3.5" TFT touch screen (Table 4.4, row 1), we visually inspect the GUI layout on the actual 3.5" screen and verify if all the data received are the same from the wearable units by printing out those data in Serial monitor. The result shows that the GUI can display all the data with a customized design.

To determine whether there are real-time data visualization components (graphs, charts, status indicators) (Table 4.4, row 2), we simulate data input for graphs, charts, and status indicators and verify real-time updates of visualizations. Then, we test different data scenarios (normal, critical, edge cases) and measure and verify update frequency matches the requirements. The results show that the real-time data are received and displayed on the user interface.

To determine whether there is an alert management system with visual and auditory cues (Table 4.4, row 3), we trigger various alert conditions and verify visual cues appear correctly on screen. Then, we test auditory alerts for proper sound and volume and confirm alert prioritization works as designed. The results show that the alert is triggered when abnormal activities occur and the text color is changed to red for abnormal status.

4.5 Mesh Network Integration Subsystem Requirements and Verification

To determine whether data transmission time from any firefighter to the central unit exceeds 15 seconds and the communication range is at least 600m in open areas and 250m in urban environments (Table 4.5, row 1), we first calculate the differences between the wearable unit packet sent time using GPS time vs the central unit received time to verify the communication time is within 15 seconds. The result shows an average of around 2 seconds of transmission time between 3 nodes. Next, we conduct two tests, one in an open area and one in an area with buildings, and measure the distance between nodes to meet the requirement. Then, we test if each node can receive data from each other. The result shows that we meet the requirement in which the nodes are capable of receiving data from the required range.

To determine whether a mesh network is created so that even if a wearable is not directly in range to the central unit it can hop between the other wearable that's in range to connect to the central unit (Table 4.5, row 2), we set up a test environment with multiple wearable units and obstacles to force multi-hop routing and gradually move units out of direct range of the central hub. Then, we verify data from out-of-range units successfully reaches the central hub via other units and use network visualization tools to confirm the mesh topology. Last, we simulate node failures to test self-healing capabilities and measure and compare latency for direct vs multi-hop communications. The result shows that the mesh network is successfully set up.

5. Conclusion

5.1 Accomplishments

The Firefighter Health Monitoring Network project has successfully achieved its primary objectives, resulting in a complete and functional product. The wearable units seamlessly integrate all four sensors - heart rate, accelerometer, temperature, and GPS - enabling comprehensive, real-time monitoring of firefighter health and location. The system effectively generates alerts based on predefined thresholds, both on the wearable units and the central monitoring hub, ensuring rapid response to potential health emergencies.

Notably, the system meets or exceeds all the high-level requirements outlined at the project's inception. The power supply for the wearable units sustains operation for more than 2 hours on a single charge, even in demanding firefighting conditions above 30°C. The LoRa-based mesh network enables reliable data transmission between wearable nodes and the central unit, automatically routing data through multiple hops when direct communication is hindered. Furthermore, the sensors achieve the required accuracy levels, providing trustworthy data for informed decision-making.

The central monitoring hub features a well-designed, user-friendly display that presents real-time health data and alerts for each firefighter. This intuitive interface empowers incident commanders to quickly assess the situation and make critical decisions to ensure the safety and well-being of their team.

5.2 Ethical considerations

Data Privacy and Security:

According to the ACM Code of Ethics, members should "respect the privacy of others" and "honor confidentiality" [8]. Monitoring firefighters' health data involves collecting sensitive personal information such as heart rate, surrounding temperature, and potentially location data. Any breach of this data could lead to privacy violations.
Solution: The team implemented strict access controls, ensuring that only authorized personnel (e.g., the incident commander) can view the data.

Informed Consent:

Firefighters must be fully informed about what data is being collected, how it will be used, and their rights to privacy under the IEEE Code of Ethics (Clause 1). This includes consent not only for data collection during their active duty but also how their data may be used in post-incident reviews.
Solution: The team ensured that firefighters provide informed consent before wearing the monitoring devices. Clear and accessible explanations were offered regarding what data will be collected, why, and how it will be protected.

5.3 Future work

To further enhance the Firefighter Health Monitoring Network, the team has identified several areas for future development:

1. Support more nodes (>10 nodes) to extend LoRa communication range (~1km)
2. Design a more compact enclosure to improve wearability
3. Develop a user interface on the wearable unit for more intuitive visuals
4. Implement more advanced algorithms for analyzing heart rate data to detect a broader range of symptoms

By addressing these future improvements, the Firefighter Health Monitoring Network can become an even more robust, user-friendly, and effective tool for ensuring the safety and well-being of firefighters in the line of duty.

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Appendix A Figures and Tables

Table 4.1 Wearable Sensor Subsystem Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. Sensors should measure each status within the tolerance a. Measures heart rate with an accuracy of ±5 bpm. b. Measures temperature with an accuracy of ±1.0°C. c. Detects motion with a resolution of ±2m/s2. d. Detects location with a tolerance of ±20m.	1. Place the device on a person equipped with Apple Watch and validate the heartbeat 2. Place a thermometer in a closed box and see if the values are the same for the device and the thermometer 3. Place the device on a steady surface and see if the acceleration read is equal to gravity (9.8m/s2) 4. Measure the current coordinate with phone and validate the values from the gps sensor in the wearable unit	Y
2. Alert is generated if a firefighter's heart rate exceeds 150 bpm or falls below 40 bpm for more than 30 seconds.	3. Simulate the heart rate of the wearable unit to monitor heart rates while gradually increasing to 160 bpm and decreasing to 35 bpm. 4. Validate that the wearable unit triggers an alert when heart rate exceeds 150 bpm for more than 30 seconds and when it falls below 40 bpm for the same duration. 5. Record response times and ensure alerts are activated correctly.	Y
3. Alert is generated when the temperature exceeds 40°C for more than 3 minutes.	4. Place the device nearby a stove (or controlled heat source) to gradually increase the temperature around the wearable unit. 5. Monitor the wearable unit's temperature sensor and record readings. 6. Validate that the wearable unit triggers an alert when the	Y

	temperature exceeds 40°C for more than 3 continuous minutes.	
4. Alert is generated if no significant movement is detected on the firefighter for over 60 seconds.	1. Secure the wearable unit to a stationary object or user. 2. Ensure that no movement is detected (within a calibrated margin) for a continuous period of 60 seconds, and verify that an alert is triggered at that moment. 3. Test with varying degrees of movement to ensure the threshold for "significant movement" is correctly calibrated.	Y

Table 4.2 Central Monitoring Hub Subsystem Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. The central unit display should be able to visualize the firefighter data holistically	1. Have two wearable device sending out simulated information to the central unit to verify it is able to display the firefighters data holistically	Y
2. Send out a critical alert and change of LED color when abnormal activities occur	1. Manually input data with different conditions (normal, abnormal, dangerous) to the subsystem and observe whether the alert is turned on or off	Y

Table 4.3 Power Subsystem Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. Wearable units should send alerts when the	1. Charge the device to 15% and operate the device until the battery	Y

battery is low (below 10%) to the central unit.	drops down to 10% measuring with a multimeter to verify if the alert is sent.	
2. Both the wearable unit and the central unit should last at least 2 hours on a single charge under typical operation conditions (temperatures above 30°C).	1. Simulate the sensor readings using ADALM2000, record the battery voltage every 5 mins to verify both the wearable unit and central unit has battery life longer than 2 hours.	Y

Table 4.4 User Interface Subsystem Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. Custom-designed graphical user interface (GUI) for the 3.5" TFT touch screen	1. Visually inspect GUI layout on the actual 3.5" screen 2. Verify if all the data received are the same from the wearable units by printing out those data in Serial monitor	Y
2. Real-time data visualization components (graphs, charts, status indicators)	1. Simulate data input for graphs, charts, and status indicators 2. Verify real-time updates of visualizations 3. Test different data scenarios (normal, critical, edge cases) 4. Measure and verify update frequency matches requirements	Y

3. Alert management system with visual and auditory cues	5. Trigger various alert conditions 6. Verify visual cues appear correctly on screen 7. Test auditory alerts for proper sound and volume 8. Confirm alert prioritization works as designed 9. Test alert acknowledgment and dismissal functionality	Y

Table 4.5 Mesh Network Integration Subsystem Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. Data transmission time from any firefighter to the central unit shall not exceed 15 seconds	1. Calculate the differences between the wearable unit packet sent time using gps time vs the central unit received time to verify the communication time is within 15 seconds.	Y
2. Create its mesh network so even if a wearable is not directly in range to the central unit it can hop between the other wearable that's in range to connect to the central unit	1. Set up a test environment with multiple wearable units and obstacles to force multi-hop routing. 2. Gradually move units out of direct range of the central hub. 3. Verify data from out-of-range units successfully reaches the	Y

	central hub via other units. 4. Use network visualization tools to confirm the mesh topology. 5. Simulate node failures to test self-healing capabilities. 6. Measure and compare latency for direct vs multi-hop communications.	

Table 4.6 Heart Rate Error Table

Heart rate beats per min error

Trial	Wearable HR (bpm)	Apple Watch HR (bpm)	Error (bpm)
1	61	61	0
2	57	54	3
3	80	76	4
4	86	89	3
5	99	102	3
6	107	109	2
		Average Error	2.5

Table 4.7 GPS Error Table

GPS Coordinate Error

Trial	Wearable Lat	Wearable Lon	iPhone Lat	iPhone Lon	Error (meters)
1	40.114368	-88.228729	40.11445	-88.2287	9.4
2	40.113426	-88.22903	40.11357	-88.229	16.2
3	40.112354	-88.230552	40.11236	-88.2305	4.5
4	40.112369	-88.23104	40.11233	-88.23106	4.7
5	40.112258	-88.229965	40.11224	-88.22992	4.3
6	40.112239	-88.229118	40.11213	-88.22901	15.2
				Average Error	9.05

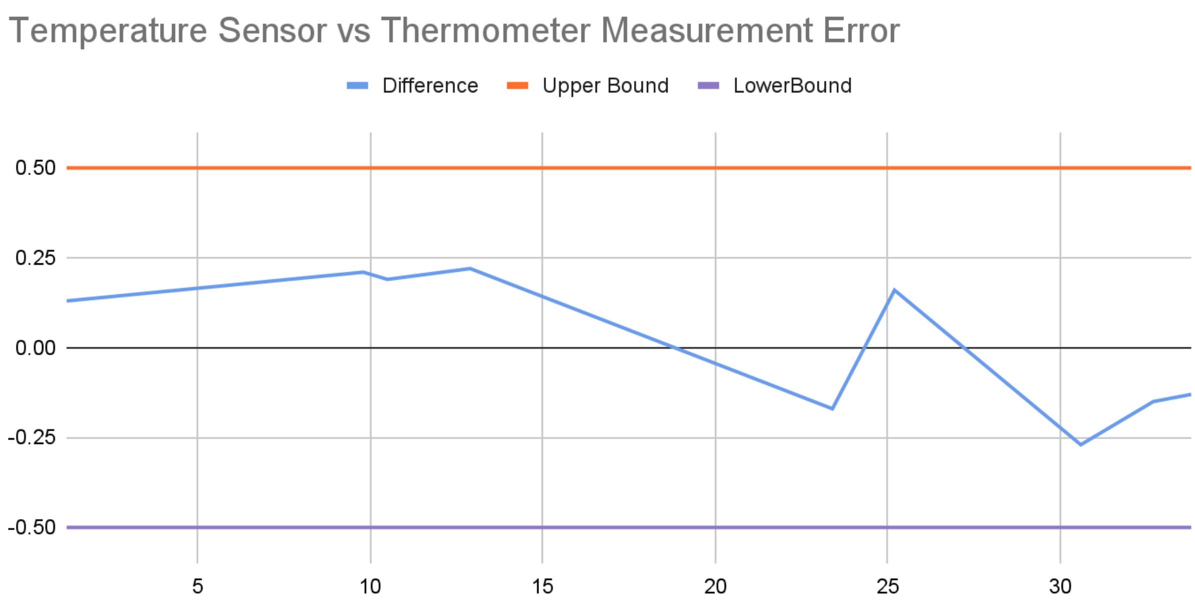

Figure 4.1 Temperature Error Table

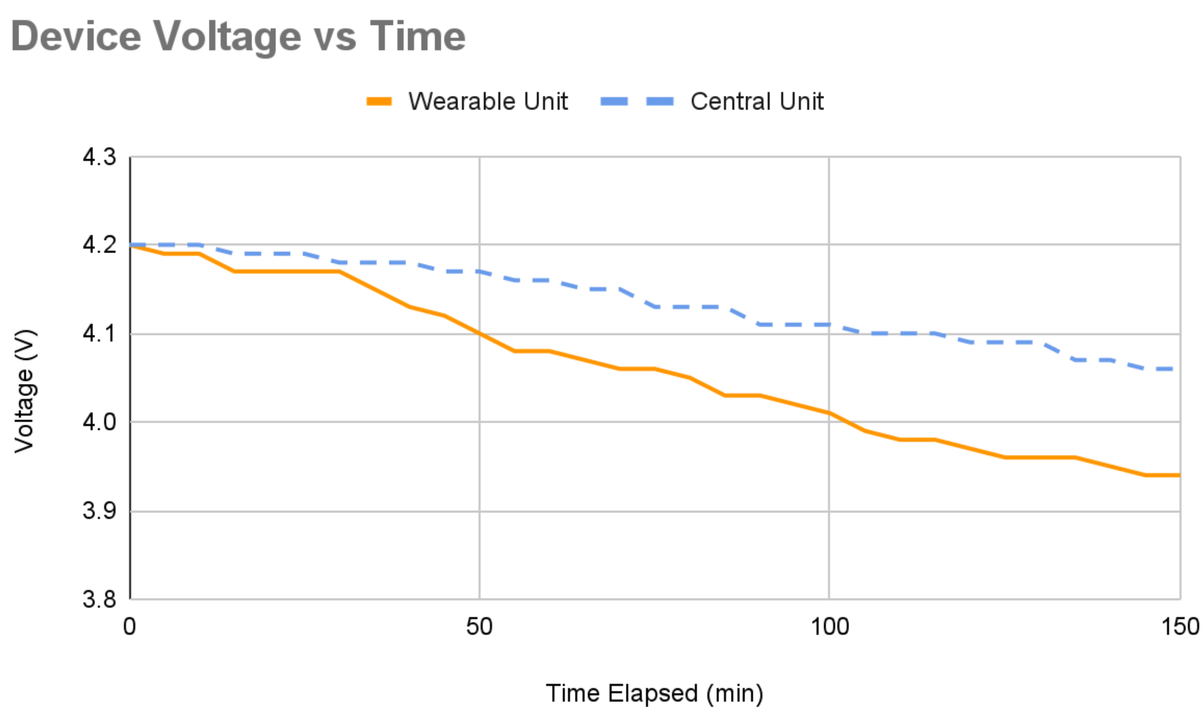

Figure 4.2 Battery Life Graph

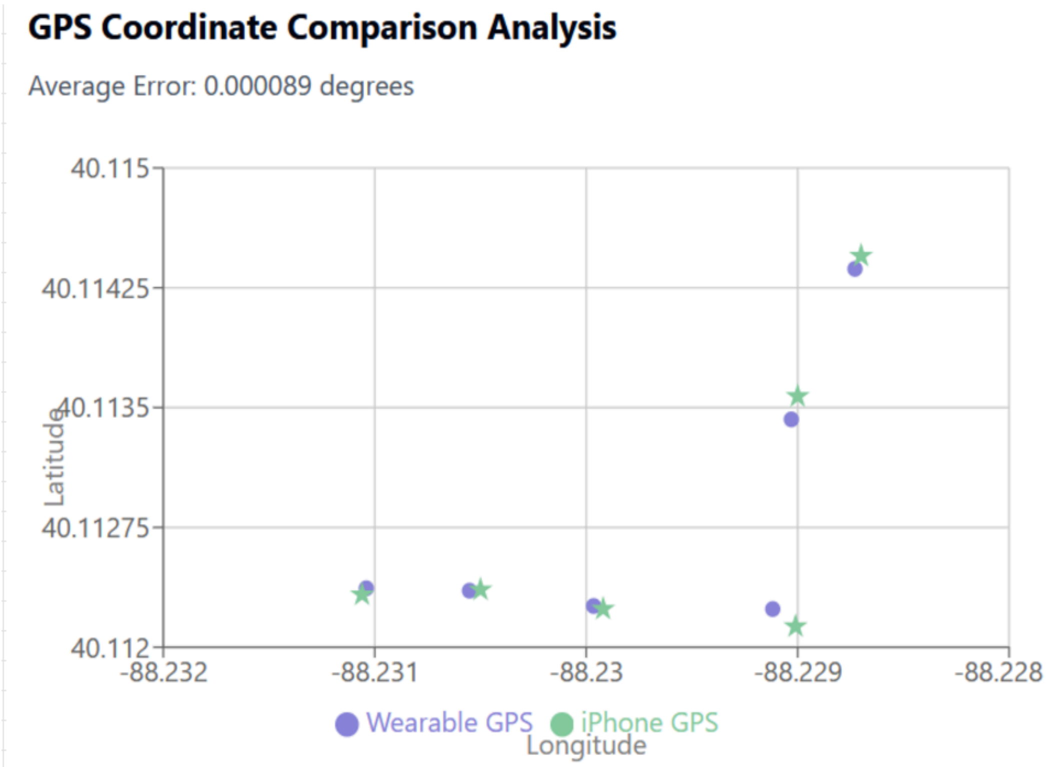

Figure 4.3 GPS Coordinate Comparison Graph

Appendix B Individual subsystem schematics and Full PCB schematic

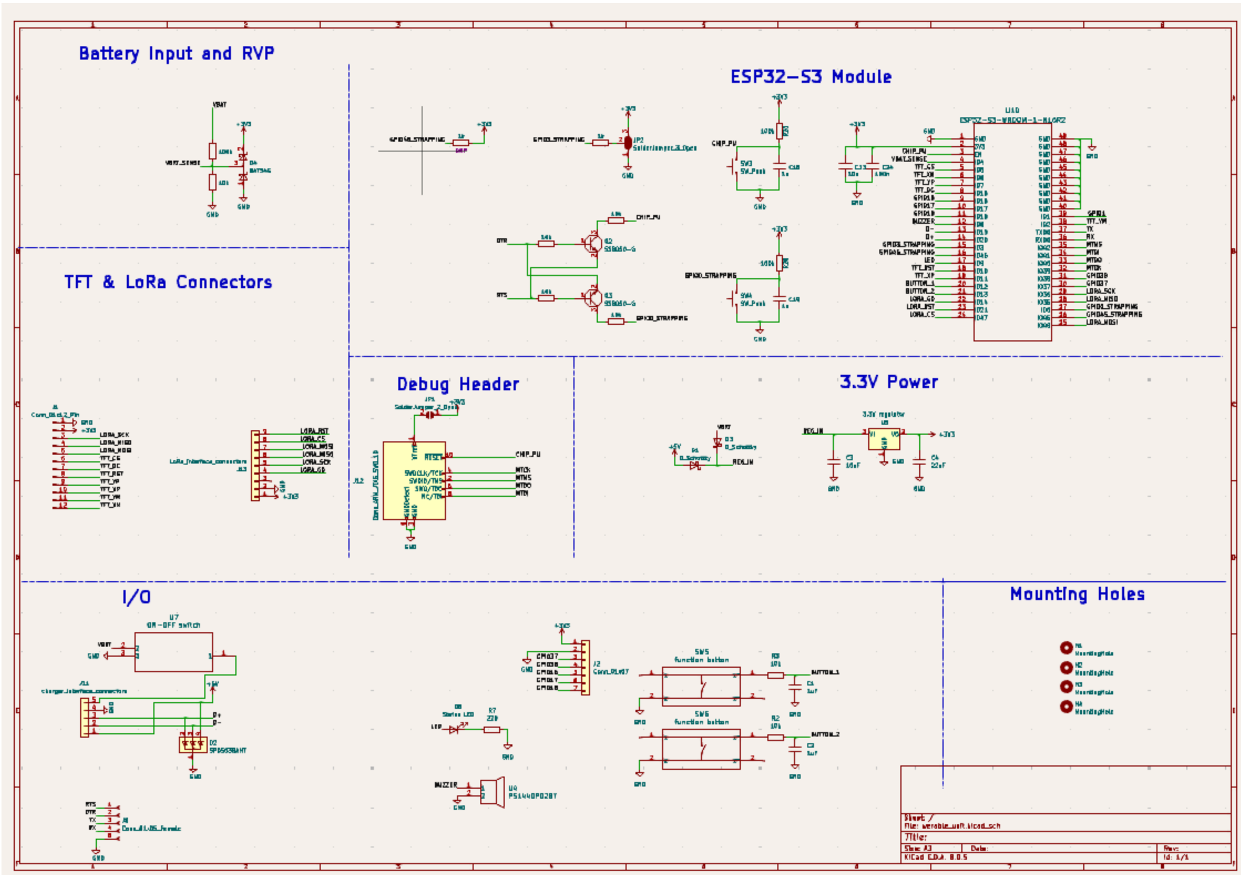

Figure 5. Wearable Unit Schematics

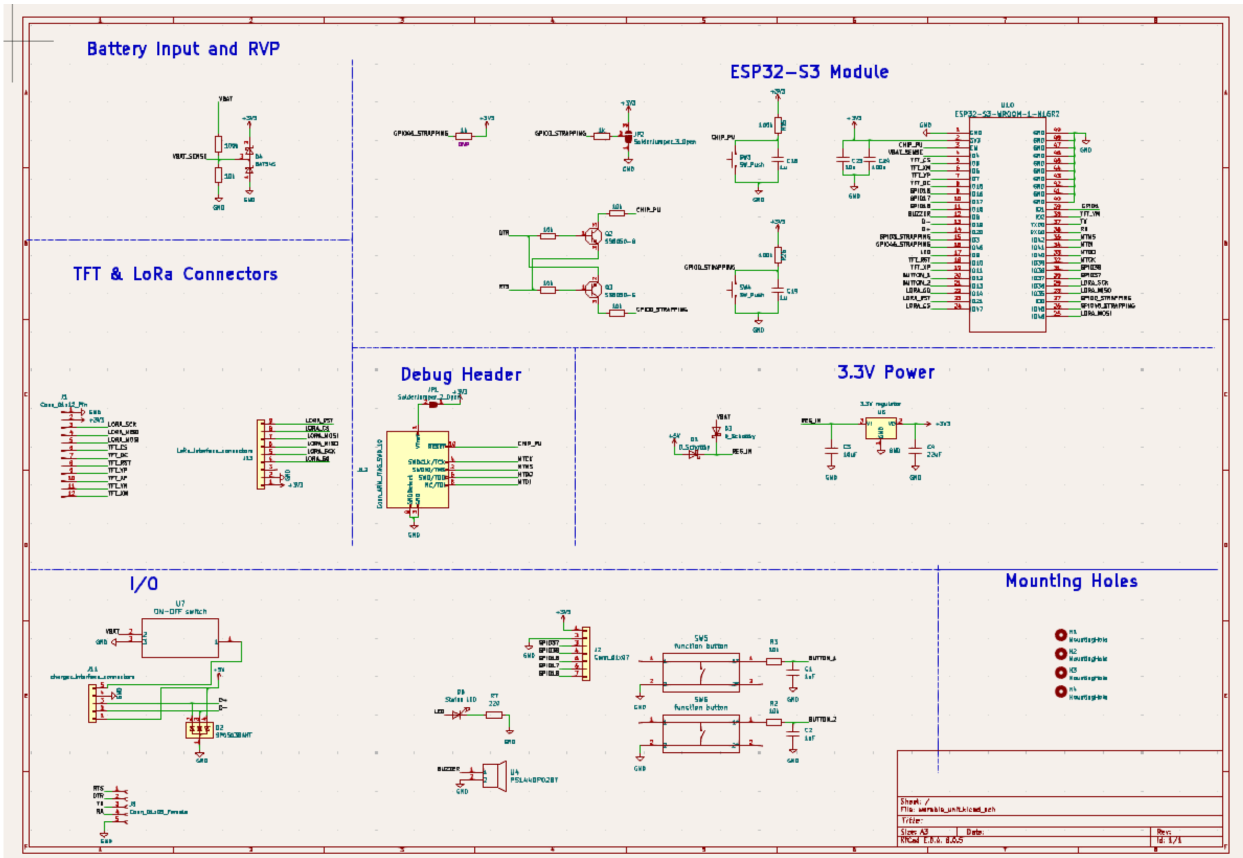

Figure 6. Central Unit Schematics