Firefighter Monitoring Network

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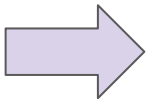
Contents

Problem & Solution

1. Problem Statement and Solution

Problems

- Work in hazardous environments
- Health and Safety are at risk
- Current monitoring methods are relying on periodic check-ins or self reporting
- Lead to delayed responses
- Challenging to make decisions
- Some symptoms are difficult to notice, such as Cardiovascular events, heat stress, and physical exertion

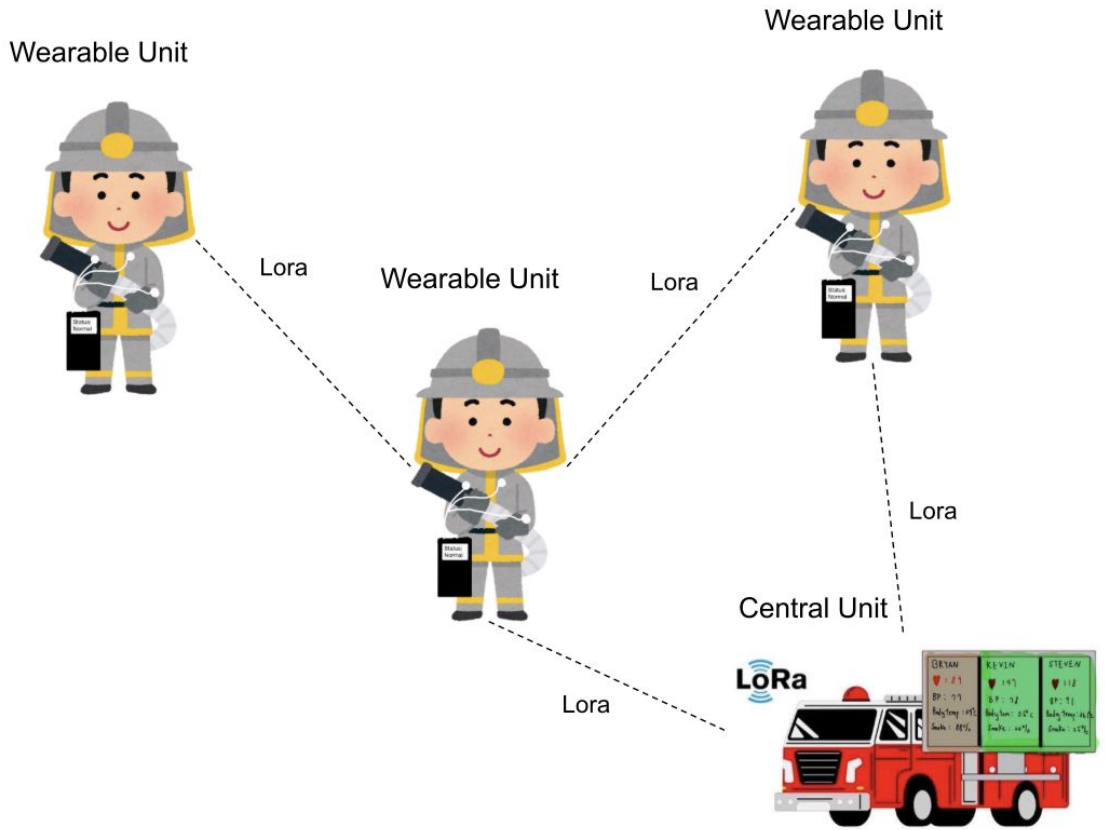


Solution

- Wearable unit that contains multiple sensors for tracking health status of individual firefighter
- Central Unit for receiving health status from all firefighters
- Mesh Network implemented with LoRa module to create a self-healing network in case if any wearable unit fails

Visual Aid

2. Visual Aid


Wearable Unit
Wearable Unit
Wearable Unit
Lora
Lora
Lora
Lora
Central Unit
LoRa

High-Level Requirements

3. High-Level Requirements

1. Data Transmission & Power

- ➔ Continuously monitor and transmit the following data with 90% accuracy
  - ◆ Heart Rate
  - ◆ GPS location
  - ◆ Motion
  - ◆ Surrounding Temperature
- ➔ Operate on a single charge for at least 2 hours in fire fighting conditions above 30°C

2. Abnormal Detections & Alert Generation

➔ Shall generate buzzer alerts on the wearable unit and central monitor within 10 seconds of abnormal detections based on thresholds on data from sensors:

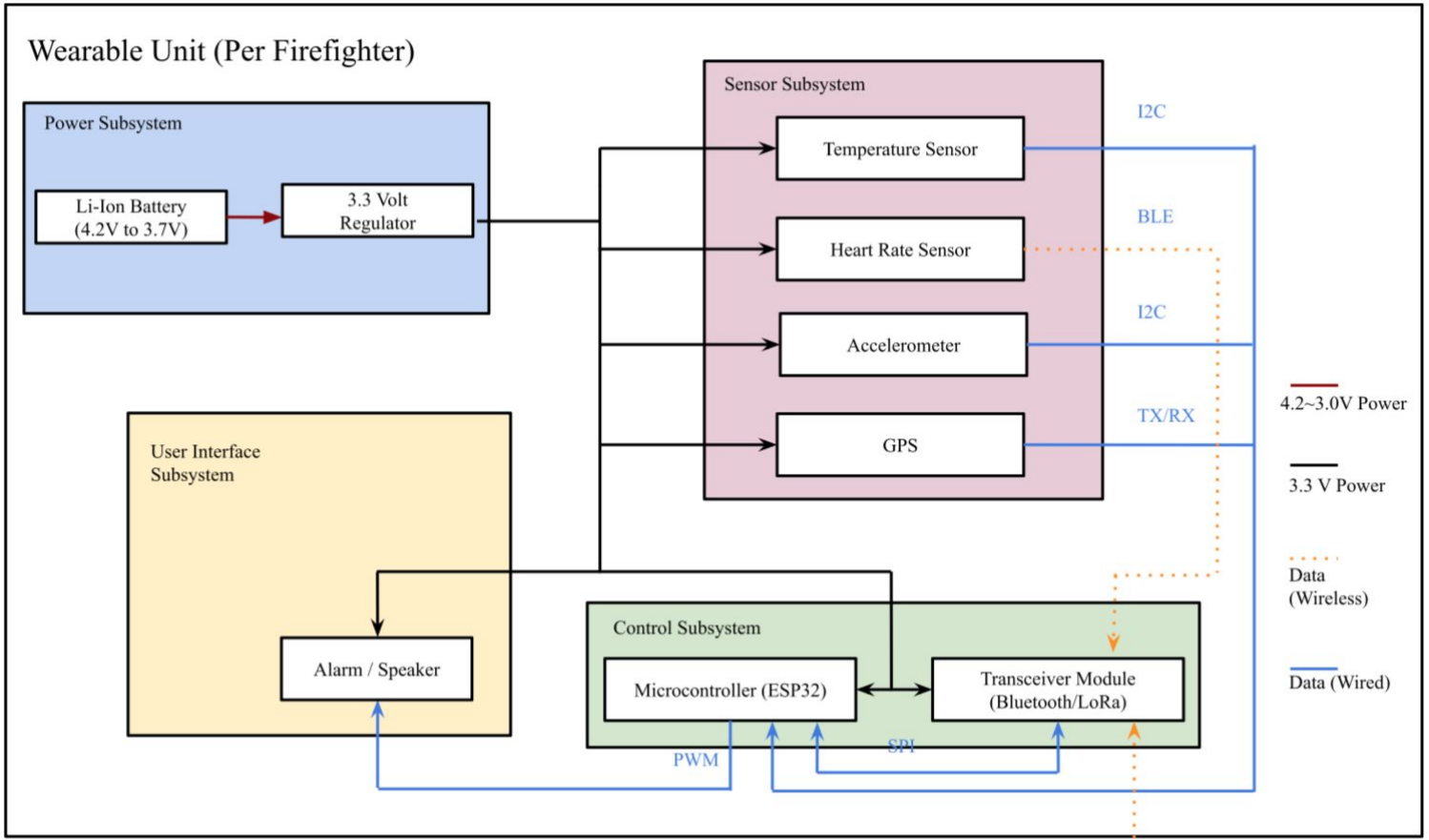
a. Heart Rate
    i. Heart rates <40 bpm or >150 bpm sustained for >30 seconds, or upon detection of specified arrhythmias.
b. Motion
    i. No significant motion detected for >60 seconds
c. Surrounding Temperature
    i. Temperature exceeds 40°C for more than 3 minutes

3. LoRa Mesh Network

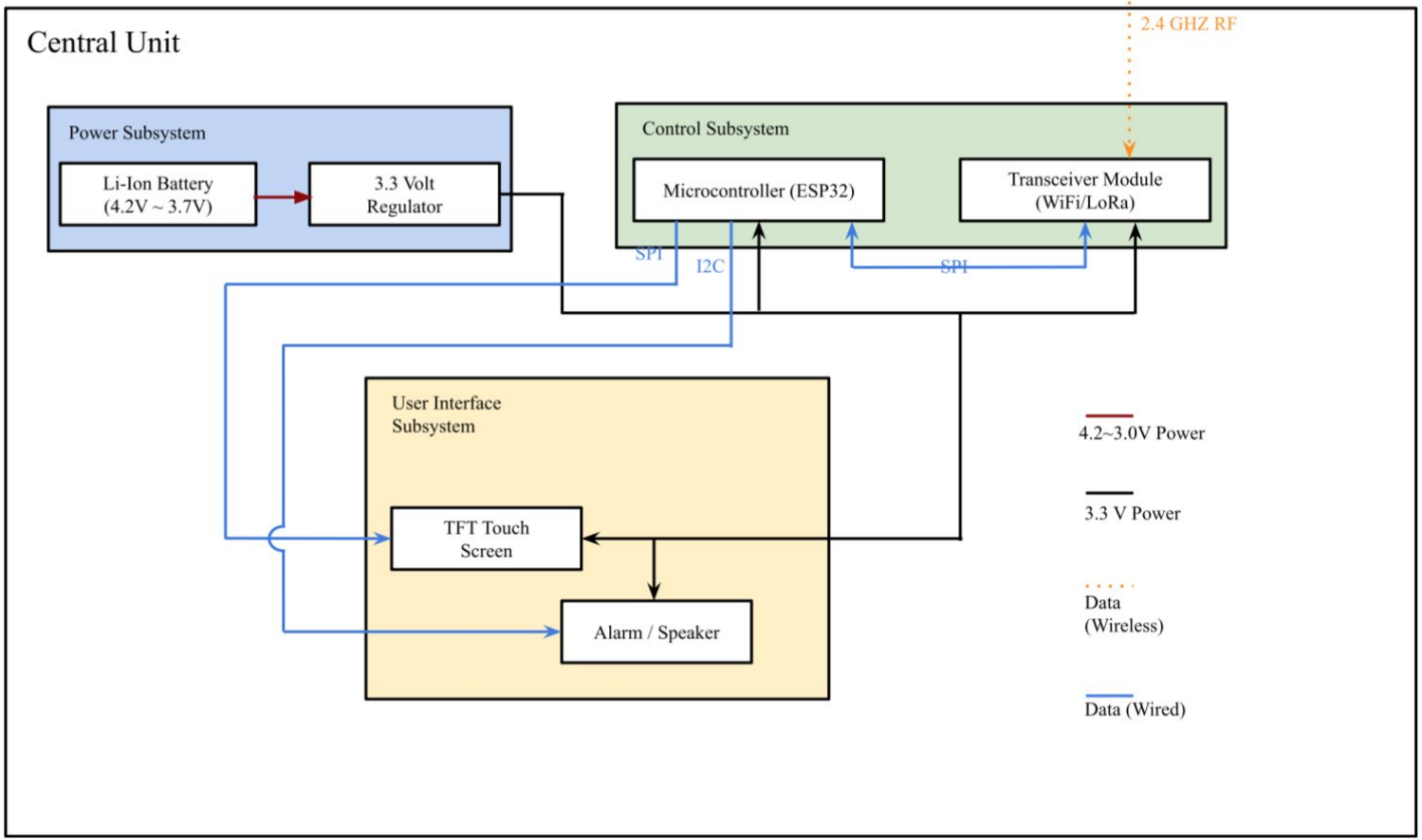
- ➔ Maintain connectivity with a minimum range of 250 meters in urban settings and 600 meters in open areas, using LoRa technology.
- ➔ Automatically route data through multiple hops (firefighter-to-firefighter) to reach the central unit when direct communication is not possible
- ➔ End-to-end data transmission time from any firefighter to the central unit shall not exceed 15 seconds, even when relaying through multiple nodes.

Block Diagram

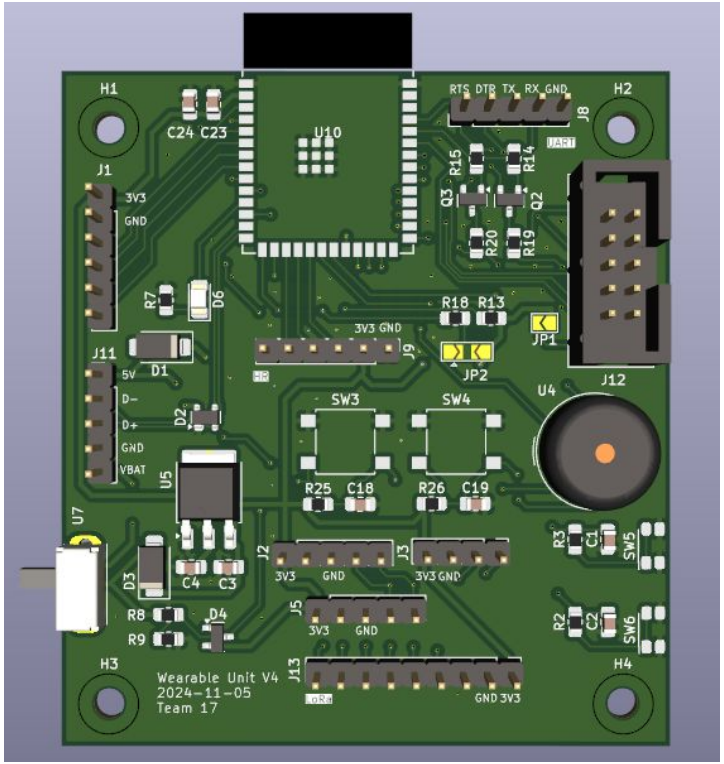
4. Block Diagram



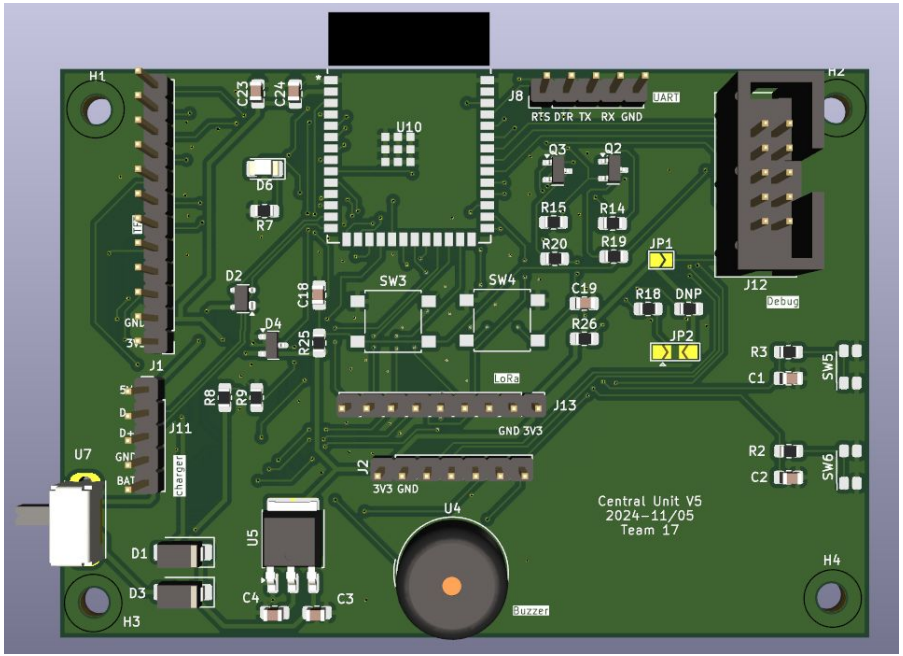
4. Block Diagram



4. Wearable Unit



4. Central Unit



Requirements & Verifications

5. Requirements and Verification

Wearable Sensor Subsystem

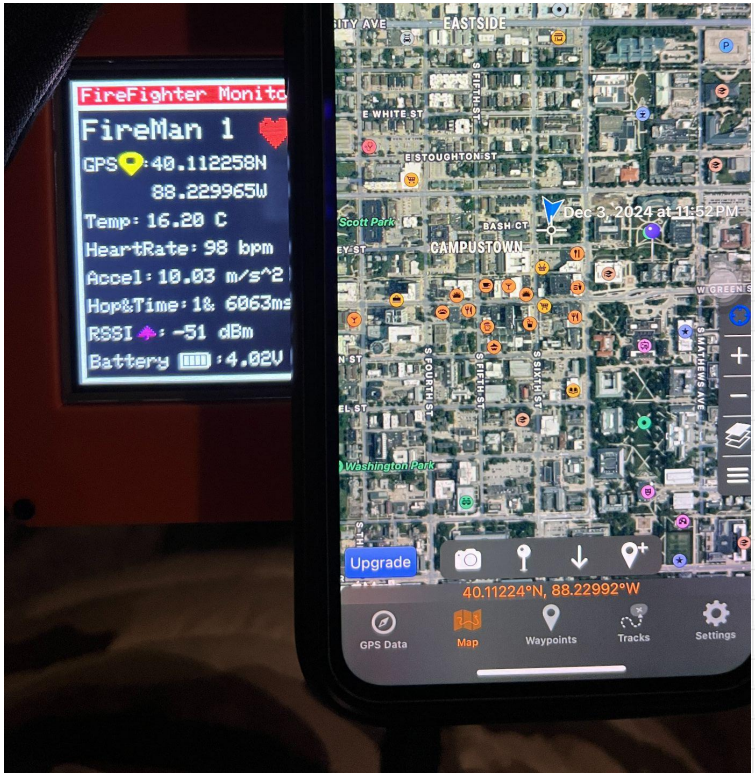
- ➔ Continuously collecting real-time health and environmental data from individual firefighters
- ➔ Track vital signs like heart rate, surrounding temperature, and motion
- ➔ Data is sent to the mesh network of the ESP32 and the central hub via reliable communication methods ESP-MESH and LoRa
- ➔ Enclosure will be printed out using a 3D printer with Polylactic acid material (PLA)

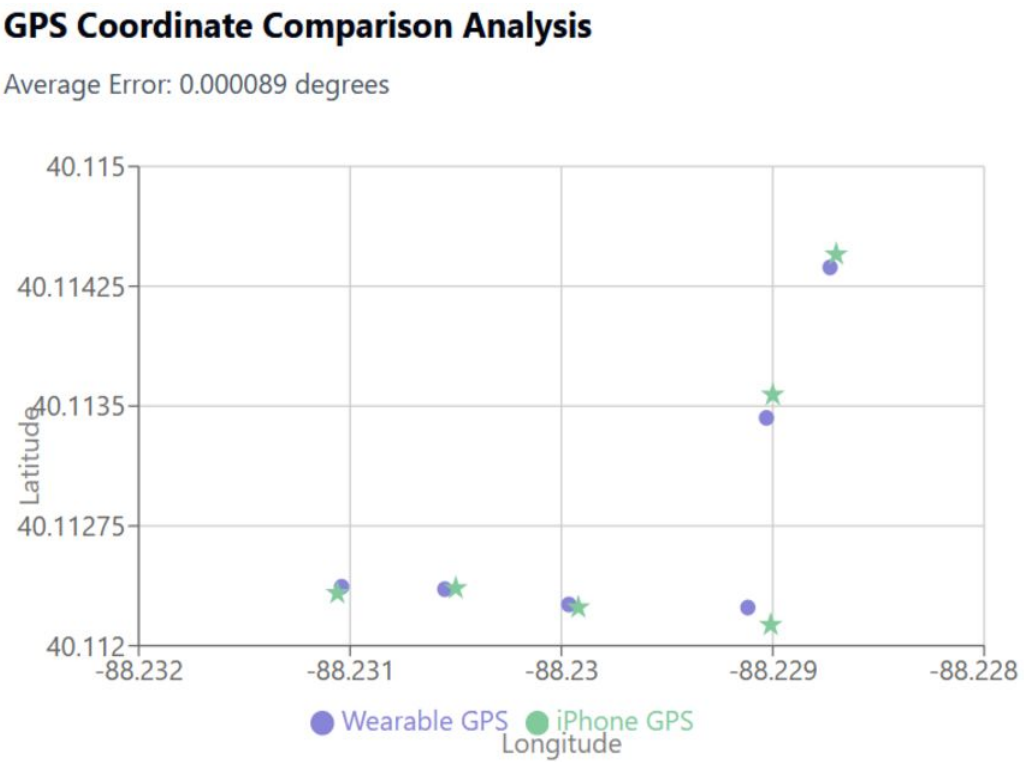
5. Requirements and Verification: Wearable Sensor Subsystem

Requirements	Verification
• Measures heart rate with an accuracy of ±5 bpm. • Measures temperature with an accuracy of ±0.5°C. • Detects motion with a resolution of ±2m/s^2. • 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

GPS Accuracy Test

Verification of Wearable Unit Coordinates





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

Heartbeat Accuracy Test

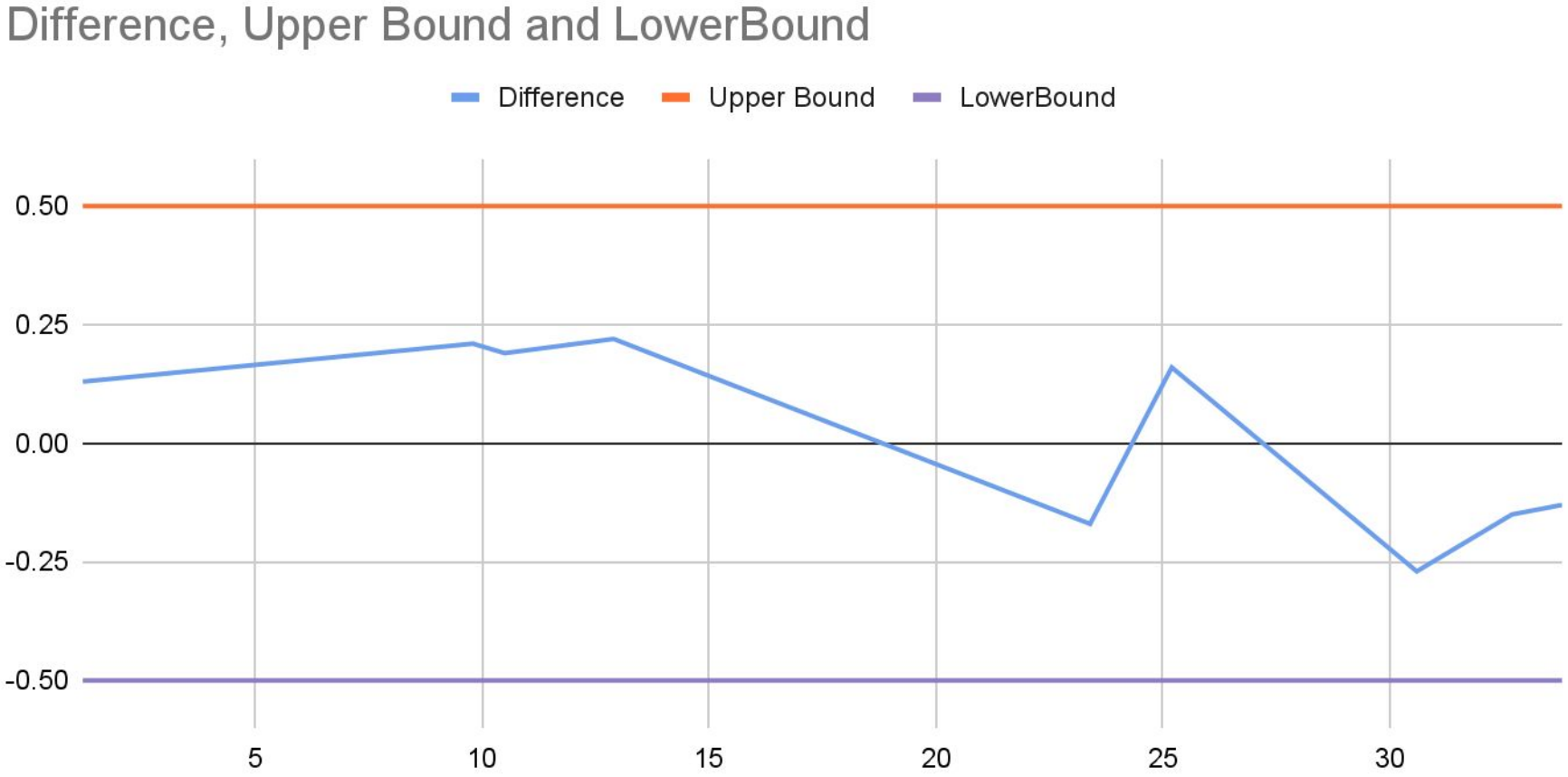
Heart rate beats per min error

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


FireFighter Monitoring Network 3.84V
FireMan 1
GPS: No Signal!
Temp: 25.30 C
HeartRate: 86 bpm
Accel: 10.09 m/s^2
Hop&Time: 1& 1129ms
RSSI: -44 dBm
Battery: 4.04V
FireMan 2
GPS:
Temp:
HeartRate:
Accel:
Hop&Time:
RSSI:
Battery: 0.00V
2:32
Current
89 BPM
89 BPM, 1m ago


FireFighter Monitoring Network 3.84V
FireMan 1
GPS: No Signal!
Temp: 26.10 C
HeartRate: 57 bpm
Accel: 10.07 m/s^2
Hop&Time: 1& 1283ms
RSSI: -36 dBm
Battery: 4.04V
FireMan 2
GPS:
Temp:
HeartRate:
Accel:
Hop&Time:
RSSI:
Battery: 0.00V
2:31
Current
54 BPM
57 BPM, 1m ago

Temperature Accuracy


Difference, Upper Bound and LowerBound
Difference
Upper Bound
LowerBound
0.50
0.25
0.00
-0.25
-0.50
5
10
15
20
25
30

Motion/Accelerometer Accuracy


FireFighter Monitoring Network
FireMan 1
GPS No Signal!
Temp: 22.20 C
HeartRate: -1 bpm
Accel: 10.01 m/s^2
Hop&Time: 1& 2413ms
RSSI: -40 dBm
Battery: 4.00V
FireMan 2
GPS
Temp:
HeartRate:
Accel:
Hop&Time:
RSSI:
Battery: 0.00V

5. Requirements and Verification: Wearable Sensor Subsystem Alert

```
struct AlertStatus{
  bool isHRAlert = false; // check if we should generate alert currently for heartrate
  bool isTempAlert = false; // check if we should generate alert currently for temperature
  bool isMotionAlert = false; // check if we should generate alert currently for no motion
  unsigned long hrAlertStart = 0; // when did heartrate start violating threshold
  unsigned long tempAlertStart = 0; // when did temperature start exceeding threshold
  float accX = 0.0; // last relevant x acc
  float accY = 0.0; // lastf relevant y acc
  float accZ = 0.0; // last relevant z acc
  unsigned long motionAlertStart = 0; // when did motion start becoming stagnant
  unsigned long lastUpdate = 0; // track last time update was sent to central
  bool inEmergency = false; // bool of whether current node is in emergency status
  bool lowBattery = false;  // check if we should generate alert currently for low battery (less than 10%)
};
```

5. Requirements and Verification: Wearable Sensor Subsystem

Requirements	Verification
• Alert is generated if a firefighter's heart rate exceeds 150 bpm or falls below 40 bpm for more than 30 seconds.	1. Simulate the heart rate of the wearable unit to monitor heart rates while gradually increasing to 160 bpm and decreasing to 35 bpm. 2. 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. 3. Record response times and ensure alerts are activated correctly.

Heart Rate Alert Demo

5. Requirements and Verification: Wearable Sensor Subsystem

Requirements	Verification
Alert is generated when the temperature exceeds 40°C for more than 3 minutes.	1. Place the device nearby a stove (or controlled heat source) to gradually increase the temperature around the wearable unit. 2. Monitor the wearable unit's temperature sensor and record readings. 3. Validate that the wearable unit triggers an alert when the temperature exceeds 40°C for more than 3 continuous minutes.
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.

Temperature Alert Demo

Motion Alert Demo

5. Requirements and Verification

Central Monitoring Hub Subsystem

- ➔ Gathering and visualize health data in real time
- ➔ Allows incident commanders to monitor the team's health status, detect potential health risks, and respond quickly to emergencies
- ➔ Rugged design ensures that it remains operational during operations in harsh environments
- ➔ The enclosure will be designed and printed out using a 3D printer with Polylactic acid material

5. Requirements and Verification: Central Monitoring Hub Subsystem

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

5. Requirements and Verification

Power Subsystem

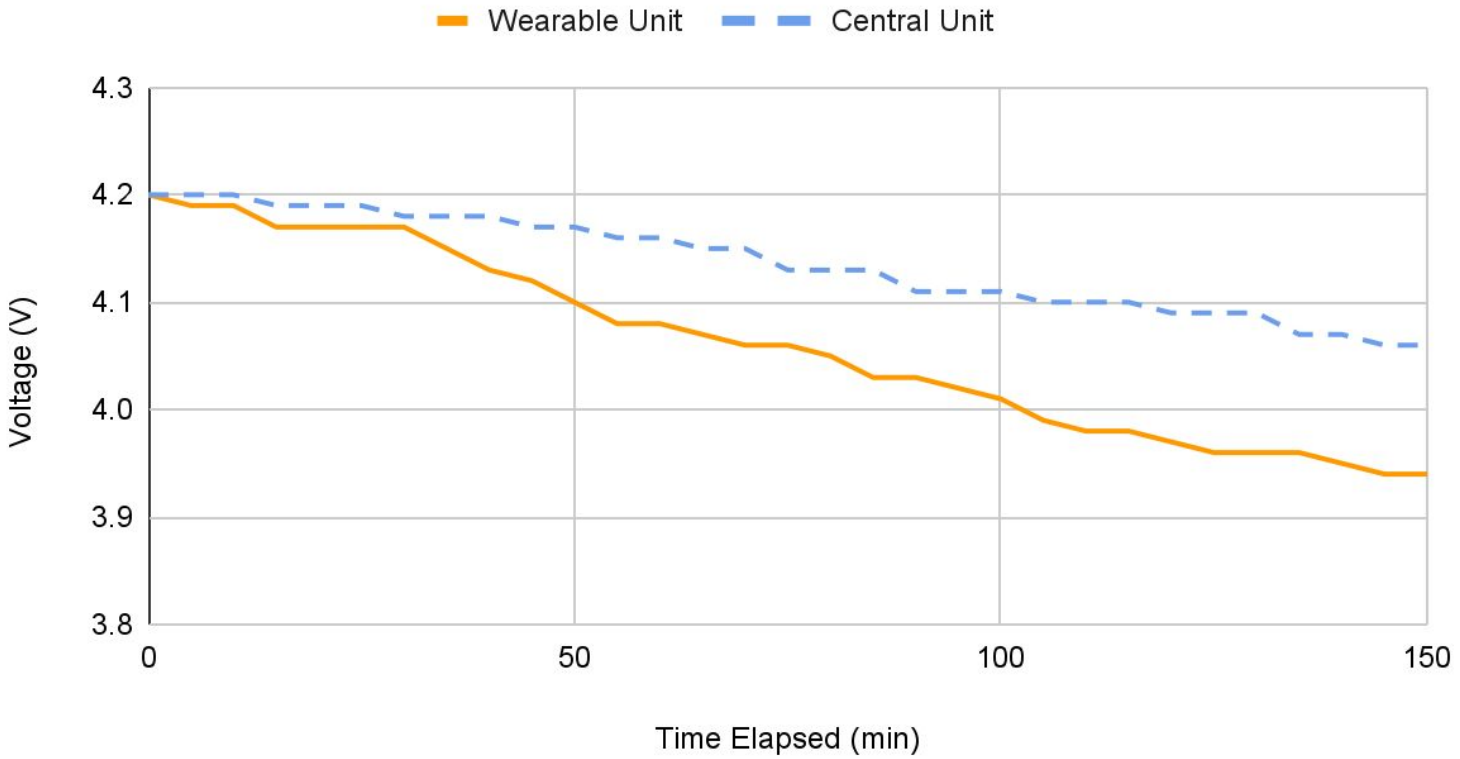
- ➔ Ensures that both the wearable units and the central hub have the energy to operate continuously.
- ➔ High-capacity lithium-ion batteries (3.7V, 2000mAh for wearables and central hub)
- ➔ Power management circuitry for efficient operation and battery protection
- ➔ USB-C charging ports for convenient recharging
- ➔ Battery Voltage measuring with the esp32 to ensure the user get alerts when at low battery (below 10%)

5. Requirements and Verification: Power Subsystem

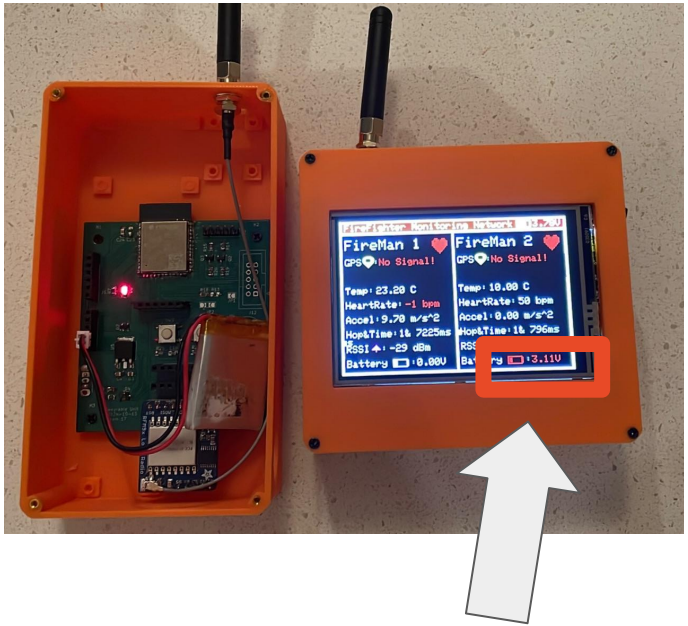
Requirements	Verification
Wearable units should send alerts when the battery is low (below 10%) to the central unit.	Charge the device to 15% and operate the device until the battery drops down to 10% measuring with a multimeter to verify if the alert is sent.
Both the wearable unit and the central unit should last at least 2 hours on a single charge under typical operation conditions (temperatures above 30°C).	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.

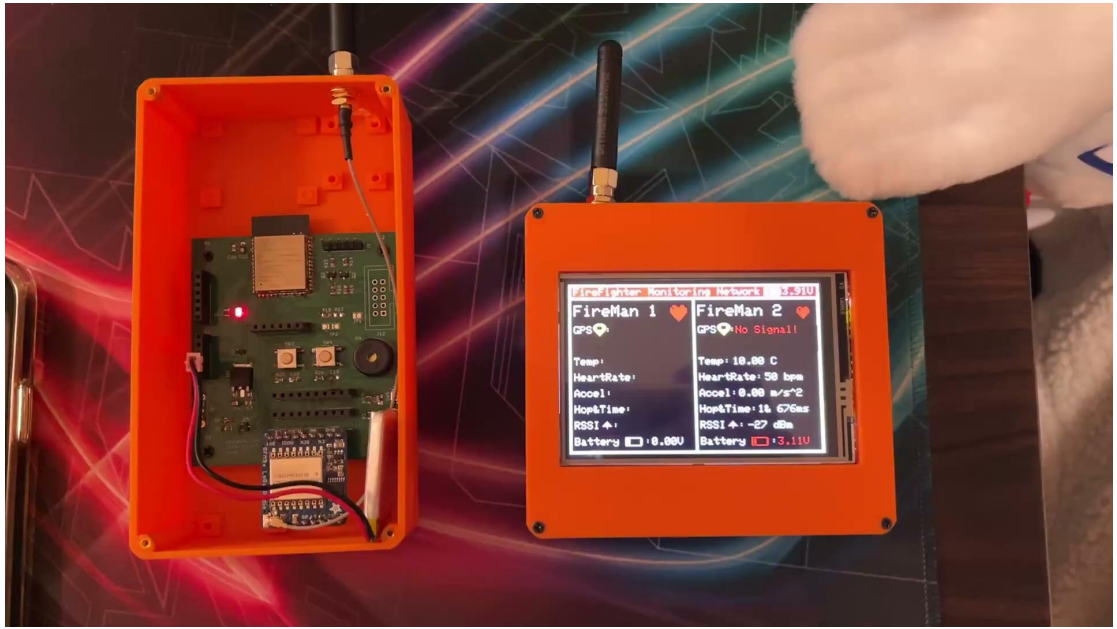
Battery Life

Device Voltage vs Time



Battery Low Power Alert





Battery dropped to 3.11V

5. Requirements and Verification

User Interface Subsystem

- ➔ Designed to provide incident commanders with a comprehensive and intuitive platform for monitoring firefighter health data in real time
- ➔ Features a custom-designed graphical user interface on a 3.5" TFT touch screen, ensuring clear visibility and easy navigation.

5. Requirements and Verification: User Interface Subsystem

Requirements	Verification
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
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

5. Requirements and Verification: User Interface Subsystem

Requirements	Verification
Alert management system with visual and auditory cues	1. Trigger various alert conditions 2. Verify visual cues appear correctly on screen 3. Test auditory alerts for proper sound and volume 4. Confirm alert prioritization works as designed 5. Test alert acknowledgment and dismissal functionality

5. Requirements and Verification

Mesh Network Integration

- ➔ Provides long-range communication between nodes, ensuring connectivity even when traditional communication infrastructure is unavailable
- ➔ Enables reliable data transmission from firefighters' wearable units to the central hub in challenging environments.

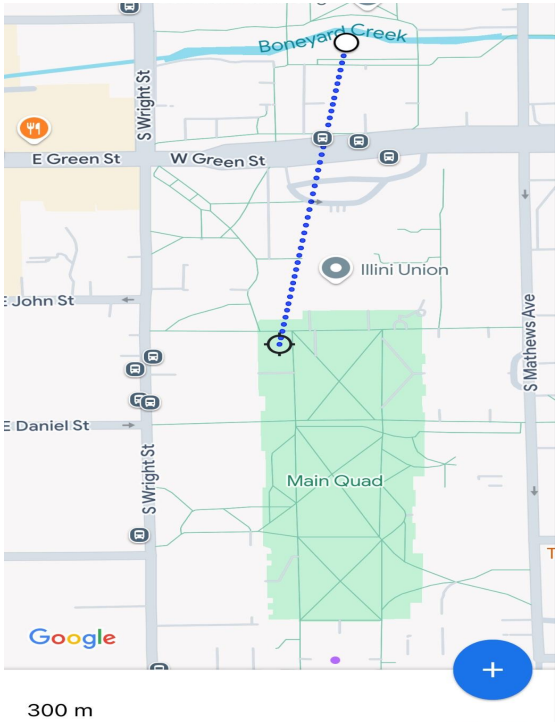
5. Requirements and Verification: Mesh Network Integration

Requirements	Verification
• Data transmission time from any firefighter to the central unit shall not exceed 15 seconds • Communication range of at least 600m in open areas and 250m in urban environments.	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.
• 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 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.

LoRa Range Test

Central Unit Display & Distance From Wearable Unit

899 Feet = Approximately 275 Meters



LoRa Meshing Demo Video

Ethics

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: Implement strict access controls so 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: Ensure that firefighters provide informed consent before wearing the monitoring devices. Offer clear and accessible explanations of what data will be collected, why, and how it will be protected.

Successes & Challenges

Successes

- **Power Supply**
  - Both our wearable unit and central unit are able to operate for >4 hr
- **LoRa Mesh Network**
  - Able to relay over 3 nodes
- **Sensors**
  - Meet the requirements for accuracy

Challenges

Power Delivery

➔ **Problem:**

- Used voltage regulator has a dropout voltage of 1.3V, reducing power delivery to 3.0 V
- Causing TFT not displaying
- GPS acting abnormally

➔ **Solution:**

- Switch to a lower dropout voltage regulator with the same footprint

Challenges

LoRa Module

➔ **Problem:**

- LoRa module is sending/receiving incorrect data after a certain range
  - Noise due to low signal strength

➔ **Solution:**

- Attach an antenna to increase the signal strength
- Develop an algorithm to drop messages with low signal strength to prevent noise

Challenges

Mesh Network

- ➔ **Problem:**
  - The central unit will receive duplicate messages as they are routed through various wearable units.
- ➔ **Solution:**
  - Assign unique message IDs and implement checks for duplicates on the central unit.

Conclusion

Conclusion

- **What we learned:**
  - How LoRa mesh network works
  - Design PCB
  - How to overcome design issue
- **What we would do differently:**
  - Consider adding more sensors (gas sensor) to monitor different status if time is sufficient

Future Work

Conclusion

➔ **Future Work:**

- Support more nodes (>10 nodes) to extend LoRa communication range (~1km)
- More compact enclosure (more wearable)
- User Interface on Wearable Unit (more intuitive visuals)
- More analysis on heart rate data (more algorithms for detecting more symptoms)