Smart Forest Management System

A Technical Report submitted to the Department of Electrical and Computer Engineering

Presented to the Faculty of the School of Engineering and Applied Science

University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science, School of Engineering

Nathan Wonil Yu

Spring, 2025

Technical Project Team Members

Sean Mahoney

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Nathan Yu

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Keith Williams, Department of Electrical and Computer Engineering

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In STS 4500
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Bachelor of Science in Electrical and Computer Engineering

By
Quentin Olsen
Nathan Yu
Johnathan Mirkovich
Sean Mahoney

December 6, 2024

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ADVISORS

Keith Williams, Department of Electrical and Computer Engineering

Statement of Work

JJ: At the beginning of the semester I worked on part research to help us decide what IR sensor and temperature sensor we were going to use. Once these parts came in, I started testing on the IR sensor. Realizing that the sensor itself was too small to access the individual pins easily, I ordered a new developmental board to test it. During this time I designed and created the entire front end of the website. The website has three pages, one that lists all of the devices with latitude, longitude sensor ID, temp sensor value, and IR sensor value. The second page is an admin page that allows the user to add more devices to the list with a password. The last page is a map that puts pins exactly where each device is deployed. I made the page that lists all of the devices flash when any sensor on any device reads a value outside of its normal range. I then spent several weeks trying to get the IR sensor to work correctly but was unsuccessful. Our group pivoted to a new analog sensor where I assisted Quentin in creating a circuit that would allow for the correct filters and gain for our analog IR sensor. During the last two weeks of the semester I assisted wherever I could including the testing of our final product and modifying our chassis. I also contributed to all of the large assignments over the semester including the project proposal, midterm design, and final report.

Nathan: I primarily worked on software and the design planning for that software. In the initial stages of the project, I did a lot of research on different tools and methods we could use to accomplish our end goals, including different low energy communication protocols and specific MCUs for those protocols. I designed the initial and final packet structures and implemented them within the Zephyr environment. I spent some time with JJ working on C++ code for interfacing with the digital IR sensor. Afterwards, I wrote Zephyr overlay files for our MCU that allows us to access the different pins and I2C buses within the Zephyr environment. I integrated the temperature sensor with the communication system and LEDs, giving us a viable product that was able to communicate with other nodes, along with visibly reacting to changes in the environment. I further developed Sean's idea of emergency states into a full alert acknowledgement system that ensures any fire alerts are transmitted down our network. I also built our majority voter system to improve system reliability and allow the system to overcome some data loss/corruption. Throughout the semester, I contributed to deliverables including the proposal and final report.

Quentin: My main job was to design the hardware of the system. There were two iterations of the main board, and three sensor breakout boards. It follows that I was the main procurer of parts, putting in orders and handling the budget. I communicated with 3W for the main board's assembly. I tested the functionality of the temperature sensor with an Arduino by writing preliminary code. After some difficulty interfacing with the digital IR flame sensor, I tested the analog sensor before laying out its breakout board. I soldered parts onto the breakout board and tested its functionality. I did research to implement a solar power charging circuit. I tested boards and the current draw on boards when sending signals and when receiving. Throughout the semester, I contributed to deliverables including the proposal and final report.

Sean: I worked primarily on the software. In the initial stages of the project this consisted of developing and testing the first iteration of the communication software. Following this, I expanded upon the communication by introducing alert bits to the packet structure and the idea of emergency/idle states. I implemented these ideas in code and then performed further testing in the lab. I also wrote code to interact with the analog IR sensor over I2C, and tested the sensor to determine threshold values for fire detection. Alongside the programming, I assisted other group members by running tests and by soldering an analog IR breakout board for the final prototype. I concluded my work on the project by performing range, signal strength, and signal-to-noise ratio testing of the communication system. Throughout the semester, I contributed to deliverables including the project proposal and the final report.

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Abstract

The **Smart Forest Management System** focuses on developing an advanced fire detection system for electrical lines in forested environments. The system deploys small, specialized devices on each electrical pole, equipped with an IR flame detector and a temperature sensor to accurately monitor for signs of fire potentially caused by electrical lines. Utilizing LoRa communication, these devices transmit real-time data to a central home controller, where information aggregates and displays on a user-friendly front-end interface. The system's weatherproof chassis ensures durability and reliability in challenging environmental conditions. Powered by a solar-powered cell, each device is designed for minimal maintenance and optimal performance. Unlike conventional forest fire detection systems, this solution provides instantaneous readings directly from power lines, enabling rapid response and preventing widespread fire damage. By integrating these technologies, the system significantly enhances fire monitoring capabilities in remote and high-risk areas.

Background

Wildfires caused by electrical infrastructure pose a significant risk to forested regions, especially in non-urban areas where detection and response times are slow. Electrical lines account for a substantial number of wildfires due to downed lines, vegetation contact, and equipment failures [1]. In 2021, the Dixie Fire, the second-largest wildfire in California's history, started when a tree fell and hit the company's electrical wires [2]. The consequences of such incidents are devastating, leading to loss of life, property damage, and destruction of natural habitats [3].

Existing fire detection systems, such as satellite imagery, aerial surveillance, and ground-based sensors, provide large-scale monitoring but lack the immediacy and precision needed to detect fires directly at their source. For instance, conventional remote sensing systems often struggle with delayed responses and limited coverage in complex terrains [4], [5]. While some IoT-based systems exist for forest monitoring, they are not specifically designed for integration with electrical infrastructure, which is crucial for targeting fire prevention at its source [6].

Our project addresses this gap by developing a fire detection system specifically for electrical poles in forested environments. The system uses IR flame detectors and temperature sensors mounted directly on each pole, providing real-time monitoring of potential fire hazards caused by electrical lines. By using LoRa communication, our devices transmit data over long distances, even in remote areas with limited cellular connectivity [7]. This approach allows for instantaneous detection and rapid response, significantly reducing the risk of widespread fire damage.

This project requires expertise in several key areas to ensure its successful design, development, and deployment. It addresses public health, safety, and welfare while considering global, social, environmental, and economic factors. Key skills include wireless communication to ensure reliable long-range data transmission for fire detection alerts, control software development to manage sensor inputs and enable efficient microcontroller operation, and PCB design to create robust and energy-efficient circuits. Additional expertise includes power system design for sustainable, long-lasting energy solutions, chassis and front-end development for a durable device with a user-friendly interface, and LoRa communication system design to optimize data transmission across multiple devices in forested environments.

Each team member brings specialized expertise tailored to these needs. Sean focuses on wireless communication and microcontroller control software, ensuring the system operates efficiently and transmits real-time alerts critical to public safety. JJ handles PCB design, front-end software, and sensor testing, contributing to the system's durability, environmental sustainability, and ease of use for stakeholders. Quentin leverages his internship experience in PCB design to develop power-efficient circuits and energy systems. Nathan designs the communication map for the LoRa system and assists with control software, ensuring the system addresses critical fire safety concerns with firsthand insight into real-world applications.

By directly monitoring power lines, our system provides a unique solution to a pressing problem. It enables rapid detection and response, reducing the risk of catastrophic wildfires and enhancing the safety and resilience of forested areas. This project not only aligns with our technical capabilities but also reflects our personal commitment to preserving the environment and preventing the devastating effects of wildfires.

Project Description

Performance Objectives and Specifications

The **Smart Forest Management (SFM)** system is designed to be an early warning system for power companies that have power lines through rural and high fire risk areas. The main objective is to be able to accurately recognize fire and then be able to relay that information over long distances to a human operator, to allow for a faster and more prepared response. To do this, our product offers a small, easily deployed node that can be strapped onto an electrical pole and monitor for fire down the line. The information the user receives is the location of a fire emergency and the parameter that triggered the alert. The node should sense any fire on the line between itself and the next pole. Its range, therefore, must be on the order of 100 feet, the length between poles in rural areas. Another consideration lies in creating a financially viable product.

Our product combines an infrared (IR) sensor as well as a temperature sensor. In case there is too much smoke for the IR sensor to properly detect the fire at a distance, the temperature sensor acts as a second stage of proof. Both of these streams of information can be accessed virtually and on the node, using an LED for power and fire. An ideal fire detection system is one with which the user can monitor data and map all the nodes on an easy-to-read interface. Our objective is to be able to display whether a fire is detected by one node. However, we consider a mapping system for many nodes to be out of the scope of this project.

Functionality

Figure 1 is an overview of the process and functionality of the fire detection system. Each sensor has two main responsibilities: to detect and notify of fire and then to act as an alert relay, sending a received alert down the chain of sensors all the way to the main computer.

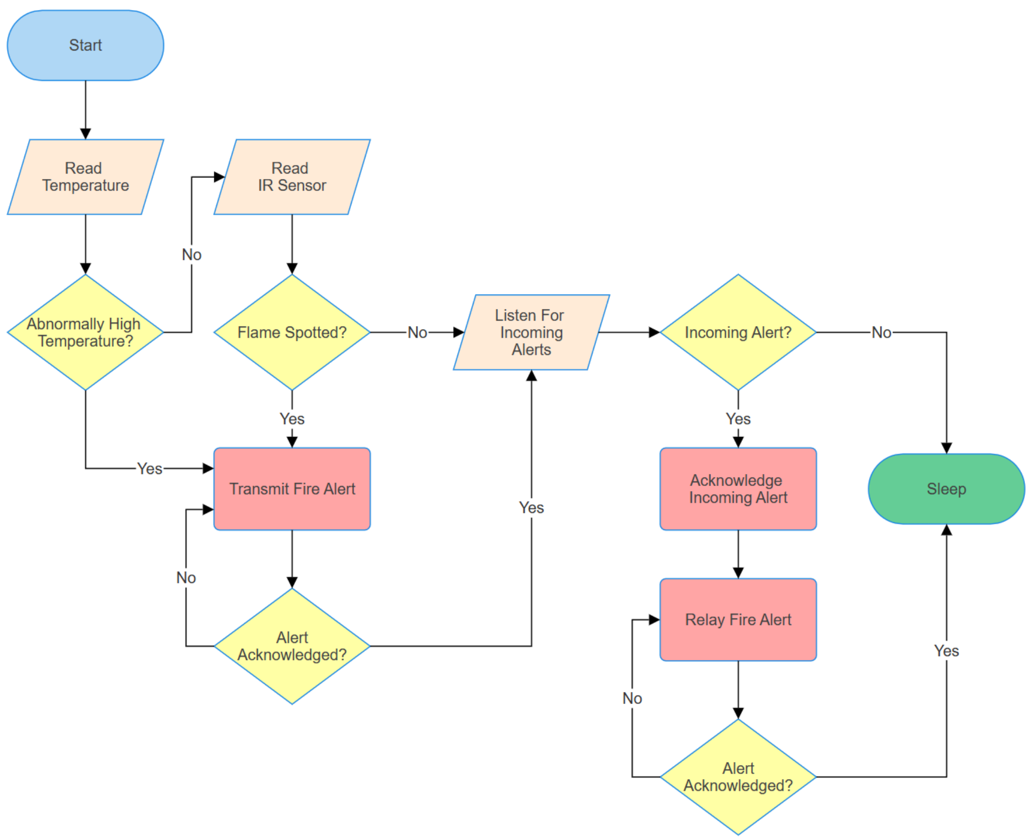


Figure 1. Functionality Flow Chart

Breaking down the fire detection procedure first:

1. The first sensor that is checked is the temperature sensor. The temperature sensor reading an abnormally high temperature is an indication that a fire is extremely large, very close to the sensor, or both. This case signifies that a significant fire has already begun and the

sensor should immediately send a fire alert. If a high temperature is measured, step 3 describes the next action, otherwise, step 2 comes next.

2. The second sensor that is checked is the IR sensor. This sensor is used to detect fire or dangerous pre-fire conditions. The sensor has a significantly higher range than the temperature sensor and will allow the system to 'see' down the power line itself. If a fire or dangerous conditions, like electrical arcing, are detected, step 3 describes the process of operator notification, otherwise, the system will listen for incoming alerts and messages.
3. If a sensor node's IR or temperature sensors detect fire, the node must relay that information back to the operator. Because this system will be deployed across long stretches of remote power lines, not every node will be able to directly communicate with the main computer and operator. The node will send an alert containing key information, like the original sensor identification number and which sensor was triggered, to nearby nodes using LoRa. The nearby nodes will then act as information relays and pass on the alert information until the main computer is reached.
4. Wireless information transmission is not completely reliable and losing a fire alert could be catastrophic. Once a fire has been detected, the original sensor node will continue to send alerts until another node acknowledges that the alert has been received. Once the first node has been acknowledged, it will begin listening for alerts originating from other sensor nodes.

Every node's secondary objective is to act as an information relay in a chain of sensor nodes that ends at the operator's computer:

1. The sensor node will begin listening for incoming fire alerts. If information is read in, the node will have to parse the message to determine if it is an acknowledgement, which it can ignore, or a fire alert. If nothing is detected, the node will go to sleep.
2. If the sensor node has received a fire alert, it will first acknowledge the previous sensor node. Then, the receiving sensor node will begin broadcasting the alert it received to the sensors closer to the main computer.
3. The node will continue to transmit the alert until it too is acknowledged by another node.
4. Once the node has relayed the incoming message, it will go to sleep until the next cycle begins.

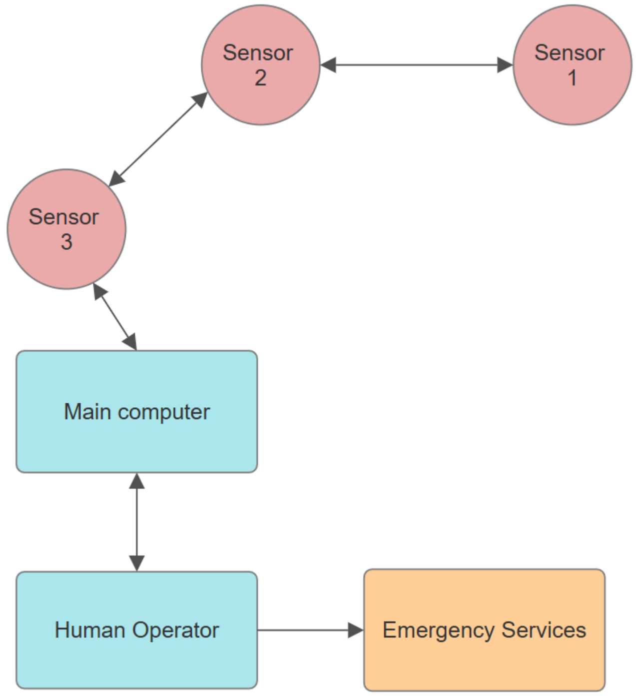


Figure 2. Full system diagram

Figure 2 is an example of what a deployed system may look like. A deployed system consists of several critical components: sensor nodes, a main computer, and a human operator. The sensors are responsible for monitoring the power lines, so they will be placed on the tops of electrical poles facing down the power line. For full coverage, a sensor should be placed on every electrical pole on a section of power line. The main computer should be placed inside of electrical substations to allow for operation by a human or access to the internet so that any alerts can be collected on a website or user interface. The human operator must also either be at the main computer or monitoring the online alert service so that if a fire alert happens, they can contact emergency services. Full electrical grid coverage would be a sensor node on every electric pole and a computer with internet access at every substation.

Technical Description

The technical description will be divided into the main technical challenges that our product faces. These are (1) implementing the temperature and IR flame sensor, (2) creating a large power supply for long term use, and (3) designing a reliable and fast communication system between nodes.

1. Hardware Overview

Below is a block diagram of the hardware system for the SFM.

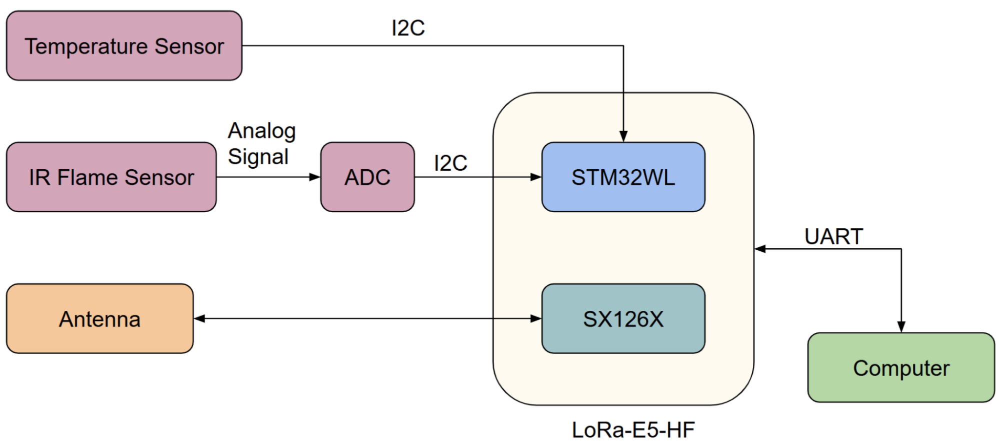


Figure 3. Sensor block diagram

a. Microcontroller

The microcontroller used for this project is the LoRa-E5-HF LoRAWAN module designed by Seeed Technology Co. It combines STM's STM32WLE5JC and LoRa's SX126X chip. It is a low cost, low power microcontroller that allows for ultra long distance communication. The microcontroller's pin-out can be seen in Figure 4.

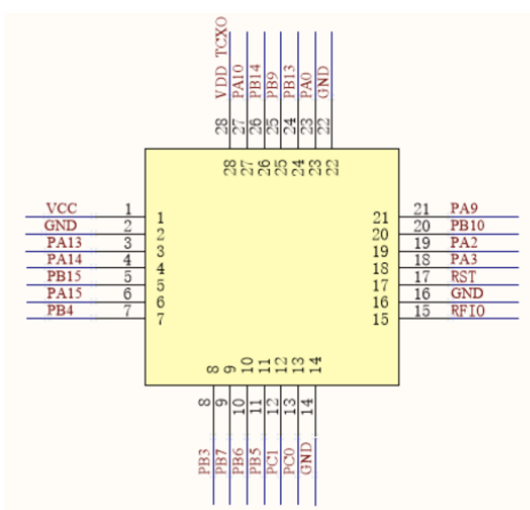


Figure 4. LoRa-E5-HF Pinout

Pins PB6 and PB7 make up the first I2C lines, while PA14 and PA15 make up the I2C2 lines. Pins PA2 and PA3 can be used for UART communication, which we use to send information to an operator's computer. RFIO is used for RF input and output.

b. Sensor Integration

Two sensors were used to detect a fire on or near the power line. The first is a Kemet Yageo QFC Analog TO39 IR flame sensor using a 5.00 µm cut-on filter [8]. The second is a 10-bit digital temperature sensor [9]. Both communicate with the microcontroller using I2C protocol. It should be firstly noted that both devices operate between -45 °C and 85 °C, which will be sufficient for our outdoor device. It should also be noted that the IR sensor and flame sensor are on two different I2C buses. This allows for continuous sampling on both lines.

Gasses of high temperature emitted by fires flicker and emit unique wavelengths in the IR frequency range. Kemet's broadband sensor passes frequencies above 5.0 µm and filters the rest out. IR waves have a longer wavelength than the visible light spectrum, so there is no worry of propagation in a low obstruction area like the ones cleared for power lines. The sensor outputs a signal centered at half of the supply rail, which for this board is 3.3V. The output signal then is filtered and amplified through a two-stage active pass band filter. Flames typically flicker at a rate of 2 - 4 Hz, so the amplification stages have a bandpass designed accordingly. The individual filters have a roll-on frequency *F1*, roll-off frequency *F2*, and gain *A* shown below.

$$F_1 = \frac{1}{2\pi \times 22\ k\Omega \times 4.7\mu F} = 1.53\ Hz$$

$$F_2 = \frac{1}{2\pi \times 750\ k\Omega \times 47nF} = 4.51\ Hz$$

$$V_{out} = V_{in} \times \frac{R_f}{R_g}$$

$$V_{out} = 1.65 \times \frac{750\ k\Omega}{22\ k\Omega}$$

$$A = 57$$

With two amplifiers cascaded together, this gives a total gain of *A* = 3,250. The amplified signal is fed into a differential ADC with an I2C interface. The ADC was chosen with simplicity of soldering in mind. The analog sensor breakout board was designed late in the semester as a means of pivoting away from a digital IR sensor, and therefore was not able to be professionally soldered. The ADC used, in a standard SOT-23-6 package not only was easy to solder but could also be soldered onto an earlier designed breakout board for quick and easy testing. To make the differential input of the ADC work with our circuit, Vin- was biased to 1.65. This way, the ADC could sample all values of the signal at the output of the amplifiers. The ADC can then be accessed as a standard I2C device.

The 110° field of view (FOV) brings up a possible concern of a fire at the node, where the field of view is somewhat narrow. However if the sensor is facing directly down the electrical lines, it should notice any fire on or near the electrical wires. If it does not, that is where the temperature sensor becomes important.

For a fire on the pole or out of the FOV of the IR sensor, the temperature sensor can detect when there might be a fire. A temperature higher than 65 °C (150 °F) could hypothetically trigger a notification to the main computer through other nodes. The temperature sensor uses the negative temperature coefficient in diodes to measure temperature. As the temperature increases, so too does Vt. In transistors, this creates an increase in V_{BE}. The difference in currents through two transistors can be measured as a ratio when input into a chopper amplifier. The output voltage is converted to a 10 bit digital output that can be read by the MCU. The temperature sensor will be laid out as per the schematic on page 7 of reference 9.

c. Power Circuitry

The power circuitry can be generalized by the diagram in Figure 5.

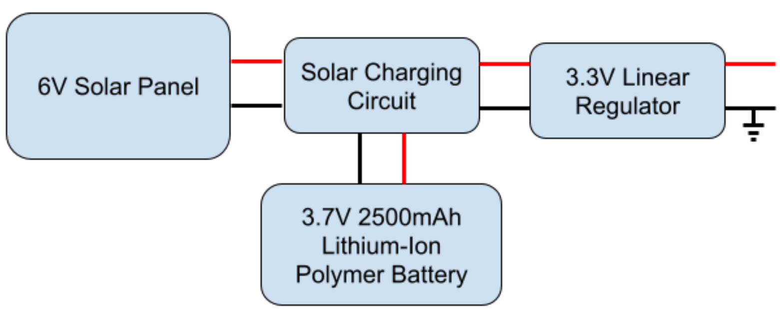


Figure 5. Power Circuitry Block Diagram

The initial proposal for this project used AAA batteries to power the SFM system. Our project, however, being on outdoor power lines that are cleared of trees, was perfect for a solar panel.

The STM32 current draw depends on whether or not it is sending a signal. When not sending a signal, and only receiving, the microcontroller draws about 7.5mA of current, measured experimentally. We expect to send a signal once a day to check if the system is still on, and otherwise only to communicate if a fire is detected. This communication takes seconds, and while the microcontroller draws more current while doing so, it can be neglected in calculations for battery power. Battery Life is calculated below.

$$\text{Battery Life} = (2500\ \text{mAh} / 7.5\ \text{mA}) \simeq 333\ \text{hours}$$

The battery can be used without a charge on this system for 2 weeks. On top of this, a solar panel and solar charger are added to recharge the battery. The 0.3W, 6V solar panel mounts on the enclosure and connects into the Adafruit 1.5A Li-Ion solar charger seen in the figure below.

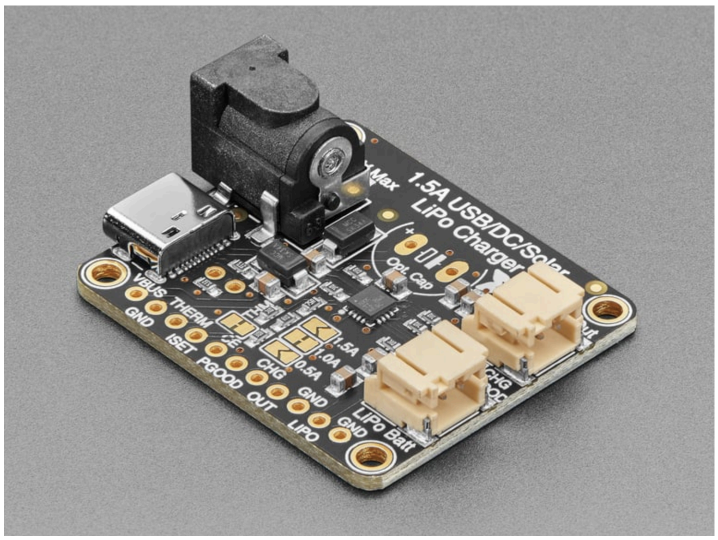


Figure 6. Adafruit Solar Charging Circuit

The solar charger prioritizes the solar power over battery power whenever the load draws current, and charges the battery with excess power. There is therefore no worry for the battery to discharge.

d. Board Layouts, BOMs, and Other Consideration

The hardware for the SFM was split into two boards to be able to change the flame sensor if needed, and to give it freedom of motion within the enclosure, so as to be able to choose its field of view. The schematic and 3D view of the main board can be seen in Figures 7 and 8.

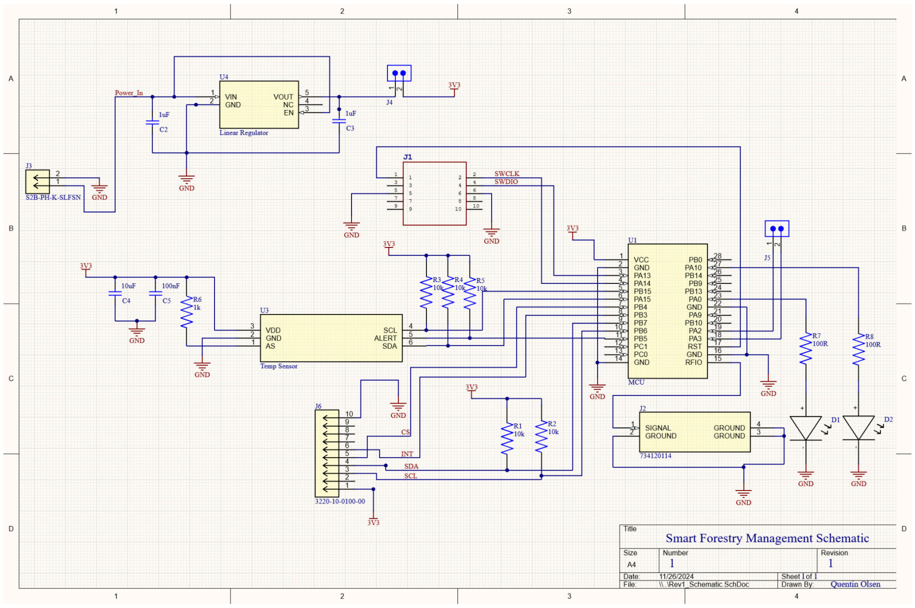


Figure 7. Schematic of Main Board

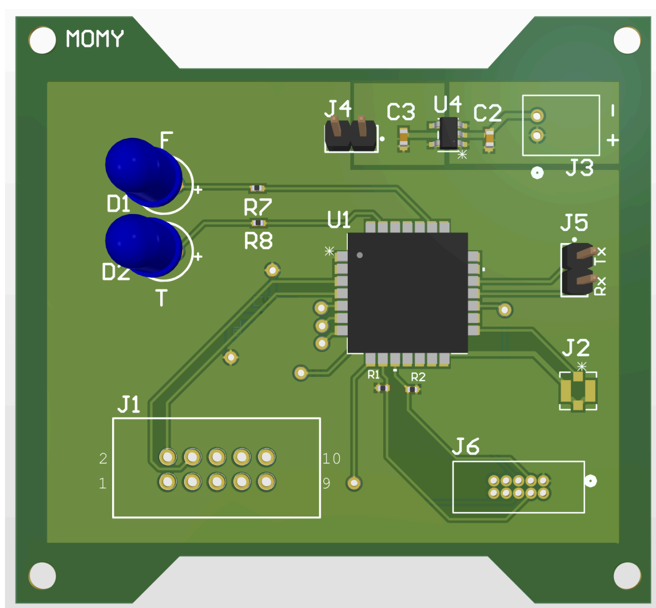


Figure 8. 3D View of Main Board

The main board regulates power, and powers the microcontroller. It is also on this board that the ST-Link, which flashes the microcontroller with code, can be plugged in (J1). The antenna also must have ease of motion, and therefore an sma cable clips onto a u.fl connector (J2). J4 is used to test current draw on the system, and J5 gives access to the microcontroller Rx and Tx UART pins. J3 connects to the solar charger for power. Two red LEDs light up whenever the board detects fire. The temperature sensor is on the back of the board. A cable on J6 connects to power, ground, and I2C lines for a modular IR sensor. The BOM for the main board can be seen in Figure 9.

Quantity	Reference Designators	Value	Manufacturer Part Number	Manufacturer
1	U1	Microcontroller	317990687	Seeed Technology Co., Ltd
1	U3	Temperature Sensor	AD7414ARTZ-0500RL7	Analog Devices Inc.
1	U4	3.3V Linear Regulator	MIC5504-3.3YM5-TR	Microchip Technology
1	J1	2x5 2.54 pitch	TST-105-01-S-D	Samtec Inc.
1	J2	u.fl Connector	C503B-RAN-CZ0C0AA2	Molex, LLC
1	J3	JST 2 pin Connector	S2B-PH-K-S	JST Sales America Inc.
2	J4, J5	Test Points	61300211121	WURTH ELECTRONICS INC
1	J6	2x5 1.27 pitch	3220-10-0100-00	CNC TECH LLC
2	D1, D2	RED LED	C503B-RAN-CZ0C0AA2	CREE LED
2	C5	100 nF	885012206071	Wurth Elektronik
2	C2, C3	1 uF	06035C105MAT2A	Kyocera AVX
1	C4	10 uF	0603YD106MAT2A	Kyocera AVX
5	R1, R2, R3, R4, R5	10 kΩ	RC1005F103CS	Samsung Electro-Mechanics
1	R6	1 kΩ	RC0402JR-071KL	Yageo
2	R7, R8	100 Ω	ERJ-2RKF1000X	Panasonic

Figure 9. BOM for Main Board

The IR sensor breakout board's schematic, 3D view, and BOM are given below.

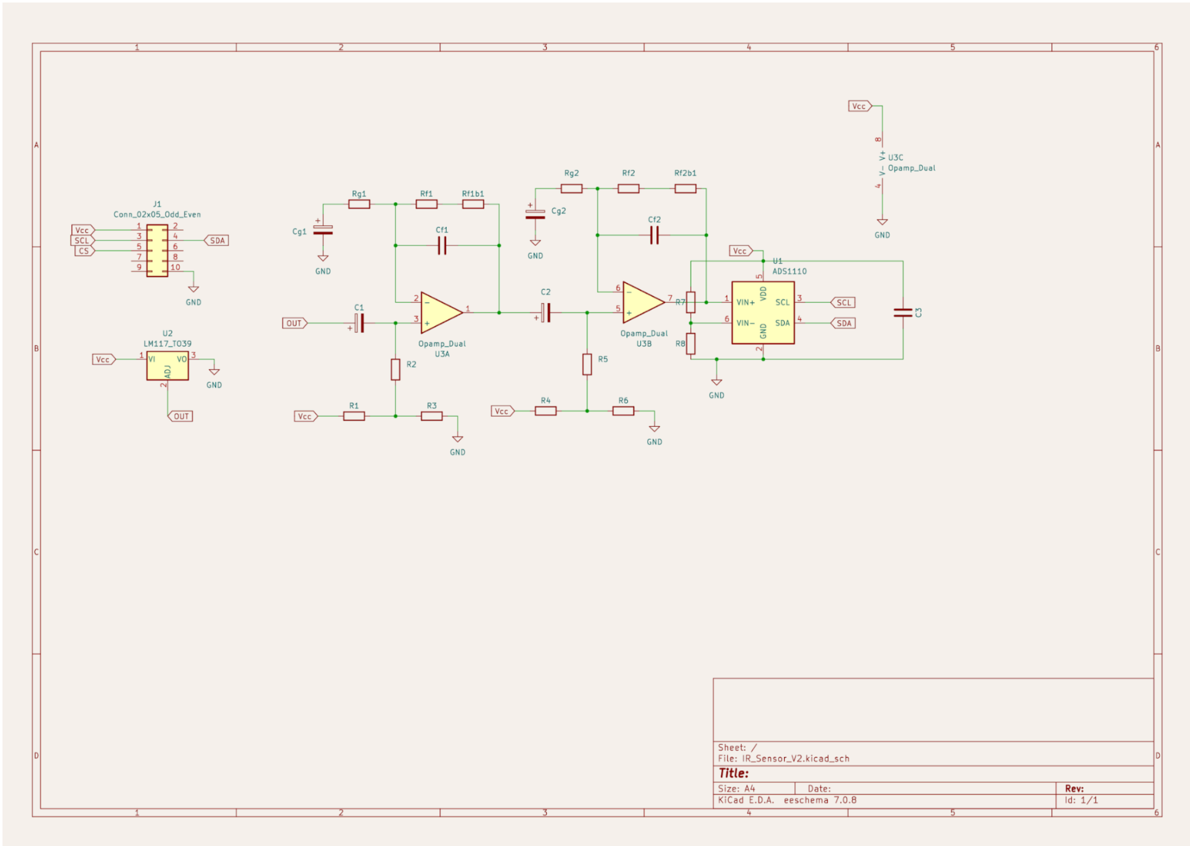


Figure 10. Schematic of IR Breakout Board

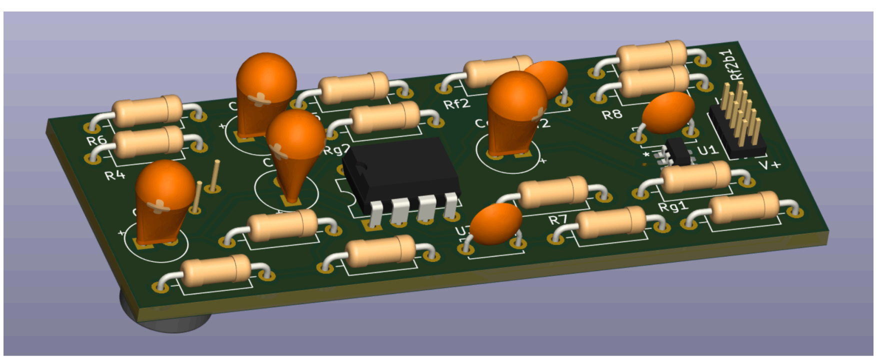


Figure 11. 3D View of IR Breakout Board

Quantity	Reference Designators	Value	Manufacturer Part Number	Manufacturer
1	U1	ADC w/ I2C interface	ADS1110A0IDBVR	Texas Instruments
1	U2	IR Flame Sensor	USEQFCSA500100	Yageo Kemet
1	U3	Dual Op-Amp	LMC6482IN	Texas Instruments
1	J1	2x5 1.27 pitch	TST-105-01-S-D	Samtec Inc.
4	C1, C2, Cg1, Cg2	4.7uF		
8	R1, R2, R3, R4, R5, R6, Rg1, Rg2	22kΩ		
2	Rf1, Rf2	68kΩ		
2	Rf1b1, Rf2b1	680kΩ		
2	R7, R8	39kΩ		
2	Cf1, Cf2	4.7nF		
1	C3	1 uF		

Figure 12. BOM for IR Breakout Board

A picture of the hardware system is shown in Figure 13.

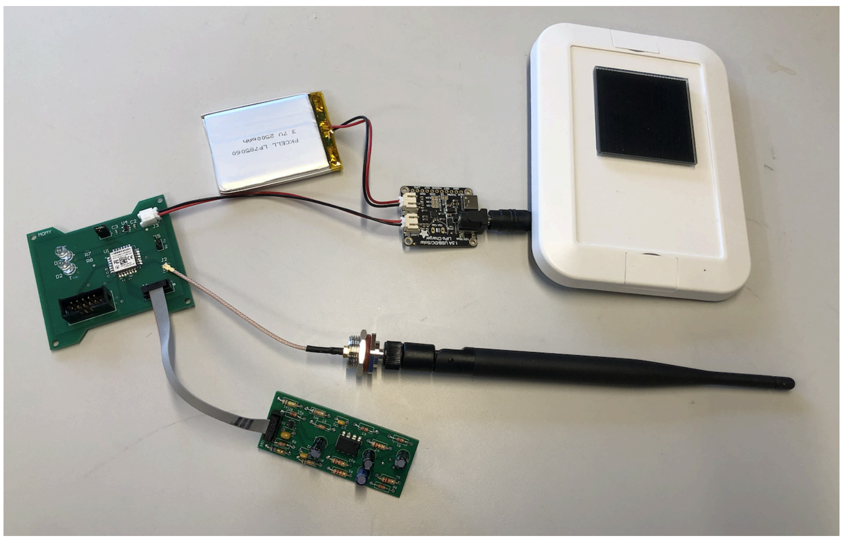


Figure 13. SFM Hardware Out of Enclosure

2. Communication System

Each sensor node will be using the LoRa-E5-HF LoRaWAN module designed by Seeed Technology Company. Long Range (LoRa) is a chirp spread spectrum modulation method that allows for highly reliable communication over long distances. LoRaWAN is the MAC layer that is built on top of LoRa [11]. LoRa was chosen as the system's communication method because it offers long range communication, which is useful for placing sensor nodes in isolated locations, and low power consumption, which aids in battery conservation. According to the LoRa-E5-HF datasheet, in an open environment, the LoRa-E5-HF module has a transmission distance of 10 kilometers, the sleep current required by the module is 2.1uA, the operational current with an active transmitter and MCU is 111mA, and the operational current with an active receiver and MCU is 6.7mA [12].

When designing our system's payload, there are several key pieces of information and ideas that must be designed around. Because the alert system revolves around sending an alert and a following acknowledgement, there are two different packet structures with different lengths and purposes. For an alert, the necessary information is the original sensor ID, the relay sensor ID, and the type of fire detected. For an acknowledgement, the necessary information is the previous relay sensor's ID and the type of fire detected.

By searching through a GIS database of PG&E's power lines in California, it was determined that the longest length of power line without an intermediate substation is 94 miles (151279 meters) [13]. The IR sensor datasheet claims a functional range of 80 meters. Using these two values, the required number of sensors can be calculated:

$$Num\ Sensors\ = \frac{151279m\ Line\ length}{80m\ Sensor\ spacing} = 1891\ sensors$$

Bits to represent each unique sensor number:

$$2^{x} \geq\ 1891 \rightarrow 2^{11}\ =\ 2048 \rightarrow 11\ bits$$

Now that the number of sensors is known, the transmission payload can be designed with the fire alert type and sensor count in mind. Figure 4 shows both the alert and acknowledgement packet structures.

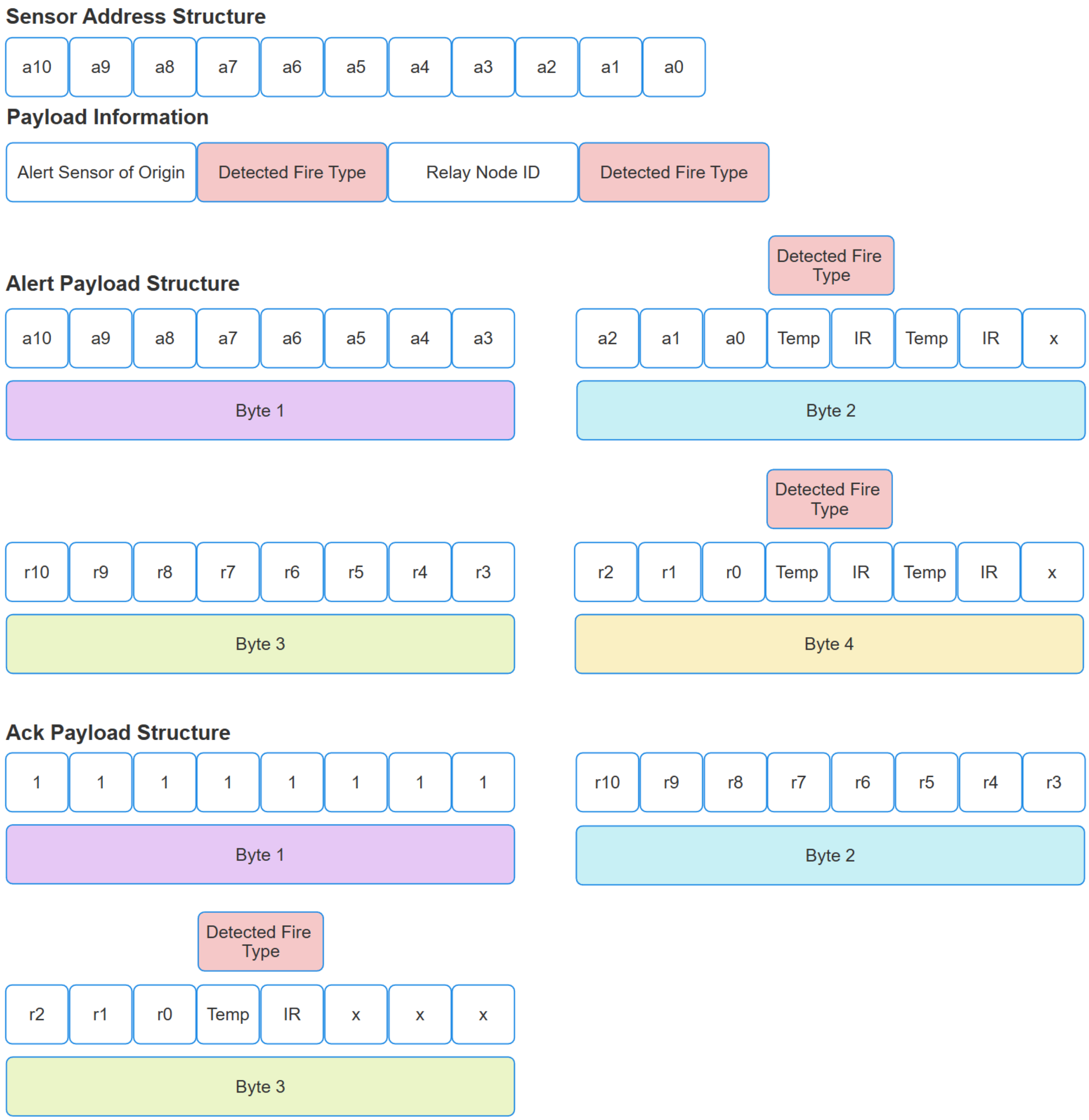


Figure 14. Payload Structure Diagram

The alert payload has three main components: the sensor of origin, the relay node, and the detected type of fire. The sensor count calculation above is why each sensor address is 11 bits long. The first part, the sensor of origin (a10-a0), allows for the main computer to determine where the fire is located, even if the alert is passed along many sensors to reach the main computer. The relay node ID (r10-r0) is primarily used when generating the acknowledgements to ensure that the correct sensor is acknowledged and the message has been passed on; a sensor that is broadcasting an alert will continue to broadcast until an acknowledgement matching its sensor ID and detected fire type is received. The fire type is a pair of bits that denote whether the IR or temperature sensor has detected the fire. This is useful because it will give operators an idea of what scene conditions may be like and allows for more reliable acknowledgements. There are four pairs of fire type bits that are duplicated within the message to increase reliability and allow for basic error detection. We have implemented a majority voter system to perform the error detection using the four bit pairs. With four bit pairs, the voter is able to correct one incorrect pair and detect two incorrect pairs. With two incorrect pairs, the voter recognizes an error but cannot decide the correct response, so it will not acknowledge and wait for a retransmission.

When a node detects a fire, it gets set in a state of 'emergency' where it continuously sends out fire alerts. To escape this state, the node listens after every alert for an acknowledgement from the next node in the network. The acknowledgement packet is generated when a listening node receives a fire alert. The acknowledgement packet has three main parts: a key, the sensor that the alert was received from, and the fire type. The beginning key is 0xFF because, given our system requirement of supporting 1891 sensors, there is no sensor that will have 0xFF as its most significant bits. So, having that header means that any sensor node that sees the acknowledgement transmission will know that it is an acknowledgement. The received sensor ID is included so that the acknowledgement is received by the correct sensor. The fire type bit pair is another level of redundancy that ensures that the acknowledgement is being sent to the correct sensor. The acknowledgement has no error checking because the nature of the looping system means that an invalid acknowledgement will not be used and a valid one will be generated. If a sensor in the alarm state receives an invalid acknowledgement, it will simply continue to broadcast until it receives a valid one.

PHY Frame	Preamble	Header	Header CRC	Payload	Payload CRC
Size	Min. 4.25 symbols	2 bytes	2 bytes	Max. 255 bytes	2 bytes

Figure 15. Lora Frame Structure [14]

Figure 5 is an example of a full LoRa packet structure, where the preamble for this project will be 12 symbols. The header, header CRC, and payload CRC are all standard for LoRa. An alert will require the sensor's identification number and the detection method that found a fire. The payload will need to be 4 bytes long and will contain the original sensor ID, the broadcasting sensor's ID, and duplicates of the detected fire type.

In total, the LoRa frame will contain 11.5 bytes or 92 bits. If necessary, adding more information to the LoRa frame is very simple, with a maximum payload of 255 bytes. Making the message as short as possible will reduce power consumption and shorten the amount of time each sensor has to listen for incoming alerts.

The LoRa-E5-HF chip uses the 915 Mhz frequency band [15]. The LoRa module will be configured with a bandwidth of 250 khz and a spreading factor of 7, as both of these settings will reduce the power consumption of the sensor node [16]. Now that the spreading factor and bandwidth have been determined, the bitrate was calculated to be 10.94 kbps [17].

Calculating alert transmission time:

$$t_{transmit} = t_{alert} + t_{ack} = \frac{bits}{bitrate}$$

$$t_{transmit} = \frac{preamble+header+header\ CRC+alert+alert\ CRC}{10940\ bits/sec} + \frac{preamble+header+header\ CRC+ack+ack\ CRC}{10940\ bits/sec}$$

$$t_{transmit} = \frac{12+16+16+32+16\ bits}{10940\ bits/sec} + \frac{12+16+16+24+16\ bits}{10940\ bits/sec} = 16.088ms$$

Given the number of sensors and the elapsed time for sending an alert and proceeding acknowledgement, the total time it would take for a message to travel from one end of the network to the other can be calculated.

$$t_{listen} = 1891\ sensors * 16.088ms = 30.422s$$

3. Physical Enclosure

The physical enclosure is meant to hold the hardware system and keep it ventilated and waterproof. This is what the enclosure from Voltaic shown in Figure 16 provides.

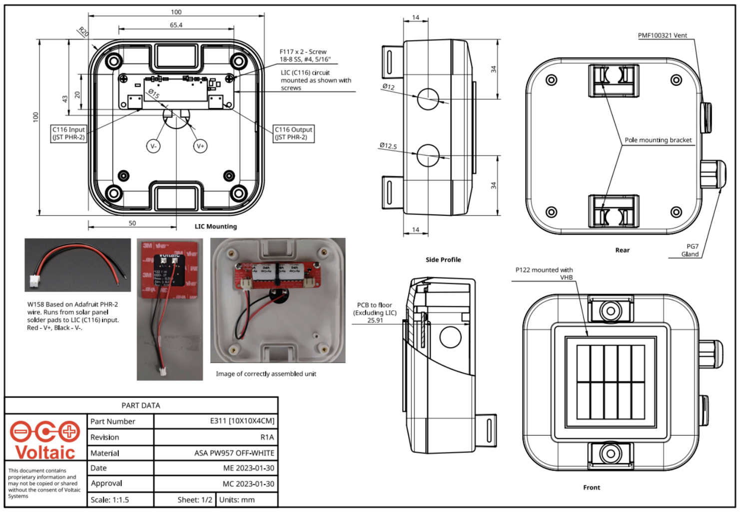


Figure 16. Voltaic Enclosure

The 6V solar panel is stuck to the top and the boards are drilled into the m4 screw holes. To adapt this enclosure to the SFM system, holes were drilled into the side for the flame sensor, with a clear tape over it to keep water out. The PG7 gland was taken off and the hole was expanded to fit the SMA antenna connector. Finally, a battery fastener was glued inside of the enclosure to keep the battery from moving around and unplugging when being deployed.

Unfortunately, Voltaic encountered inventory issues and could only procure the larger size enclosure. The SFM's enclosure can be secured onto any pole as seen in Figure 17.

Figure 17. Voltaic Enclosure On Pole

Testing Plan

The bulk of our early testing was performed on the communication subsystem. This first involved establishing reliable communication between two microcontrollers. We tested this by flashing code to two Wio-E5 Mini development boards and monitoring sent and received data over USB. The Wio-E5 Mini is a development board that contains the LoRa E5 microcontroller that we used in our final project. Once we established that we could send and receive data using the breakout boards, we moved onto testing with our own PCBs. During this initial testing phase, the software was also being further developed for readability and functionality. Once the PCBs had been manufactured, we began testing by sending and receiving signals in the lab. We read the received data using an Arduino Uno and the Arduino Serial Monitor in the absence of a USB connection. At this point in our testing we established that signals could be received and sent by a PCB not powered from a laptop connection. This was confirmed after disconnecting our first prototype, using a portable battery pack, and observing the incoming traffic from another board.

One of the initial redesigns we made as a result of our testing was increasing the power of the batteries. We noticed from testing that the PCBs would sometimes fail to transmit signals after being disconnected from laptop power, even though they could transmit fine when being supplied by a laptop. It was eventually deduced that the transmit power we were using (20 dBm) was too high for the batteries to reliably generate. This led to the decision to use lithium-ion batteries with a higher capacity to allow a higher transmit power.

The communications testing was concluded after the second iteration of our PCBs were manufactured and soldered. We flashed the newest iteration of our code and tested the boards in a controlled environment. Following this, we went outside to test parameters like maximum possible range, signal strength, and signal-to-noise ratio as a function of transmit power. We noticed at this stage that the cold weather might also be a long-term problem for systems using battery power, but at this stage no effective solution could be reached.

Testing the temperature sensor was relatively straightforward. Initial testing involved looking at the output of the sensor under different conditions using an Arduino Uno and the Arduino Serial Monitor. Once an understanding had been established of how to communicate and read data from the sensor, code was written to communicate with the sensor from our microcontroller. Following this, testing was done to determine a reasonable threshold to consider a fire-emergency. This mostly involved trial and error of changing a single threshold value and observing the sensitivity of the system.

The most challenging part of the project to test was the IR flame sensor. Initial testing was performed on a breakout board purchased from Yageo Kemet for the purpose of prototyping. We struggled initially to interact with the sensor in a basic way, including resetting the sensor, reading data from the sensor, and changing parameters like gain and filtering. This was partly because the documentation was poor and often confusingly written. Once we were able to consistently read data from the sensor, we attempted to determine some threshold values that might indicate a fire was detected. This ultimately proved challenging. Over the course of several weeks we observed the output of the sensor under fire conditions and tried to find a consistent pattern in the output. During these weeks, all possible combinations of gain, sampling rate, and filtering were tried and communication software was rewritten in an attempt to get more sensible data. After failing for multiple weeks we decided that we needed to pivot and move to a different sensor. Data could be read from the sensor and nothing appeared to be broken or causing errors, but no pattern could ever be found and the data being read from the IR sensor was useless.

After deciding to abandon this sensor we pivoted to an analog IR module. This pivot involved a significant amount of work because an entirely new board needed to be developed with an ADC for the analog sensor. After the board was manufactured and soldered, we initially tested the sensor by observing the analog output using an oscilloscope. We looked at the waveform generated when the sensor was idle and when the sensor was presented with a flame. We also saw how the sensor responded to quick movements at close range, and how sensitive the sensor was to flames from a long distance. After concluding our analog testing, we were satisfied that the sensor had a much clearer pattern to its output and moved onto testing the board's digital output. Similar to the temperature sensor, this involved reading the digital output under different conditions and deciding on a threshold value based on these observations.

Our final testing deviated noticeably from our initial test plan. The most significant changes came from the difficulties we had with the IR sensor. Getting the IR sensor to produce reliable data was difficult, and as a result of this, much of the testing we had planned for the IR sensor did not take place. We were not able to test the IR sensor under different weather conditions or using different sources of fire and heat. We performed basic testing of the sensor at different ranges, but did not collect enough data to make any determinations about effective range. With more time we would have liked to more rigorously test the IR sensor.

Physical Constraints

Design and Manufacturing Constraints

The finished product requires an IR sensor, temperature sensor, STM microcontroller, 915 MHz antenna, solar panel, solar charging circuit, and a linear regulator to be assembled. The project also requires various basic electrical components including capacitors, resistors, and lithium ion batteries. The primary concern for part availability is the IR sensor, which has a limited number of units in stock on Newark. Besides the IR sensor, every component is readily available and has hundreds of units in stock. All software used to program the microcontroller was free and is therefore not a limiting factor.

The SFM must also fit into an enclosure that was designed externally. The boards were designed to screw into the enclosure. This physical size of the enclosure was a significant constraint on our hardware system.

Tools Used for Project

- Altium
- DC Power Source
- Oscilloscope
- Arduino IDE
- Arduino Uno

- VSCode
- Zephyr RTOS
- STM32CubeProgrammer
- ST-Link V2
- ReactJS

A power source and an oscilloscope were used to analyze the analog signal from the IR sensor and confirm the sensor was functioning correctly. The Arduino IDE and an Arduino Uno were used throughout the development process for testing and debugging. We did not design our boards with USB ports so print debugging was performed using an Arduino Uno, the Arduino Serial Monitor, and UART connections. VSCode was used as the primary IDE for software development. Zephyr was the RTOS (real time operating system) we chose for our microcontroller and was used to handle low-level functionality, including the sending and receiving of wireless signals and setup of some peripherals. The STM32CubeProgrammer was primarily used to disable write protections on the LoRa E5 microcontrollers, which we learned early on in the project come shipped with protections that prevent reprogramming. The ST-Link V2 was used to communicate with our microcontrollers and reprogram them when necessary.

Cost Constraints

The total estimated cost of a single prototype is 170$. This includes board manufacturing, assembly, and shipping from many different sources. The unit cost is found to reduce to $17 when ordering for 10,000 parts. For this reason we do not consider cost to be a significant concern or a limiting factor. Low cost of production will also benefit our customers, since our product is intended to be purchased in large quantities. See the Cost section for more detailed information.

Steps Needed to Create Viable Production Version

To make a viable production version of our prototype, the most important steps we would need to take would be additional testing. We have data focusing on range, signal strength, and signal-to-noise ratio as a function of transmit power, but very little data concerning range and accuracy of each of our sensors. We also have little data focusing on rates of false positives or failed detections. All of this data would be important to a customer and would inform us about the viability of our product. After collecting this data, changes could be made by adding or exchanging sensors to increase range, accuracy, and reliability. To create a viable production version of our product, we would also need to design a waterproof case that more closely suits our needs, properly fits our boards and internal parts, and costs less. The new enclosure would have waterproof windows for our IR and temperature sensors and would be rigorously tested to ensure it could withstand harsh conditions. Finally, to make our product viable we would determine an effective way to deploy our sensors. An updated data interface would be designed for scale and ease of use, accounting for the thousands of sensors being deployed. A barcode, unit number, or other identification would be introduced to quickly register a unit into the data interface.

Societal Impact

Public Health, Safety, and Welfare

This product addresses critical public health and environmental challenges caused by forest fires. Between 2016 and 2020, an average of 88% of forest fires in the U.S. are human-caused, often originating from equipment failure and sparks from power lines [17]. In 2022, outdoor fires, including wildfires, account for 3.1% of all fire-related deaths and 9.5% of injuries in the U.S. [18]. These statistics highlight the severe public health risks associated with forest fires, as well as the role power companies play in contributing to these incidents. Forest fires also generate 40% of particulate matter in the air, a pollutant linked to respiratory and other health issues [19].

From an environmental perspective, forest fires cause widespread devastation, destroying ecosystems, displacing wildlife, and contributing significantly to economic losses. The Joint Economic Committee estimates that wildfires cost the U.S. up to $893 billion annually, primarily from watershed pollution and property damage [20]. Given these factors, this product aligns with the urgent need to mitigate wildfire risks and their associated public health and environmental impacts.

The product itself minimizes its environmental footprint. With a durable construction that withstands harsh conditions, it requires minimal maintenance and operates with low power consumption. While the initial prototype uses AAA batteries, the final product incorporates solar panels for power. This design ensures the system’s environmental impact remains low while maximizing operational longevity and sustainability.

Ethical and Environmental Considerations

In addition to protecting public health and the environment, this product raises several ethical considerations that are carefully addressed. One important issue is the potential for electronic waste at the end of the device's lifespan. The use of solar panels helps mitigate this concern, as each device is designed to last at least 10 years before any sensor or PCB requires replacement.

The potential impact on wildlife is also considered. The device mounts on electrical poles, which are already part of the environment and do not introduce significant additional hazards to wildlife. The design avoids sharp edges, exposed wires, or other elements that could harm animals, and it operates with minimal noise and emissions to reduce disturbance.

By addressing these issues, this project demonstrates a commitment to ethical design and implementation. It mitigates risks associated with its operation while considering the broader impacts of its development and lifecycle, ensuring its benefits outweigh any potential harm to stakeholders or the environment.

External Standards

During the design of our project, several external industry standards were considered and incorporated to ensure compliance, safety, and reliability. These standards guided the design and implementation of the system's wireless communication and PCB design.

Wireless Communication Standards

The device uses a LoRa module operating at 915 MHz, which is classified as a radio frequency device under the Federal Communications Commission (FCC) regulations. Specifically, Title 47, Chapter I, Subchapter A, Part 15, Subpart C of the FCC's Code of Federal Regulations governs intentional radiators like our device. The following sections were relevant to our project:

Section §15.247 provides the following regulations for intentional radiators [21]:

1. In any 100 kHz bandwidth outside the operating frequency band, the radiated power must be at least 20 dB below the peak power within the band.
2. The minimum 6 dB bandwidth for digitally modulated systems must be at least 500 kHz.
3. The power spectral density transmitted to the antenna must not exceed 8 dBm in any 3 kHz band during continuous transmission.

Section §15.249 provides the following regulation for operation in the 902-928 MHz band [22]:

1. Emissions outside the specified frequency bands must be attenuated by at least 50 dB below the fundamental frequency.
2. At a distance of 3 meters, the maximum permitted field strength is 50 mV/m for the fundamental frequency and 500 µV/m for harmonics.

Section §15.249 also includes the table below, which provides limits for the maximum field strength of the fundamental frequency and of harmonics:

Fundamental frequency	Field strength of fundamental (millivolts/meter)	Field strength of harmonics (microvolts/meter)
902-928 MHz	50	500
2400-2483.5 MHz	50	500
5725-5875 MHz	50	500
24.0-24.25 GHz	250	2500

Figure 18. Field Strength Table

Compliance with these standards was ensured by carefully configuring the LoRa module, minimizing out-of-band emissions, and adhering to power density limits. This allows the device to operate lawfully and interference-free in the 915 MHz ISM band.

Printed Circuit Board (PCB) Design Standards

The design and manufacturing of the PCBs followed the guidelines set forth by the Institute for Printed Circuits (IPC), specifically the IPC-2221 standard, which is the generic standard for PCB design [23]. Key considerations included:

- Track and Pad Spacing:
    - Adequate spacing was maintained to prevent short circuits and arcing, adhering to the IPC-2221 recommended clearances based on voltage and environmental conditions.
- Trace Width for Current Carrying Capacity:
    - Trace widths were calculated to ensure they could handle the expected current loads without excessive heating, using IPC-2221 standards as a guide.
- Component Placement and Assembly:
    - Parts were spaced to facilitate manufacturability and repairability, minimizing the risk of solder bridges or mechanical stress during operation.

Impact on Project

These external standards influenced both the wireless communication configuration and the physical PCB layout. By following FCC regulations, the wireless communication system was optimized to balance long-range capabilities with low power consumption while maintaining compliance with emission limits. Similarly, adhering to IPC standards ensured the PCBs were robust, reliable, and suitable for the environmental conditions they will face during deployment.

Overall, these industry standards were vital for ensuring the system's performance, longevity, and regulatory compliance. By adhering to these guidelines, the project team was able to create a safe and efficient product that meets industry norms and stakeholder expectations.

Intellectual Property Issues

To assess the patentability of our Smart Forest Management System, we analyzed its features in comparison with three existing patents that have similar goals. The first patent, *Forest Fire and Wildfire Detection System* [24], describes a system that uses ionization, smoke, and temperature sensors in outdoor enclosures to detect fire conditions. This system transmits data through telemetry or cellular networks to a central command center. Our project differentiates itself by employing IR flame detectors and LoRa communication. The use of LoRa provides long-range, low-power transmission, making it ideal for remote deployment, while the design is specifically tailored for real-time monitoring of power lines, addressing a distinct application not covered by this patent.

The second patent, *Forest Surveillance and Monitoring System for Early Detection of Forest Fires* (US5734335), details a monitoring system that utilizes infrared sensors and video cameras for fire detection, with data transmitted via telemetry to a central processing system [25]. While both systems use infrared sensors, our project diverges in key aspects. It integrates IR flame detectors with temperature sensors for increased precision and situational awareness, specifically for monitoring electrical poles. Additionally, our reliance on LoRa communication, rather than telemetry, offers a more energy-efficient and cost-effective solution for deployment in forested and remote areas. These features establish a clear functional and technological distinction between our system and this patent.

The third patent, *Forest Fire Extinguisher and Prevention System and Method* (20230256275), combines fire detection with an extinguishing mechanism that deploys automatically in response to detected fires [26]. In contrast, our project is solely focused on early detection and reporting. This streamlined approach makes our system simpler and more cost-effective while catering specifically to utility companies managing electrical poles in high-risk areas. Unlike the broader scope of this patent, our system's design is narrowly focused on its intended use case, which further distinguishes it.

Our project introduces several unique features that establish its patentability. These include the integration of IR flame and temperature sensors for precise fire detection on power lines, the use of LoRa communication for long-range and low-power data transmission, and a modular, pole-mounted design optimized for deployment by utility companies. These innovations provide significant advancements over the claims in the referenced patents, particularly in the context of power line fire monitoring. While our project shares some broad goals with these patents, its novel application, focused design, and technological integration clearly differentiate it. This ensures the system is likely patentable, as it meets the criteria for novelty and non-obviousness while addressing a specific and unmet need in fire hazard monitoring for electrical infrastructure.

Timeline

WBS NUMBER	TASK TITLE	Group Members	START DATE	DUE DATE	Week 1 9/9-9/15					Week 2 9/16-9/22					Week 3 9/23-9/29					Week 4 9/30-10/6				
					M	T	W	R	F	M	T	W	R	F	M	T	W	R	F	M	T	W	R	F
1	Important Dates																							
1.1	Project Proposal	ALL	9/12/2024	9/20/2024																				
1.2	Fall Break	ALL	10/14/2024	10/15/2024																				
1.3	Midterm Design Review	ALL	10/10/2024	10/17/2024																				
1.4	Thanksgiving Break	ALL	11/27/2024	11/30/2024																				
1.5	Final Report	ALL	11/29/2024	12/6/2024																				
1.6	Demo Day	ALL	12/9/2024	12/9/2024																				
2	Components/Research																							
2.1	Order Communicaiton Parts	Sean/Nathan	9/12/2024	9/18/2024																				
2.2	Order PCB Parts	JJ/Quentin	9/12/2024	9/18/2024																				
2.3	Order Microcontroller	ALL	9/12/2024	9/18/2024																				
3	PCB																							
3.1	Design Schematic Layout	Quentin	9/23/2024	10/8/2024																				
3.2	Prototype/Sensor Testing	Quentin/JJ	10/9/2024	11/8/2024																				
3.2.1	Power Design	Quentin	10/25/2024	11/15/2024																				
3.2.2	Final Board Iteration	Quentin/JJ	10/25/2024	11/26/2024																				
3.3	Final Testing	Quentin/JJ	11/4/2024	11/26/2024																				
4	Communications																							
4.1	LoRa Basic Communication	Sean/Nathan	9/23/2024	10/18/2024																				
4.2	Sensor Data Communication	Sean/JJ	10/9/2024	11/8/2024																				
4.3	Mesh Node Communication	Sean/Nathan	10/29/2024	11/26/2024																				
5	Front End Software																							
5.1	Design Front End Interface	JJ	9/30/2024	10/11/2024																				
5.2	Integrate the Input of Real Data	JJ	11/18/2024	12/2/2024																				

Figure 19. Original Gantt Chart Weeks 1-4

WBS NUMBER	TASK TITLE	Group Members	START DATE	DUE DATE	Week 1 9/9-9/15	Week 2 9/16-9/22	Week 3 9/23-9/29	Week 4 9/30-10/6
1	Important Dates							
1.1	Project Proposal	ALL	9/12/2024	9/20/2024				
1.2	Fall Break	ALL	10/14/2024	10/15/2024				
1.3	Midterm Design Review	ALL	10/10/2024	10/17/2024				
1.4	Thanksgiving Break	ALL	11/27/2024	11/30/2024				
1.5	Final Report	ALL	11/29/2024	12/6/2024				
1.6	Demo Day	ALL	12/9/2024	12/9/2024				
2	Components/Research							
2.1	Order Communicaiton Parts	Sean/Nathan	9/12/2024	9/18/2024				
2.2	Order PCB Parts	JJ/Quentin	9/12/2024	9/18/2024				
2.3	Order Microcontroller	ALL	9/12/2024	9/18/2024				
3	PCB							
3.1	Design Schematic Layout	Quentin	9/23/2024	11/13/2024				
3.2	Prototype/Sensor Testing	Quentin/JJ	10/9/2024	12/3/2024				
3.2.1	Power Design	Quentin	10/25/2024	11/25/2024				
3.2.2	Final Board Iteration	Quentin/JJ	11/11/2024	11/25/2024				
3.3	Final Testing	Quentin/JJ	11/26/2024	12/6/2024				
4	Communications							
4.1	LoRa Basic Communication	Sean/Nathan	9/23/2024	10/18/2024				
4.2	Sensor Data Communication	Sean/Nathan	10/15/2024	12/3/2024				
4.3	Mesh Node Communication	Sean/Nathan	11/11/2024	11/28/2024				
5	Front End Software							
5.1	Design Front End Interface	JJ	9/30/2024	10/4/2024				
5.2	Integrate the Input of Real Data	JJ	11/27/2024	12/4/2024				

Figure 20. Final Gantt Chart Weeks 1-4

WBS NUMBER	TASK TITLE	Group Members	START DATE	DUE DATE	Week 5 10/7-10/13	Week 6 10/14-10/20	Week 7 10/21-10/27	Week 8 10/28-11/3
1	Important Dates							
1.1	Project Proposal	ALL	9/12/2024	9/20/2024				
1.2	Fall Break	ALL	10/14/2024	10/15/2024				
1.3	Midterm Design Review	ALL	10/10/2024	10/17/2024				
1.4	Thanksgiving Break	ALL	11/27/2024	11/30/2024				
1.5	Final Report	ALL	11/29/2024	12/6/2024				
1.6	Demo Day	ALL	12/9/2024	12/9/2024				
2	Components/Research							
2.1	Order Communicaiton Parts	Sean/Nathan	9/12/2024	9/18/2024				
2.2	Order PCB Parts	JJ/Quentin	9/12/2024	9/18/2024				
2.3	Order Microcontroller	ALL	9/12/2024	9/18/2024				
3	PCB							
3.1	Design Schematic Layout	Quentin	9/23/2024	10/8/2024				
3.2	Prototype/Sensor Testing	Quentin/JJ	10/9/2024	11/8/2024				
3.2.1	Power Design	Quentin	10/25/2024	11/15/2024				
3.2.2	Final Board Iteration	Quentin/JJ	10/25/2024	11/26/2024				
3.3	Final Testing	Quentin/JJ	11/4/2024	11/26/2024				
4	Communications							
4.1	LoRa Basic Communication	Sean/Nathan	9/23/2024	10/18/2024				
4.2	Sensor Data Communication	Sean/JJ	10/9/2024	11/8/2024				
4.3	Mesh Node Communication	Sean/Nathan	10/29/2024	11/26/2024				
5	Front End Software							
5.1	Design Front End Interface	JJ	9/30/2024	10/11/2024				
5.2	Integrate the Input of Real Data	JJ	11/18/2024	12/2/2024				

Figure 21. Original Gantt Chart Weeks 5-8

WBS NUMBER	TASK TITLE	Group Members	START DATE	DUE DATE	Week 5 10/7-10/13	Week 6 10/14-10/20	Week 7 10/21-10/27	Week 8 10/28-11/3
1	Important Dates							
1.1	Project Proposal	ALL	9/12/2024	9/20/2024				
1.2	Fall Break	ALL	10/14/2024	10/15/2024				
1.3	Midterm Design Review	ALL	10/10/2024	10/17/2024				
1.4	Thanksgiving Break	ALL	11/27/2024	11/30/2024				
1.5	Final Report	ALL	11/29/2024	12/6/2024				
1.6	Demo Day	ALL	12/9/2024	12/9/2024				
2	Components/Research							
2.1	Order Communicaiton Parts	Sean/Nathan	9/12/2024	9/18/2024				
2.2	Order PCB Parts	JJ/Quentin	9/12/2024	9/18/2024				
2.3	Order Microcontroller	ALL	9/12/2024	9/18/2024				
3	PCB							
3.1	Design Schematic Layout	Quentin	9/23/2024	11/13/2024				
3.2	Prototype/Sensor Testing	Quentin/JJ	10/9/2024	12/3/2024				
3.2.1	Power Design	Quentin	10/25/2024	11/25/2024				
3.2.2	Final Board Iteration	Quentin/JJ	11/11/2024	11/25/2024				
3.3	Final Testing	Quentin/JJ	11/26/2024	12/6/2024				
4	Communications							
4.1	LoRa Basic Communication	Sean/Nathan	9/23/2024	10/18/2024				
4.2	Sensor Data Communication	Sean/Nathan	10/15/2024	12/3/2024				
4.3	Mesh Node Communication	Sean/Nathan	11/11/2024	11/28/2024				
5	Front End Software							
5.1	Design Front End Interface	JJ	9/30/2024	10/4/2024				
5.2	Integrate the Input of Real Data	JJ	11/27/2024	12/4/2024				

Figure 22. Final Gantt Chart Weeks 5-8

WBS NUMBER	TASK TITLE	Group Members	START DATE	DUE DATE	Week 9 11/4-11/10	Week 10 11/11-11/17	Week 11 11/18-11/24	Week 12 11/25-12/1	Week 13 12/2-12/8	Week 14 12/9-12/15
1	Important Dates									
1.1	Project Proposal	ALL	9/12/2024	9/20/2024						
1.2	Fall Break	ALL	10/14/2024	10/15/2024						
1.3	Midterm Design Review	ALL	10/10/2024	10/17/2024						
1.4	Thanksgiving Break	ALL	11/27/2024	11/30/2024						
1.5	Final Report	ALL	11/29/2024	12/6/2024						
1.6	Demo Day	ALL	12/9/2024	12/9/2024						
2	Components/Research									
2.1	Order Communicaiton Parts	Sean/Nathan	9/12/2024	9/18/2024						
2.2	Order PCB Parts	JJ/Quentin	9/12/2024	9/18/2024						
2.3	Order Microcontroller	ALL	9/12/2024	9/18/2024						
3	PCB									
3.1	Design Schematic Layout	Quentin	9/23/2024	10/8/2024						
3.2	Prototype/Sensor Testing	Quentin/JJ	10/9/2024	11/8/2024						
3.2.1	Power Design	Quentin	10/25/2024	11/15/2024						
3.2.2	Final Board Iteration	Quentin/JJ	10/25/2024	11/26/2024						
3.3	Final Testing	Quentin/JJ	11/4/2024	11/26/2024						
4	Communications									
4.1	LoRa Basic Communication	Sean/Nathan	9/23/2024	10/18/2024						
4.2	Sensor Data Communication	Sean/JJ	10/9/2024	11/8/2024						
4.3	Mesh Node Communication	Sean/Nathan	10/29/2024	11/26/2024						
5	Front End Software									
5.1	Design Front End Interface	JJ	9/30/2024	10/11/2024						
5.2	Integrate the Input of Real Data	JJ	11/18/2024	12/2/2024						
5	Chassis Design									
5.1	Chassis Basic Design	JJ	11/11/2024	11/22/2024						

Figure 23. Original Gantt Chart Weeks 9-14

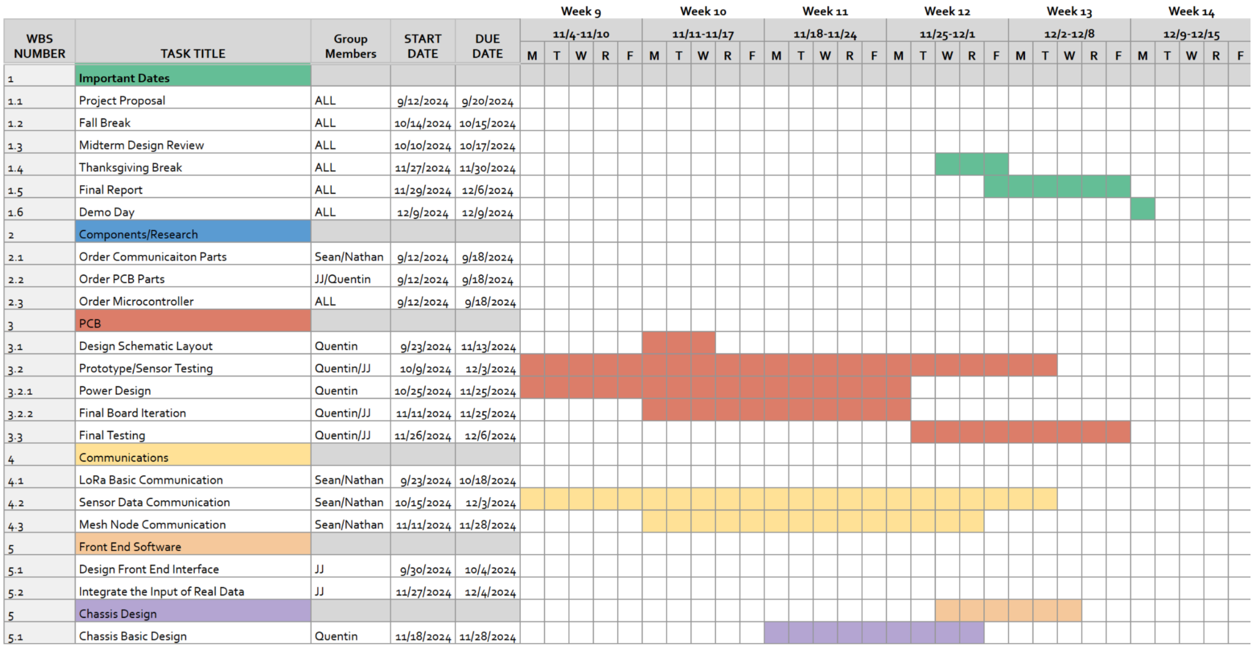


Figure 24. Final Gantt Chart Weeks 9-14

The Gantt charts above outline the timeline of our project, detailing all important deadlines and milestones. The project is organized into several major components: important dates, components/research, PCB and power system design, communications development, chassis construction, and front-end software development.

Figures 19 and 20 show our original and final Gantt charts for the first four weeks of the semester. We successfully completed all our component research on time and ordered our initial parts as planned. Additionally, we started the design schematic for the PCB and basic LoRa communication as scheduled. The only change was that JJ began the front-end interface design two days later than expected. However, this did not impact the overall timeline, as Figure 21 shows that this task was completed a week earlier than planned.

Figures 21 and 22 illustrate our original and final Gantt charts from weeks 5 to 8. While there were some changes to the original plan, none of them caused significant issues. The first adjustment was in the design schematic layout under the PCB section. Initially, we scheduled PCB design from 9/23 to 10/8. During this time, we completed the first iteration of the PCB design, but later in the semester, we designed and ordered two additional PCBs. This included a second iteration of the main board and a configuration circuit for a new IR flame sensor we decided to use late in the semester. The separate board for the sensor became necessary when we pivoted to a different IR sensor after ordering the final PCB board. Another change was delaying the submission of our final PCB board, which was sent on 11/11 instead of 10/28 as originally planned. Similarly, we started sensor data communication a week later than planned (10/15 instead of 10/8). This delay occurred because it took considerable time to decide on the appropriate libraries for communication, prompting a pivot from our original plan.

Figures 23 and 24 depict our original and final Gantt charts for weeks 9 to 14. A major change was the delay in finalizing the prototype and sensors, which took until 12/3 instead of the planned 11/10. This month-long delay was due to numerous issues encountered with the original IR flame sensor. After extensive testing, we could not get the sensor to function fully and had to pivot to an analog IR flame sensor. This required designing and building a circuit with the correct parameters for the flame we wanted to detect, which further delayed completion until 12/3. Despite pushing back the start of our final PCB design by a week, we managed to finish it by the original deadline. However, the use of a new IR flame sensor delayed final testing by three weeks, though we successfully completed everything in time for demo day. Sensor data communication was similarly delayed until the IR sensor was fully operational. Mesh node communication began two weeks later than planned but was completed on time, as Sean and Nathan had to wait for the IR sensor's completion to proceed with that aspect of the project. Finally, instead of designing and building our own chassis, Quentin identified an off-the-shelf option with a built-in solar panel, which we opted to use. This decision introduced solar power as the device's power source instead of batteries. While this change delayed chassis implementation by a week, it streamlined the process and added an innovative element to the project.

Costs

	Description	Sales Amounts	Sales Taxes	Shipping Costs		Total
Development Tools	2 Lora Dev Boards	$43.80				
	2 Digital IR Sensor Boards	$63.56				
Electronic Parts	2 Analog Sensors	$35.45	$1.88	$9.99		
	4 Digital Sensors	$61.16				
	Cabling	$26.70				
	Components	$272.99	$9.01	$9.99		
Mechanical Parts / Other	Solar Panel Enclosure	$58.00		$8.39		
	Solar Charger Board	$29.90				
	Li-Ion Batteries	$15.90	$3.84	$11.84		
Board Manufacturing	Main Board v1	$4.00		$5.00		
	Main Board v2	$4.00		$9.03		

	Digital Sensor Breakout	$2.00	$1.28	$9.03		
	Analog Sensor Breakout v1	$2.00	$0.53	$8.06		
	Analog Sensor Breakout v2	$2.00	$1.06	$18.06		
Board Assembly	4 Boards, 25 Parts each (estimate)	$50.00				
Grand Total		$671.46	$17.60	$89.39		$778.45

Figure 25: Total Project Cost

Figure 13 shows a total project cost of $778.45. The project could have saved money in shipping bulk orders. Instead, many purchases were shipped individually towards the end of the project timeline to be able to produce a final product within the given timeframe. These individual orders could have been avoided, and were often due to oversights and insufficient planning.

	Description	Sales Amounts	Sales Taxes	Shipping Costs		Total
Electronic Parts	Cabling	$13.00				
	Components	$50.95				
Mechanical Parts / Other	Solar Panel Enclosure	$29.00				
	Solar Charger Board	$14.95				
	Li-Ion Battery	$7.95		$11.84		
Board Manufacturing	Main Board Manufacturing	$4.00				
	Analog Sensor Board Manufacturing	$2.00		$18.06		
Board Assembly	1 Board, 25 Parts (Estimate)	$12.50				
Grand Total		$134.35	$6.72	$29.90		$170.97

Figure 26: Unit Cost of Prototype

Figure 14 shows the minimum amount of money it would cost to design a single prototype. As part of the project, the team has produced two complete units for $778.45, rather than $341.94, twice the cost of the minimum prototype cost. This means 400$ were spent in development tools, redundant shipping, and major design pivots.

	Description	Sales Amounts	Sales Taxes	Shipping Costs		Total	Unit Cost
Electronic Parts	Components	$153,935.00					
Mechanical Parts / Other	Solar Panel Enclosure	$1,110.00					
	Li-Ion Battery	$1,227.00					
Board Manufacturing	Main Board Manufacturing	$1,891.10					
	Analog Sensor Board Manufacturing	$886.60		697.19			
Board Assembly	10,000 Boards, 25 Parts Each	$2,387.00					
Grand Total		$161,436.70	$8,071.84	$697.19		$170,205.73	$17.02

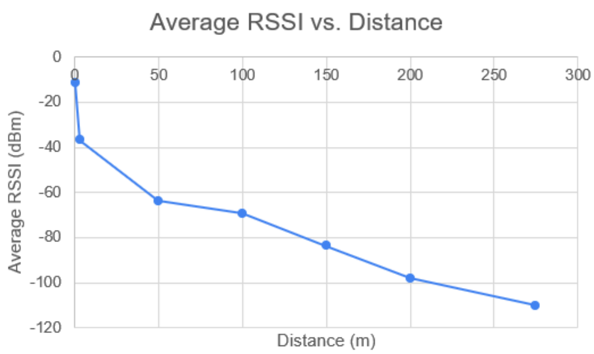
Figure 27: Unit Cost With Mass Scale Production (10,000 units)

Figure 15 assumes boards are ordered and assembled by JLC PCB. It does not include the cost of procurement or testing. A 5% tax is added to the final sales amount. The shipping cost is given by JLC PCB "overseas shipping", which ships boards within 30 Business Days. The total cost per unit comes out to $17.02. The longest US power line is owned by PG&E, and earlier calculations indicate 1891 total sensors necessary for total coverage. The total cost to safeguard this transcontinental power line would therefore be $32,184.82.

Final Results

Our final product incorporates two sensors, an IR flame sensor and a temperature sensor. Our IR sensor does not accurately detect flames up to our original goal of 100 feet because we had to pivot and choose a new IR flame sensor over halfway through the semester. The sensor can detect a flame from a handheld lighter accurately up to approximately 8 feet away. However it was able to detect a flame from a large outdoor fire in a firepit up to approximately 65 feet away. Our temperature sensor works how we planned and can measure a temperature change up to approximately 3 feet away. This is great as the temperature sensor is a redundancy used to check if a fire is very close if the IR sensor did not catch it. Our final product incorporates a weatherproof chassis designed to protect the internal components from environmental factors such as rain, dust, and debris. However, to allow the IR flame detector and temperature sensor to function accurately, small holes were cut into the chassis, enabling the sensors to read real environmental data. While this design choice is necessary for the sensors to operate effectively, it introduces a potential issue in extreme weather conditions, such as heavy rain or snow, which may compromise the chassis's waterproofing.

Our final product achieves wireless communication using a 915 MHz antenna, a LoRa E5 microcontroller, and the LoRa communication protocol. The product can effectively communicate at ranges greater than 100 feet, which satisfies the initial requirements laid out in the project proposal. The signal strength and signal-to-noise ratio at this distance was also determined to be acceptable. Example plots of signal strength and SNR for 20 dBm transmit power are provided below as evidence of this claim. We tested the system up to 275 meters, but data indicates that the range could be extended even further.



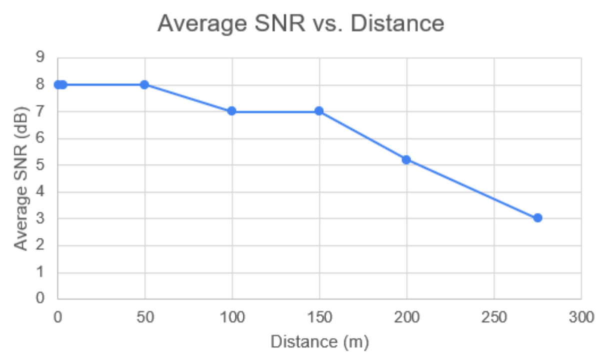


Figure 28: RSSI and SNR Plots

Communication can successfully occur between individual sensor modules and a central computer/controller, which satisfies all the requirements initially laid out for the communication software. An onboard solar panel and a lithium ion battery provide continual recharging and ensure the battery life of our project can exceed one year, which satisfies the power requirements established in the proposal. The front end software designed to interface with our project is clean and easy to understand, which fulfills the expectation of an easy to read user interface.

The overall result of our communication software is a system that is robust against data corruption, efficient with power usage, and has a high rate of successful transmission. Our project also incorporates a front end environment that is easy to use and understand for customers. This makes our product useful for the proposed function of fire detection in remote environments and establishes that we hit most of our criteria for success.

Grading

PCB (2 Points)

Both the IR flame detector and temperature sensor work in tandem to detect fire-related conditions. During testing, the sensors consistently provide reliable readings when exposed to controlled flame and temperature changes. Their integration onto the PCB ensures stable operation and seamless communication with the microcontroller. This functionality demonstrates that the system meets the highest level of performance for this criterion.

Communication System (2 Points)

The communication system, leveraging LoRa technology, reliably transmits data from devices to the central controller. This capability is crucial for ensuring the system can operate effectively in remote and forested environments. Despite challenging terrain or environmental interference, the devices consistently maintain strong communication links, exceeding the expectations outlined in our proposal. The communication system enables real-time monitoring, which is vital for early fire detection and response.

Range (1 Point)

The communication range of the system far surpasses the required 100 feet, with successful data transmission over much longer distances. This performance showcases the reliability of LoRa in facilitating long-range communication. However, the IR sensor does not achieve the original goal of detecting fire at 100 feet. Due to challenges in making the initial sensor functional, we pivoted to a different IR flame sensor with a smaller detection range. While this sensor properly detects a fire, it has not been fully tested to confirm its range of 100 feet.

Battery Life (2 Points)

The power system exceeds expectations, integrating solar panels that recharge the battery and provide a sustainable energy solution. This design ensures the device operates continuously without requiring maintenance or battery replacement. The combination of low power consumption and renewable energy significantly enhances the system's reliability and reduces environmental impact, fully meeting the highest level of this criterion.

Data Interface (2 Points)

The front-end interface is clear, user-friendly, and well-organized. Data from the sensors, including real-time readings of temperature and flame detection status, is displayed on the website in a clear format. The interface allows users to easily interpret data, enabling swift decision-making in case of a fire. This functionality fully satisfies the success criteria for data readability.

Final Points

Based on this assessment, we earn 9 points, which falls within the 8–10 point range for an A according to our grading scale. Therefore, we should receive an A.

Engineering Insights

One of the initial difficulties we encountered when designing the software for our project was the lack of available resources and libraries for wireless communication. We initially planned on programming the LoRa E5 microcontroller using the STM32CubeIDE and STM32 libraries, but quickly realized that this would be too difficult to achieve with the time we had. We decided to pivot and use the Zephyr RTOS with Zephyr libraries, and program using VSCode. These challenges taught us about the complexity of wireless communication software and the value in pre-built libraries that handle low-level logic. We acquired technical skill in using these Zephyr libraries for LoRa communication and in building a Zephyr app folder. We also learned how to interface with the LoRa E5 at a low level using an ST-Link. This was especially important when the write protections of the microcontroller needed to be changed, since the LoRa E5 is shipped by default with write protections that prevent reprogramming.

In terms of higher level code, we learned about new concepts including error checking, acknowledgements, and networking. These concepts were explored when designing the communication software for our project. Error checking was implemented by sending multiple redundant bytes in a packet and making use of a majority voter system. Acknowledgement bits were used in later iterations of our code to ensure emergency alerts were received by other sensors, and to conserve power by deactivating sensors that had successfully transmitted an alert down the chain. Networking concepts were also explored when we examined how different sensors could be connected in overlapping networks using modulus math.

From a non-technical perspective, one of the most important lessons we learned during this project was the need to recognize when to pivot and move on from a failing approach. We spent far too much time trying to make our original IR flame sensor work. Despite countless hours of testing and troubleshooting, we couldn't achieve the functionality we needed, which left us weeks behind our timeline. In hindsight, we should have accepted earlier that the sensor was not going to work as expected and pivoted sooner to an alternative solution. By delaying this decision, we not only wasted valuable time and resources but also inadvertently delayed other aspects of the project, as team members had to wait on the sensor's functionality to proceed with their work. This experience highlighted the importance of time and resource management in the engineering process. When something consistently doesn't work despite exhaustive efforts, it's crucial to step back, assess the situation, and make the hard decision to change direction. Doing so would have saved us weeks of work and prevented unnecessary stress across the team.

This project also taught our group a lot about time management and teamwork. The time constraint of a single semester helped teach us to work efficiently and consistently. We also learned the value in having well-defined roles. One of our greatest strengths as a group was that each member had a very clear, well-defined role in the project and this allowed us to accomplish tasks quicker and minimize time wasting. Another lesson we learned over the course of our capstone was the value in having frequent team meetings and communication. Having meetings multiple times a week allowed us to communicate difficulties with each other, discuss our progress, and decide on alternative courses of action if something wasn't working. In terms of resource management, the most significant lesson we learned was how to effectively manage a budget. Purchasing parts for the capstone project forced us to keep accurate records of our expenditures, and the $500 limit taught us to be frugal and spend money wisely.

If we had to give advice to a future capstone student, we would tell them to communicate as often as possible with their group mates and to make steady progress, as opposed to bursts of productivity followed by inaction. Capstone projects inevitably require you to pivot or find workarounds when issues arise, and solving these issues is easiest when you have good communication with your group mates and a lot of time to address these problems. Working in big bursts and in isolation can make solving these problems much harder than they need to be.

Future Work

Our project could be improved in several key ways. One of the greatest difficulties we faced was integrating an IR flame sensor with the PCB. In future iterations, additional flame sensor options could be explored to overcome this challenge. Our flame sensor choices were limited by budget constraints, so future work could benefit from considering more expensive sensors with greater range and accuracy. Another potential improvement involves incorporating additional sensors to enhance fire detection reliability. Our project was limited in accuracy because it only included a basic flame sensor and an IR flame sensor. Greater accuracy could potentially be achieved by adding sensors such as humidity, wind speed, and gas detection modules. Our primary advice for future groups working with sensors is to test and integrate them into the project as early as possible. We underestimated the time required to get the sensors fully operational, which caused delays and complications for the overall project.

Improvements could also be made to the waterproof enclosure. The company that manufactured our enclosure encountered an issue and had to ship us a unit that was larger than we had originally specified. While this did not cause serious problems, it did impact the form factor and appearance of the project. Future groups could address this by sourcing enclosures earlier in the process to account for unexpected delays or sizing issues. Another improvement to the enclosure would be the addition of a small heating element. During testing, we discovered that batteries become significantly less efficient in cold temperatures. This affected the maximum transmit power of our system, which varied considerably between lab and outdoor environments. Adding a small heating element to the enclosure would help maintain a consistent operating temperature, improving performance in colder conditions.

Another area for improvement involves optimizing power management. While our project successfully integrated solar power, future iterations could explore additional power sources or more advanced energy optimization techniques. For example, energy harvesting methods, such as capturing vibrations from power lines or utilizing temperature gradients, could provide supplementary energy to improve efficiency and further reduce reliance on batteries.

The communication system can also be improved in a few ways that allow for faster message transmission and higher reliability. In the initial project proposal, a design for splitting all of the sensors into different sub-networks was presented. This split network system has been implemented, but not enough testing has been completed to consider it reliable and complete. We would also like to develop a universal message type that all sensors, regardless of which network they are connected to, will hear. This would allow us to still send fire alerts, even when key nodes within the network are offline. The implementation of both of these systems would increase the reliability of our system.

This project could also be expanded upon by developing a system for deploying the sensors on electrical poles. One of the biggest weaknesses of our project is that deploying these sensors in remote areas would likely be expensive and logistically challenging. Developing a drone or similar technology to attach these sensors to electrical poles could greatly improve the feasibility of the product. This would reduce deployment costs and make the system more viable for power companies, increasing overall utility and scalability.

Finally, future iterations of this project could focus on integrating the system with existing fire detection and management platforms already used by power companies or government agencies. Ensuring compatibility with current tools would streamline the adoption process and allow the system to be part of a larger fire prevention and management network. This integration could make the product even more attractive to stakeholders, enhancing its impact and scalability.

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Appendix

	Description	Sales Amounts	Sales Taxes	Shipping Costs		Total
Development Tools	2 Lora Dev Boards	$43.80				
	2 Digital IR Sensor Boards	$63.56				
Electronic Parts	2 Analog Sensors	$35.45	$1.88	$9.99		
	4 Digital Sensors	$61.16				
	Cabling	$26.70				
	Components	$272.99	$9.01	$9.99		
Mechanical Parts / Other	Solar Panel Enclosure	$58.00		$8.39		
	Solar Charger Board	$29.90				
	Li-Ion Batteries	$15.90	$3.84	$11.84		
Board Manufacturing	Main Board v1	$4.00		$5.00		
	Main Board v2	$4.00		$9.03		
	Digital Sensor Breakout	$2.00	$1.28	$9.03		
	Analog Sensor Breakout v1	$2.00	$0.53	$8.06		
	Analog Sensor Breakout v2	$2.00	$1.06	$18.06		
Board Assembly	4 Boards, 25 Parts each (estimate)	$50.00				
Grand Total		$671.46	$17.60	$89.39		$778.45

Appendix A. Total Spent

	Description	Sales Amounts	Sales Taxes	Shipping Costs		Total
Electronic Parts	Cabling	$13.00				
	Components	$50.95				
Mechanical Parts / Other	Solar Panel Enclosure	$29.00				
	Solar Charger Board	$14.95				
	Li-Ion Battery	$7.95		$11.84		
Board Manufacturing	Main Board Manufacturing	$4.00				
	Analog Sensor Board Manufacturing	$2.00		$18.06		
Board Assembly	1 Board, 25 Parts (Estimate)	$12.50				
Grand Total		$134.35	$6.72	$29.90		$170.97

Appendix B. Cost of Single Prototype

	Description	Sales Amounts	Sales Taxes	Shipping Costs		Total	Unit Cost
Electronic Parts	Components	$153,935.00					
Mechanical Parts / Other	Solar Panel Enclosure	$1,110.00					
	Li-Ion Battery	$1,227.00					
Board Manufacturing	Main Board Manufacturing	$1,891.10					
	Analog Sensor Board Manufacturing	$886.60		697.19			
Board Assembly	10,000 Boards, 25 Parts Each	$2,387.00					
Grand Total		$161,436.70	$8,071.84	$697.19		$170,205.73	$17.02

Appendix C. Cost of 10,000 Units