ECE 445

SENIOR DESIGN LABORATORY

Firefighter Health Monitoring Network

Project Proposal

Team 17

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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.
- 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.
- 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.
- 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.
- 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.

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

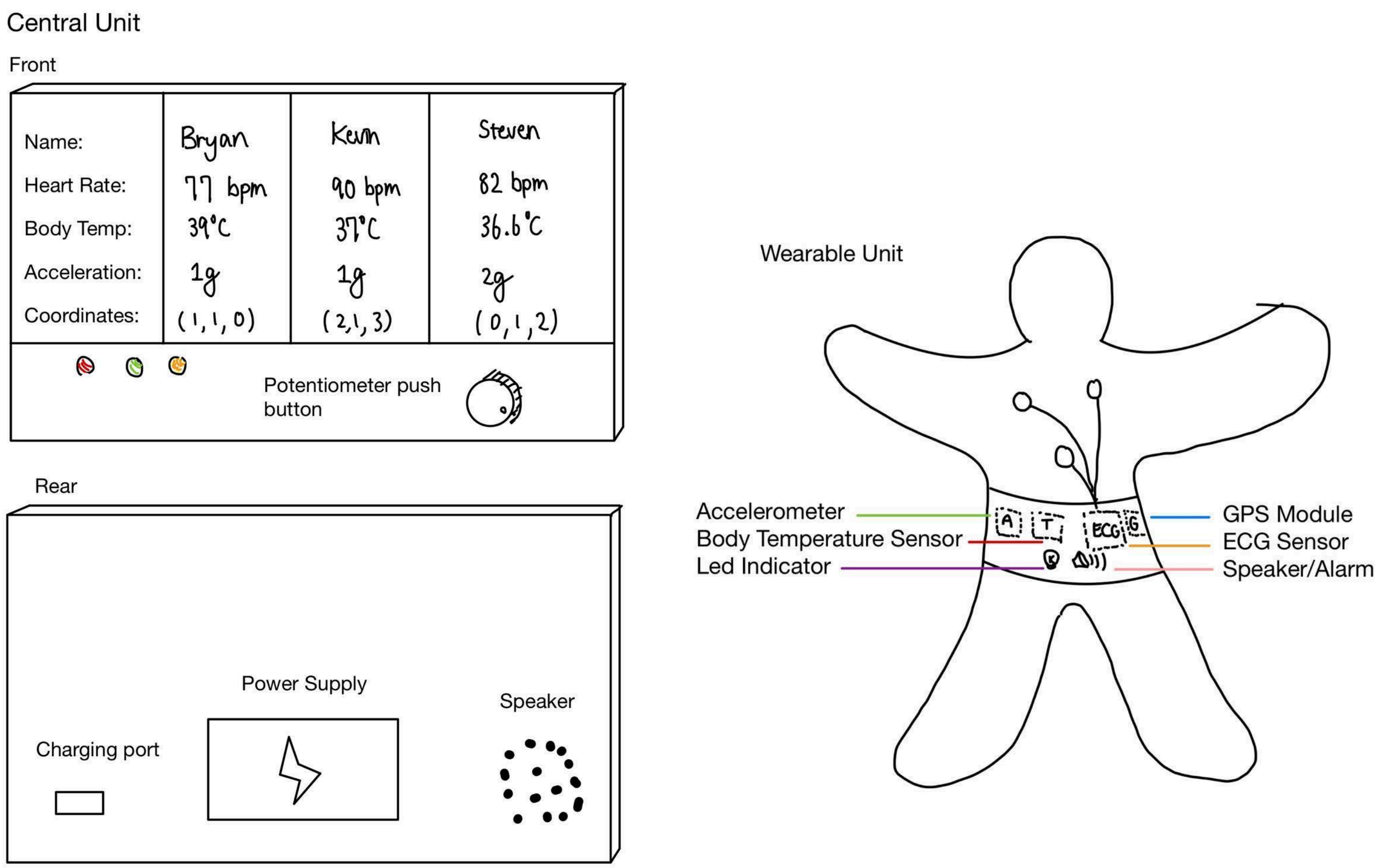

Figure 1. Design of the Monitoring Devices

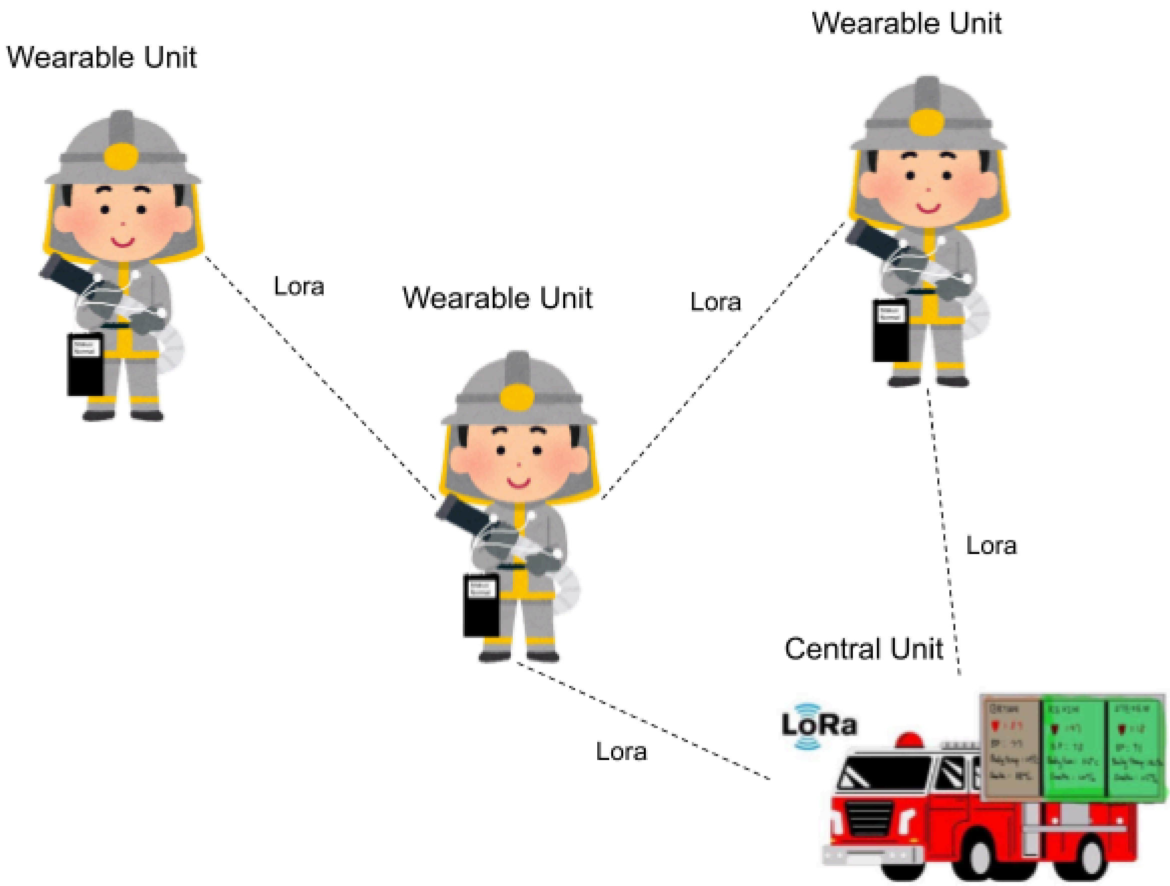

Figure 2. Visualization of the Firefighter Monitoring Network

1.4 Higher Requirements

- The system shall continuously monitor and transmit vital signs data and generate automatic alerts for abnormal vital signs (irregular heart rate pattern) or lack of movement (when the accelerometer measures a constant number) within 10 seconds of detection.
  - If a person sits on the floor without moving, the accelerometer should return $9.8 m/s^2$ (gravity when data is non-normalized) and alert the commander after 10 seconds.
- Wearable units shall operate on a single charge for at least 2 hours in typical firefighting conditions.
  - The wearable units should operate for at least 2 hours with all functions turned on and under a temperature of 40℃ (close to body temperature).
- The mesh network shall maintain connectivity in challenging environments (e.g., inside buildings and around obstacles).
  - The person with a monitoring device should be able to receive data from the wearable units (100 m away) in another building.

2. Design

2.1 Block Diagram

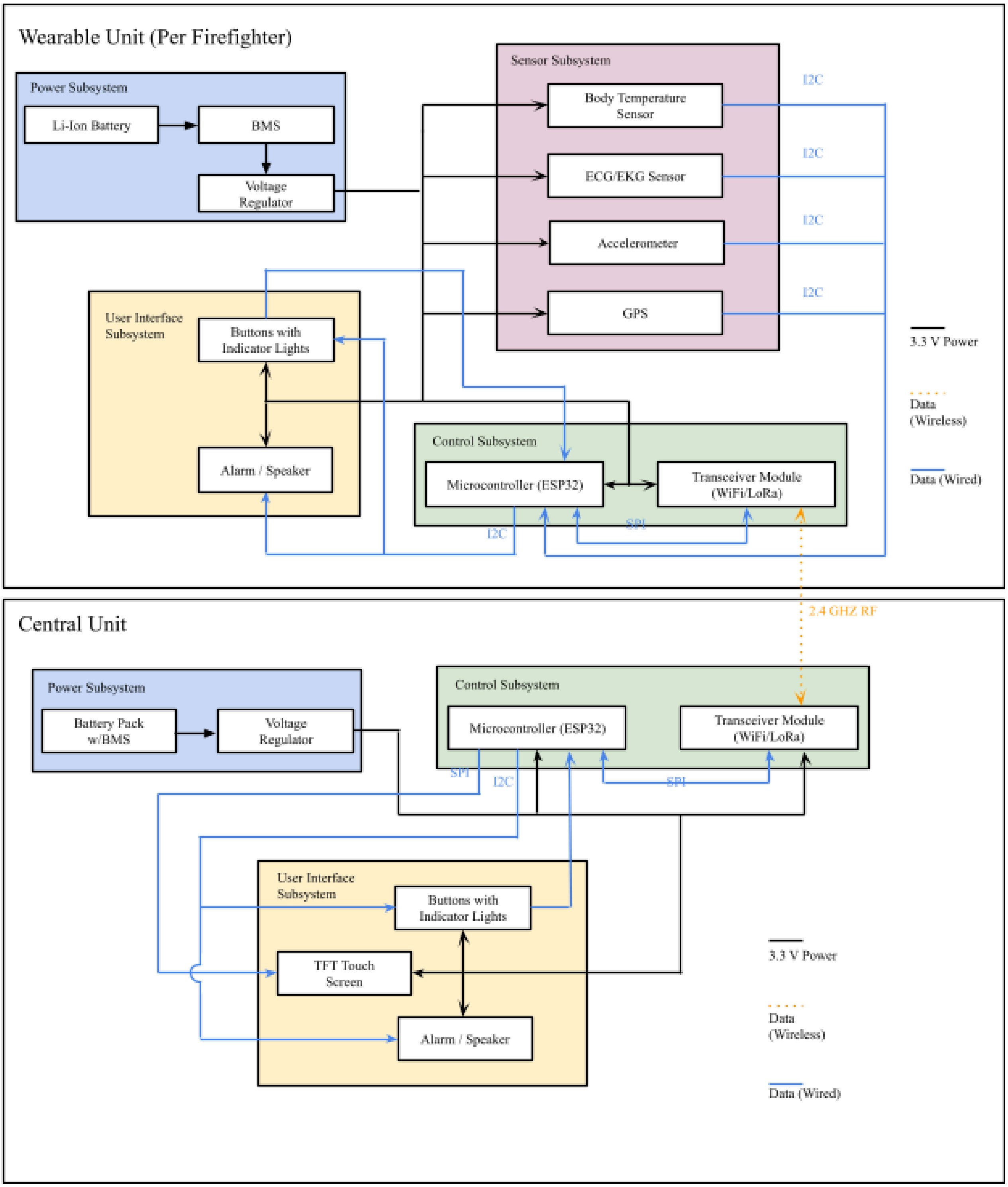

Figure 3. Block Diagram

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, body temperature, and motion. The data is sent to the mesh network of the ESP32 and the central hub via a reliable communication methods ESP-MESH and LoRa.

1. ESP32 microcontroller
2. Electrocardiogram sensor (ECG/EKG sensor)
    - Should accurately measure heart rate with a range of 40-220 bpm and an accuracy of ±2 bpm.
3. Body temperature sensor (MLX90614)
    - Must measure temperatures from 30°C to 45°C with an accuracy of ±0.1°C
4. Accelerometer for motion detection (GY-521 MPU-6050)
    - The accelerometer/gyroscope must detect motion with a resolution of ±2g for accelerometers
5. GPS Module (Neo-6m-000-1)
    - The GPS module should detect location with a tolerance of ±10m
6. LoRa module for extended communication
    - LoRa module must ensure a communication range of at least 2 km in open areas and 500 meters in urban or obstructed environments
7. Small, rechargeable battery
    - The system should last at least 2 hours on a single charge under typical operation.
8. Buttons and LEDs for simple setting configuration

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 extended battery life and rugged design ensure that it remains operational during prolonged operations in harsh environments.

1. An ESP32-based device with a larger battery capacity
2. 7" 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 2 km in open areas and 500 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

2.2.3 Power Subsystem

The power subsystem ensures that both the wearable units and the central hub have the energy to operate continuously in extreme conditions. Larger batteries in the central hub support extended use, while the power management circuitry optimizes battery life. Heat-resistant lithium-ion batteries for wearable units.

1. Larger capacity battery for the central hub
2. Power management circuitry for efficient operation

2.2.4 Software

1. Embedded software for wearable units to collect and transmit sensor data
2. Mesh networking protocol implementation
3. Data processing algorithms for health status assessment
4. Central hub software for data visualization and alert management
5. Health analytics/ algorithm for abnormal health data detection

2.2.5 Mesh Network Integration

1. Utilize LoRa's long-range capabilities for a self-forming, self-healing network
2. Implement secure, low-latency data transmission protocols
3. Develop network management software for the central hub

2.2.6 Subsystem Integration

- Wearable units continuously collect and transmit health data through the mesh network
- The central hub receives, processes, and displays data from all connected firefighters
- The mesh system should alert every firefighter in site for faster response time

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 2 km in open areas and 500 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 2 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 (2000)

f = frequency in Hz (assume 915 MHz for US LoRa)

FSPL = 20 * log10(2000) + 20 * log10(915*10^6) - 147.55 ≈ 106 dB

Link Budget = 14 + 2 - 106 + 2 + 137 = 49 dB

This positive link budget suggests that communication at 2 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 500 meters in an urban environment:

FSPL = 20 * log10(500) + 20 * log10(915*10^6) - 147.55 ≈ 94 dB

Total Path Loss = 94 dB + 25 dB (urban environment) = 119 dB

Link Budget = 14 + 2 - 119 + 2 + 137 = 36 dB

This positive link budget indicates that communication at 500 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:

$n=15000 \text{ ms} / 640 \text{ ms} \approx 23.44$ 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.

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." Monitoring firefighters' health data involves collecting sensitive personal information such as heart rate, body 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

- Follow the lab safety rules when soldering and assembling the components
- Ensure that the testing environment is safe with everyone else at a safe distance
- Clearly read and understand the datasheet of each component to know their operable environment and prevent any hazardous objects near the components
- As the product is equiped on the firefighter's body, make sure the final product will not cause damage
- Make sure the batteries of the device are not overloaded, which might cause hazards like fire

4. References

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