FIREFIGHTER HEALTH MONITORING NETWORK

ECE 445 PROJECT PROPOSAL - FALL 2024

Team 17

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Contents

1. Introduction
    1.1. Problem……………………………………………..2
    1.2. Solution……………………………………………..3
    1.3. Visual Aids…………………………………………4
    1.4. High-Level Requirements…………………………6
2. Design
    2.1. Block Diagram……………………………………..7
    2.2. Subsystem Overview and Requirements…………...8
        2.2.1. Wearable Sensor………………………………..8
        2.2.2. Central Monitoring Hub……………………..…12
        2.2.3. Power……………………………………………...13
        2.2.4. User Interface……………………………………...15
        2.2.5. Health Status Assessment Data Processing……..16
        2.2.6. Mesh Network Integration……………………...20
    2.3. Tolerance Analysis…………………………………21
        2.3.1. LoRa Communication Range…………………...21
        2.3.2. Resilience of Mesh Network Communication…23
        2.3.3. Power Management……………………………25
3. Ethics and Safety………………………………………26
    3.1. Ethical Issues……………………………………..26
    3.2. Safety Issues………………………………………27
4. Reference……………………………………………...29

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 ECG/EKG 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 Visual Aids

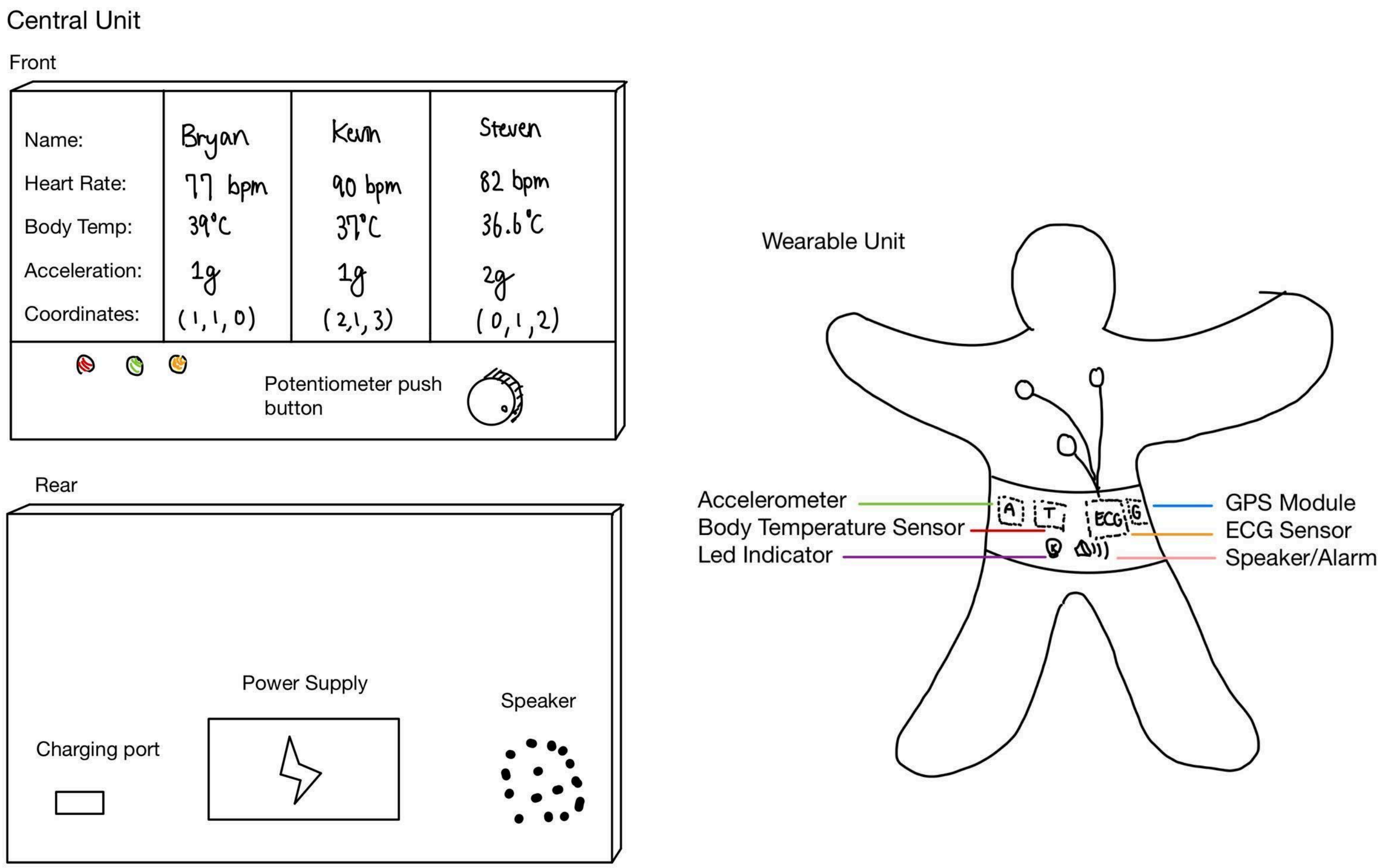

Figure 1. Design of the Monitoring Devices

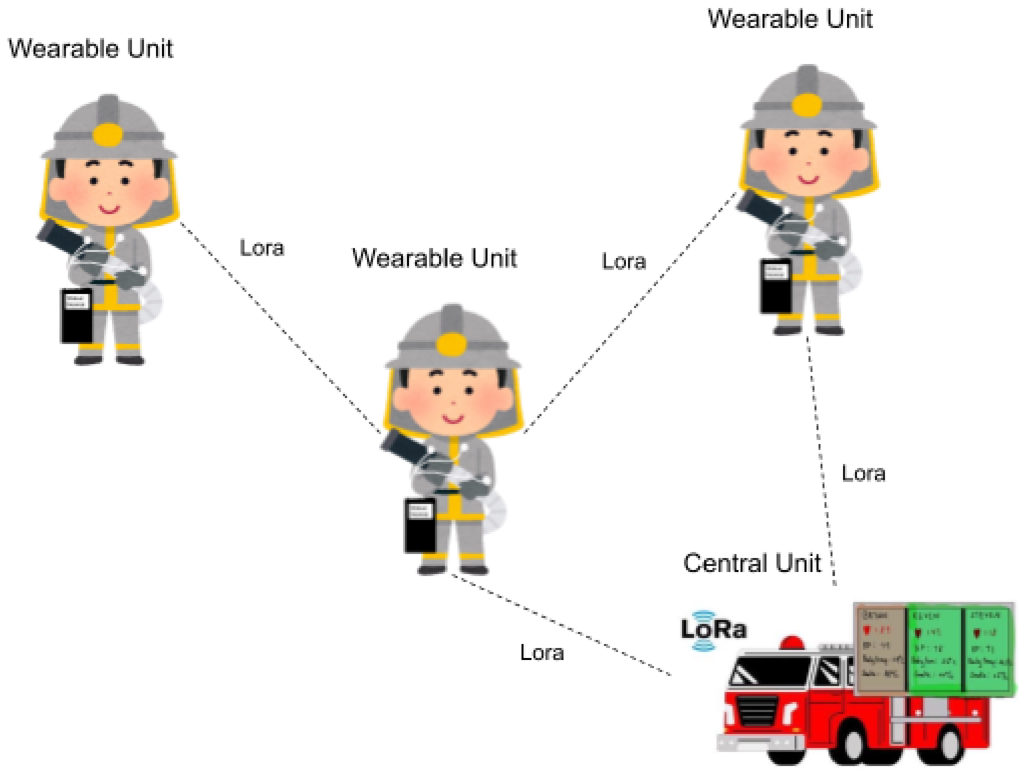

Figure 2. Visualization of the Firefighter Monitoring Network

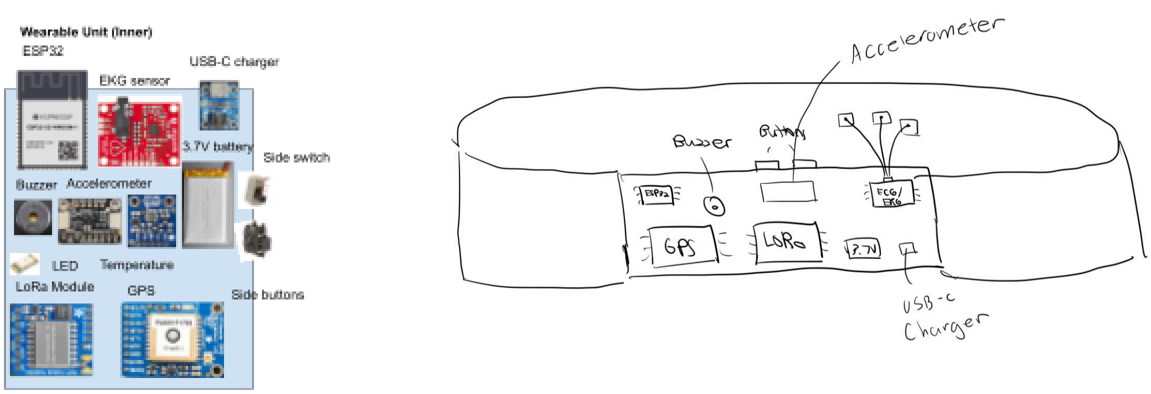

Figure 3. Wearable Unit Illustration

1.4 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. ECG/EKG 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. ECG/EKG Data
        i. Heart rates <40 bpm or >150 bpm sustained for >30 seconds, or upon detection of specified arrhythmias.
    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 300 meters in urban settings and 1 km 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.

2. Design

2.1 Block Diagram

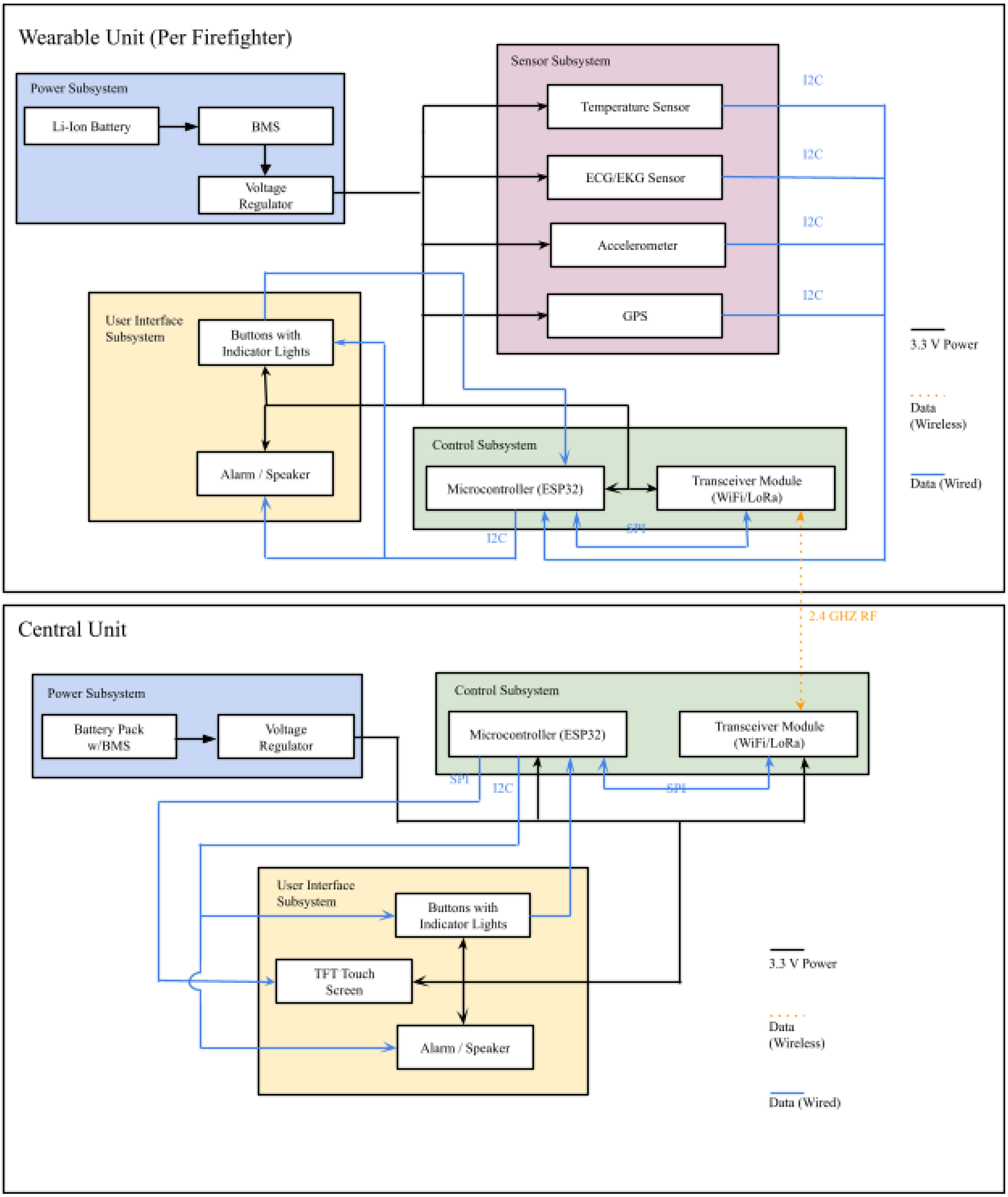

Figure 4. Block Diagram

2.2 Subsystem Overview and Requirements

2.2.1 Wearable Sensor Subsystem

This subsystem is responsible for continuously collecting real-time health and environmental data from individual firefighters. The sensors track vital signs like heart rate, surrounding temperature, and motion. The data is sent to the mesh network of the ESP32 and the central hub via reliable communication methods ESP-MESH and LoRa. The enclosure will be designed using 3D Computer-aided design software and printed out using a 3D printer with Polylactic acid material (PLA). Although PLA might have lower heat-resistance, other material like Polyetheretherketone (PEEK) could be replaced with the same design but with higher cost. For the purpose of this project, we will prioritize the design.

1. ESP32 Microcontroller
    - Processor:
        i. Dual-core Xtensa LX6 microprocessor
        ii. Clock speed: 240 MHz
        iii. Performance: Minimum 600 DMIPS (Dhrystone MIPS)
    - Memory:
        i. RAM: Minimum 520 KB SRAM
        ii. Flash memory: Minimum 4 MB
        iii. Support for external SPI flash up to 16 MB
    - Peripherals:
        i. The ESP32 must provide sufficient interfaces and GPIO pins to support simultaneous connection of:
            1. ECG/EKG Sensor

2. Temperature Sensor
3. Accelerometer/Gyroscope
4. GPS Module
5. LoRa Module
6. Piezo Buzzer

ii. Key interface requirements:

1. At least 1 ADC channel for ECG/EKG sensor
2. I2C interface for temperature and accelerometer/gyroscope sensors
3. UART interface for GPS module
4. SPI interface for LoRa module
5. 1 additional GPIO for the buzzer
6. Total GPIO pins required: Minimum 14

- Power Management:
  i. Deep sleep current: < 10 μA
  ii. Light sleep current: < 800 μA
  iii. Operating voltage: 3.0V to 3.6V

2. Electrocardiogram Sensor (ECG/EKG Sensor)
   - Measures heart rate with a range of 40-220 bpm and an accuracy of ±2 bpm.
   - Alert is generated if a firefighter's heart rate exceeds 150 bpm or falls below 40 bpm for more than 30 seconds. These thresholds account for both sustained tachycardia and bradycardia, indicating potential danger to the firefighter's health.
3. Temperature Sensor
   - Measures temperature from 30°C to 45°C with an accuracy of ±0.1°C

   - Alert is generated when temperature exceeds 40°C for more than 3 minutes
4. Accelerometer for Motion Detection
   - Detects motion with a resolution of ±2g for accelerometers
   - Alert is generated if no significant movement is detected for over 60 seconds, which may indicate that the firefighter has fallen or is immobilized.
5. GPS Module
   - Detects location with a tolerance of ±10m.
   - In emergency situations where one or more alerts have been triggered, the update frequency increases from every 30 seconds to every 5 seconds.
6. LoRa Module for Extended Communication
   - LoRa mesh network must ensure a communication range of at least 1 km in open areas and 300 meters in urban or obstructed environments
   - 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.
7. Buzzer to send out a critical alert to the watch commander
8. Lithium-Ion Rechargeable Battery
   - The system should last at least 2 hours on a single charge under typical operation conditions (temperatures above 30°C)
9. Buttons for Simple Setting Configuration

Requirements	**Verification**

Wearable unit measures the surrounding temperature, heart rate, acceleration, and location of the user and sends it to the Central Monitoring Hub subsystem. ● Measures heart rate with an accuracy of ±2 bpm. ● Measures temperature with an accuracy of ±0.1°C. ● Detects motion with a resolution of ±2g. ● Detects location with a tolerance of ±10m.	1. Place a thermometer in a closed box and see if the values are the same for the device and the thermometer 2. Place the device on a person equipped with Apple Watch and validate the heartbeat count 3. Place the device on a steady surface and see if the acceleration read is equal to gravity ($9.8 m/s^2$) 4. Measure the current coordinate with phone and validate the values from the gps sensor in the wearable unit 5. Output the readings to a terminal and confirm that the central unit is reading the values in real time
Alert is generated if a firefighter's heart rate exceeds 150 bpm or falls below 40 bpm for more than 30 seconds. These thresholds account for both sustained tachycardia and bradycardia, indicating potential danger to the firefighter's health.	1. Simulate the heart rate readings using ADALM2000 2. Set the wearable unit to monitor heart rates while gradually increasing to 160 bpm and decreasing to 35 bpm. 3. 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. 4. Record response times and ensure alerts are activated correctly.
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.
In emergency situations where one or more alerts have been triggered, the GPS update frequency increases from every 30 seconds to every 5 seconds.	1. Trigger one of the alerts (heart rate, temperature, or motion) while monitoring the GPS update frequency. 2. Have the person wearing the monitoring unit be continuously moving. 3. Record the GPS update intervals to verify that the unit updates every 5 seconds during an alert condition.
Reset the device if the button is pressed	1. Press the button and verify the device restarts

2.2.2 Central Monitoring Hub Subsystem

The central hub acts as the control center for the network, gathering and visualizing health data from all firefighters in real time. It allows incident commanders to monitor the team's health status, detect potential health risks, and respond quickly to emergencies. Its rugged design ensures that it remains operational during operations in harsh environments. The enclosure will be designed using 3D Computer-aided design software and printed out using a 3D printer with Polylactic acid material (PLA). Although PLA might have lower heat-resistance, other materials like Polyetheretherketone (PEEK) could be replaced with the same design but with higher cost. For the purpose of this project, we will prioritize the design.

1. An ESP32-based device.

2. 3.5" TFT touch screen for data visualization and input
    a. The screen should be able to visualize the firefighter data holistically
3. LoRa module for extended communication
    a. LoRa module must ensure a communication range of at least 1 km in open areas and 300 meters in urban or obstructed environments
4. Buzzer to send out a critical alert to the watch commander
5. Buttons and LEDs for simple setting configuration

Requirements	Verification
The central unit display should be able to visualize the firefighter data holistically	Have three 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 and whether the LED color changes according to the condition

2.2.3 Power Subsystem

The power subsystem ensures that both the wearable units and the central hub have the energy to operate continuously.

1. High-capacity lithium-ion batteries (3.7V, 2000mAh for wearables and central hub)
2. Power management circuitry for efficient operation and battery protection
3. USB-C charging ports for convenient recharging
4. Battery Voltage measuring with the esp32 to ensure the user get alerts when at low battery (below 10%)

Power Consumption for Wearable Unit:

1. ESP32 Microcontroller (DOIT ESP32 DEVKIT V1)
    a. Voltage: 2.2V to 3.6V
    b. Current Consumption: ~100mA to 200mA (Active)
2. Electrocardiogram Sensor (ECG/EKG Sensor) (SEN-12650)
    a. Voltage: 3.3V to 5V
    b. Current Consumption: ~10 mA
3. Temperature Sensor (BMP 180)
    a. Voltage: 3.3V
    b. Current Consumption: ~5 µA (1 sample/second in standard mode)
4. Accelerometer for Motion Detection (LSM6DS032)
    a. Voltage: 1.71V to 3.6V
    b. Current Consumption:~1.5 mA (Active Operation) and ~0.5 µA (Low-Power Mode)
5. GPS Module (MAX-M10S)
    a. Voltage: 3.3V VCC
    b. Current Consumption: ~6mA to ~25mA
6. Buzzer (PS1240)
    a. Voltage: 1.71V to 3.6V
    b. Current Consumption: ~20mA
7. LoRa Module for Extended Communication (RFM95W)
    a. Voltage: 1.8V to 3.7V
    b. Current Consumption: 13.5 mA (Transmission) and 10 mA (Reception)

Power Consumption for Central Monitoring Unit:

1. ESP32 Microcontroller (DOIT ESP32 DEVKIT V1)
    a. Voltage: 2.2V to 3.6V
    b. Current Consumption: ~100mA to 200mA (Active)
2. LoRa Module for Extended Communication (RFM95W)
    a. Voltage: 1.8V to 3.7V
    b. Current Consumption: 13.5 mA (Transmission) and 10 mA (Reception)
3. 3.5" TFT Touch Screen (HX8357D)
    a. Voltage: 3.3V
    b. Current Consumption: ~20 mA to ~40 mA
4. Buzzer (PS1240)
    a. Voltage: 1.71V to 3.6V
    b. Current Consumption: ~20mA

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.

2.2.4 User Interface Subsystem

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

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. Perform touch interaction tests covering all UI elements 3. Verify responsiveness and accuracy of touch inputs
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
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
User input handling for system configuration and data queries	1. Test all system configuration options 2. Verify data query functionality with various input parameters 3. Confirm changes are applied and persist after system restart 4. Test edge cases and invalid inputs for proper error handling

2.2.5 Health Status Assessment Data Processing Subsystem

1. ECG/EKG Signal Processing and Analysis

a. Signal Preprocessing:

   i. Use filtering techniques, such as a low-pass filter with a cut-off frequency of 100 Hz to remove high-frequency noise, combined with a stop-band filter around 60 Hz to eliminate electrical noise interference.

   ii. Apply the Butterworth or Chebyshev filter to ensure sufficient attenuation of at least -60 dB/decade in the stopband, preserving the integrity of the ECG signal's primary components (P, QRS, T waves).

   iii. Evaluate the spectrum of the signal using a Fast Fourier Transform (FFT) to identify high-intensity peaks and confirm most energy resides in the low-frequency range.

   iv. Display the raw and filtered ECG signal using waveform graphs, with frequency components plotted based on the FFT results.

b. Heartbeat Detection:

   i. Implement the Pan-Tompkins algorithm to detect the R-peaks in the ECG signal after filtering. This algorithm is effective in isolating the QRS complex while minimizing the impact of noise or other disturbances.

   ii. Use the Peak Detector subVI to locate R-peaks in real-time and extract the R-R intervals. Subtract the lower peak index from the higher index and multiply by the sampling period $T = 1/fs$ to compute the R-R interval.

   iii. Calculate the heart rate from the R-R intervals and monitor for abnormal fluctuations that could indicate arrhythmias (e.g., atrial fibrillation).

2. Surrounding Temperature Monitoring

   a. Calculate moving averages of surrounding temperature to smooth fluctuations.

   b. Detect abnormalities in temperature trends. A sudden increase or sustained temperature above 40°C could indicate heat exhaustion or dehydration, triggering an alert.

3. Motion and Activity Recognition
   a. Motion State Classification:
      i. Use an algorithm like a finite state machine to classify motion states (e.g., active, running, immobile), based on acceleration of movement.
      ii. Apply thresholding techniques to accelerometer data to determine periods of inactivity, potentially indicating a fall or injury.
4. GPS Data Processing
   a. Location Tracking and Mapping:
      i. Continuously update and log the firefighter's position.
5. Health Risk Assessment Algorithm
   a. Multivariate Health Risk Scoring:
      i. Combine data from heart rate, surrounding temperature, and motion sensors to generate a health risk score.
      ii. For instance, an elevated heart rate, combined with a rising surrounding temperature and lack of movement, could indicate a critical health issue like heat stroke or cardiac distress, triggering a high-risk alert
6. Alert System
   a. Buzzer Alerts on Firefighter Suits:
      i. When a critical condition is alerted, such as abnormal heart rate, high surrounding temperature, or low motion activity, the system will trigger a

buzzer on the firefighter's suit. This immediate, localized alert will draw the attention of nearby firefighters, enabling them to respond to potential health risks or environmental dangers in real-time.

b. Central Monitoring Hub Alerts:

    i. Simultaneously, the central monitoring hub will receive the same critical alert. A loud, distinct buzzer will go off at the hub to notify supervisors of the issue. The monitoring interface will also highlight the affected firefighter's status, displaying which vital sign or condition triggered the alert and allowing for quick decision-making, such as sending backup or ordering the firefighter to retreat for safety.

Requirements	Verification
For ECG signals, use filtering techniques, such as a low-pass filter with a cut-off frequency of 100 Hz to remove high-frequency noise, combined with a stop-band filter around 60 Hz to eliminate electrical noise interference	1. Use Matlab to plot raw and filtered ECG signals in the time domain. 2. Compare frequency spectra of raw and filtered signals using FFT. 3. Verify attenuation above 100 Hz and at 60 Hz. 4. Calculate SNR improvement. 5. Ensure no significant loss of important ECG features. 6. For ECG signals, apply the Butterworth or Chebyshev filter to ensure sufficient attenuation of at least -60 dB/decade in the stopband, preserving the integrity of the ECG signal's primary components (P, QRS, T waves). | 1. Apply chosen filter to known ECG signal in Matlab. 7. Measure stopband attenuation (confirm ≥ -60 dB/decade). 8. Compare original and filtered signals in time/frequency domains. 9. Quantify preservation of P, QRS, T waves (e.g., cross-correlation).

For ECG signals, apply the Butterworth or Chebyshev filter to ensure sufficient attenuation of at least -60 dB/decade in the stopband, preserving the integrity of the ECG signal's primary components (P, QRS, T waves).	1. Apply the chosen filter (Butterworth or Chebyshev) to a known ECG signal. 2. Plot the frequency response of the filter and measure the attenuation in the stopband to confirm it meets or exceeds -60 dB/decade. 3. Compare the filtered signal with the original in both time and frequency domains to ensure preservation of P, QRS, and T waves. 4. Perform a quantitative analysis (e.g., cross-correlation) between original and filtered signals to verify integrity of primary components.

2.2.6 Mesh Network Integration

The LoRa Mesh Network provides long-range communication between nodes, ensuring connectivity even when traditional communication infrastructure is unavailable. This system enables reliable data transmission from firefighters' wearable units to the central hub in challenging environments.

Requirements	Verification
End-to-end (including hops) data transmission time from any firefighter to the central unit shall not exceed 15 seconds, even when relaying through multiple nodes. Communication range of at least 1 km in open areas and 300 meters 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.
The devices should be able to 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.

2.3 Tolerance Analysis:

2.3.1 LoRa Communication Range

One of the most critical aspects of the Firefighter Health Monitoring Network is the ability to maintain reliable communication between the wearable units and the central monitoring hub. The project relies on LoRa (Long Range) technology for extended communication, especially in challenging environments. If the LoRa modules fail to achieve the required range, it could compromise the entire system's effectiveness and potentially endanger firefighters' lives.

Requirement:

The LoRa module must ensure a communication range of at least 1 km in open areas and 300 meters in urban or obstructed environments.

Analysis:

To assess the feasibility of meeting this requirement, we'll consider the following factors:

- LoRa Link Budget
- Environmental Factors
- Transmission Power

1. LoRa Link Budget

The LoRa link budget can be calculated using the following equation:

Link Budget = Transmitter Power + Transmitter Antenna Gain - Path Loss + Receiver Antenna Gain - Receiver Sensitivity

Assuming typical values for a LoRa system:

- Transmitter Power: 14 dBm (25 mW)
- Transmitter Antenna Gain: 2 dBi
- Receiver Antenna Gain: 2 dBi
- Receiver Sensitivity: -137 dBm (for SF12, BW125)

The path loss for 1 km in an open area can be estimated using the free-space path loss formula:

FSPL (dB) = 20 * log10(d) + 20 * log10(f) - 147.55

Where:

- d = distance in meters (1000)
- f = frequency in Hz (assume 915 MHz for US LoRa)

FSPL = 20 * log10(1000) + 20 * log10(915*10^6) - 147.55 ≈ 92 dB

Link Budget = 14 + 2 - 92 + 2 + 137 = 63 dB

This positive link budget suggests that communication at 1 km in open areas is feasible.

2. Environmental Factors

In urban or obstructed environments, additional path loss occurs due to obstacles. We can estimate this additional loss to be around 20-30 dB. For 300 meters in an urban environment:

- FSPL = 20 * log10(300) + 20 * log10(915*10^6) - 147.55 ≈ 81 dB
- Total Path Loss = 81 dB + 25 dB (urban environment) = 106 dB
- Link Budget = 14 + 2 - 106 + 2 + 137 = 49 dB

This positive link budget indicates that communication at 300 meters in urban environments is also feasible.

3. Transmission Power

The analysis uses 14 dBm (25 mW) as the transmission power. Many LoRa modules can transmit at up to 20 dBm (100 mW), which would add an extra 6 dB to the link budget if needed.

2.3.2 Resilience of Mesh Network Communication to Maximum Allowable Delay

Maintaining effective communication among firefighters and with the central command is critical during emergencies. Environmental factors may disrupt direct connections. Therefore, we need to ensure that data can still be transmitted even if one firefighter loses connection to the central hub, all while adhering to a maximum allowable delay of 15 seconds for data transmission.

Requirements:

1. Node Connectivity: Each wearable device must communicate with neighboring devices to relay data back to the central hub.
2. Maximum Latency: The total transmission delay from a firefighter's device to the central unit must not exceed 15 seconds.

Analysis:

1. Transmission Time Using LoRa:

LoRa communication allows for long-range transmission with low data rates. Assuming a payload size of 400 bytes (3200 bits) and using a data rate of 5 kbps:

Transmission Time = 3200 bits / 5000 bps = 0.64 seconds (640 ms)

This calculation indicates that transmitting data between neighboring firefighters will take approximately 640 ms per hop.

2. Maximum Number of Hops

Given a maximum allowable total delay of 15 seconds, we can calculate the maximum number of hops n:

n=15000 ms / 640 ms ≈ 23.44 hops

While this theoretical maximum is high, practical application in a firefighting context is much lower. Considering a typical firefighting team size of 4 to 10 members, our analysis demonstrates that the mesh network can reliably support up to 23 hops between firefighters while still adhering to the 15-second maximum allowable delay for data transmission. This is based on a payload size of 400 bytes and a data rate of 5 kbps using LoRa communication.

Based on our analysis of the data transfer rate using LoRa and the calculation of the maximum number of allowable hops within the 15-second delay, we conclude that our requirements are satisfactory for a typical firefighting team of 4 to 10 people. The proposed mesh network architecture, utilizing LoRa communication, is well-suited to meet the communication requirements of firefighting teams. The ability to support up to 23 hops provides a robust and reliable solution for ensuring effective and timely information exchange in emergencies.

2.3.3 Power Management

The wearable devices are required to operate continuously for extended periods during a firefighting mission. The primary risk is the battery depleting too quickly, leading to a loss of communication or sensor data. This risk increases with high power demand from sensors, mesh network communication, and temperature effects on the lithium-ion batteries.

Requirements:

1. The battery should last at least 2 hours on a single charge under typical operation conditions (temperatures above 30°C).

Analysis:

- Battery Capacity (C): 2000 mAh lithium-ion battery.
- Power Consumption (P): Total power consumption depends on the combined power draw of the sensors, ESP32 microcontroller, and communication modules (LoRa, ESP-MESH). The following current draw is based on the upper bound of current consumption data included in the power subsystem section.
  - ESP32 microcontroller: 200 mA during active use.
  - EKG sensor: 10 mA.
  - Temperature sensor: 5 µA.
  - GPS sensor: 25 mA
  - Motion sensors (accelerometer/gyroscope): 1.5 mA.
  - LoRa module: 13.5 mA during transmission.
  - Buzzer: 20 mA
- Battery Discharge Efficiency (n): Efficiency factor, assume 60% due to heat and inefficiencies in power delivery (conversion losses).

Battery Runtime Calculation:

To calculate the battery runtime, we can use the following formula:

$$t = \frac{C*n}{P}$$

Where:

- t is the battery runtime in hour
- C is the battery capacity in mAh

- n is the battery discharge efficiency
- P is the total power consumption

$$P = 200\,mA + 10\,mA + 5\,\mu A + 25\,mA + 1.5\,mA + 13.5\,mA + 20\,mA <= 271mA$$

As a result, we get $t = \frac{C*n}{P} = \frac{2000*0.6}{271} = 4.43hr \approx 4hr$

Thus, the battery is expected to last approximately 4 hours under typical usage conditions, which satisfies the requirement of

3. Ethics and Safety

3.1 Ethical Issues

3.1.1 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.

3.1.2 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.

3.2 Safety Issues

3.2.1 Fire and Water Resistance

Given that firefighters operate in extreme environments, we made the design choice to house the wearable unit within the protective layers of the firefighter's suit. This placement ensures that the components are shielded from direct exposure to high temperatures and water. While this reduces risks, we acknowledge that no system can fully eliminate all dangers. We aim to improve safety standards by enhancing the protection of critical electronics without compromising the function or comfort of firefighting gear. By situating the electronics inside the suit, we significantly reduce the risk of component failure due to environmental factors, contributing to both firefighter safety and operational reliability, in line with the IEEE's Code of Ethics Section I.5 to "be honest and realistic in stating claims or estimates" [3].

3.2.2 Lithium-Ion Battery Safety

Lithium-ion batteries, while efficient, can pose risks such as overheating or physical damage, leading to dangerous conditions like thermal runaway—a situation where excessive heat can trigger a self-sustaining reaction resulting in fire or explosion [5]. To mitigate these risks, we will implement general safety precautions when using lithium-ion batteries, including:

- Proper Storage: Store batteries in a cool, dry place away from flammable materials to prevent overheating and reduce fire risk.

- Avoiding Physical Damage: Ensure that batteries are not exposed to impacts, punctures, or other physical stresses that could compromise their integrity.
- Safe Charging Practices: Use compatible chargers and avoid overcharging batteries, as this can lead to thermal runaway. Disconnect chargers once the battery reaches full charge. Ensure that charging is performed using LiPo safety bags.
- Regular Inspections: Conduct regular inspections of the battery for signs of swelling, leakage, or corrosion, and replace any batteries that show these signs.

By integrating these precautions and following best practices for lithium-ion battery usage, our design aligns with the IEEE's ethical commitment to enhancing the safety, health, and welfare of the public [3]. These measures ensure the reliability and long-term safety of our monitoring system, supporting firefighter operations in hazardous environments.

4. References

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