Remote Viewing within a High Voltage Apparatus

Blake Bagley, Julia Garcia, Erica Mathew

CONCEPT OF OPERATIONS

REVISION – Draft
14 September 2024

Concept of Operations
for
Remote Viewing within High Voltage Apparatus

Team <54>

Approved by:

Project Leader Date

Prof. Kalafatis Date

T/A Date

Change Record

Rev.	Date	Originator	Approvals	Description
-	9/14/2024	Remote Viewing within High Voltage Apparatus		Draft Release

Table of Contents

List of Figures

1. Executive Summary

As the industry demand grows, space within medium voltage switchgear has become increasingly limited. Manufacturers once had the luxury of allotting one device to a dedicated space, but now they must fit multiple apparatus for different functions into that same confined space. Manufacturers are additionally being asked to include safety devices within the switchgear. These safety devices are often not in areas that are easily accessible by the operator which makes visual inspection challenging. The goal of this project is to create a solution that enables operators to remotely view the safety devices inside the switchgear. This will significantly improve both safety and efficiency for the customer by providing continuous monitoring of the mechanical switches.

2. Introduction

This document is an introduction to our Proposed Thermal Remote Viewing System within High Voltage, a system capable of monitoring the mechanical safety switches within medium voltage switchgears. This project will allow operators to remotely confirm the state of the switchgear without putting themselves in danger.

2.1. Background

Currently, there is not a good system for monitoring the inside of a switchgear. Operators currently rely on a flashlight through a small window to get a view of the inside. This method is extremely inefficient because it provides very limited visibility and is unable to view regions that are covered by wires. This can also be very dangerous and can expose the operator to the dangers of high-voltage.

Our plan of creating a remote viewing system will allow operators to monitor the switchgear from a distance. Real time streaming with the use of thermal sensors will provide a comprehensive view of the switchgears. By placing thermal sensors close to the safety switches, we are able to get a visual representation of hard-to-reach areas.

2.2. Overview

Our system will be used to monitor safety switches within a medium voltage switchgear to check for gaps between contacts. We will use thermal sensors to create a temperature profile of the switchgear in real time. This raw thermal data from the sensor is sent to our microcontroller which converts the data into a video stream. Here we will have to perform linear interpolation to smooth the images. Our microcontroller would then send the processed data over a network via Wi–Fi. Finally we will create a website for the operators to easily interface with that displays the thermal video stream.

2.3. Referenced Documents and Standards

- IEEE Standard C37.20.2 IEEE Standard for Metal-Clad Switchgear
- IEEE Standard C37.04 IEEE Standard for Ratings and Requirement for AC High-Voltage Circuit Breakers with a Rated Maximum Voltage Above 1000V
- IEEE Standard C37.09 IEEE Standard Test Procedures for AC High-Voltage Circuit Breakers with Rated Maximum Voltage Above 1000 V
- ANSI C37.54 American National Standard for Alternating Current High-Voltage Circuit Breakers Applied in Metal-Enclosed Switchgear—Conformance Test Procedures
- NFPA 70E Standard for Electrical Safety in the Workplace
- NFPA 70 National Electrical Code

3. Operating Concept

3.1. Scope

The goal of this project is to create a system that allows for operators to remotely view a switch within a switchgear without opening it to ensure safe grounding. When an operator wants to see if the designated switch is open or closed, he/she will open a computer application that will connect to the microcontroller. A thermal image sensor will first capture a video of the designated switch; then the microcontroller will send that video to the application. One of the big constraints of this project is that we need to make sure that the dielectrics that are already in the switchgear still operate within industry standards. Due to budget constraints, the project will entail making this system for only one vertical tower of switchgear. We will still make this system expandable by having multiple towers connected to the application with their own dedicated sensors and microcontrollers. This system will help to make switchgear operators' jobs much more safe and convenient.

3.2. Operational Description and Constraints

This system is intended to be used by switchgear operators to make sure switchgear can be safely operated. The operator should be able to open an application on a computer and connect to the switchgear he/she is operating on to see the desired switch's state. An image will be taken by a thermal image system placed in the switchgear, which will then be sent to an application through a microcontroller for the operator to see. According to the sponsors of this project, the system must allow for the users to see the designated switch. Graphical representations are not enough for customers, and are not enough for operators to feel certain that the switchgear they are operating on is in the right state. The system must not cause the dielectrics to fail integrity tests because of the system's addition to the switchgear. Also, no modifications will be made to the switchgear other than allowing for the ability to mount the system. The system is purely an addition to the switchgear.

3.3. System Description

There are three main parts of this system. The first part of this system is the thermal image sensor. This is what will create the image of the switch needed to be examined. The sensor will be placed within the switchgear at a respectful distance from the switch so that interference isn't a problem. The second part of the system is the microcontroller. This part will configure the sensor, process the information read from the sensor, turn the information into something readable by an application, and send off the information through wi-fi. The final part of the system is an application that will take the information sent from the microcontroller and transform it into a viewable format for the operator. The system can be expanded upon by having more vertical towers connected to the application. Each vertical tower will have its own microcontroller and thermal image sensor to allow the application to connect to and view the inside of each tower.

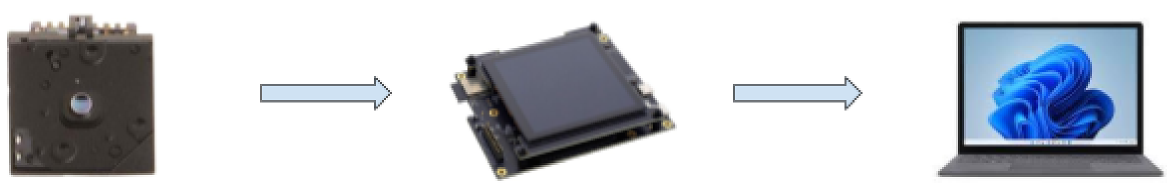

Figure 1: Thermal Remote Viewing System Overview

3.4. Modes of Operations

The operator only needs to view the switch through some type of produced image. The only difference between cases is that the switch might be located in a different part of the switchgear, which will cause the sensor to be placed in a new location. If this project were to be later expanded for the use of multiple towers, then this could entail the operator choosing which tower of switchgear to view.

3.5. Users

The users of this system, as stated throughout this report, will be switchgear operators. These operators are highly trained and knowledgeable of the hardware being observed by the proposed system. It is common for these users to have engineering and/or technical degrees. Thermal sensors are commonly used in procedures for switchgear, so operators should have some knowledge of how they work. Being that a big portion of these operators' jobs is maintenance and safety, our system will ensure that their job is much easier by giving the operator a good visualization of the state that the switchgear is in.

When it comes to the proposed system, there won't need to be any training for installation. The only training needed will probably be for the use of the application. The application should be simple to learn as it is supposed to be a tool for visualization.

3.6. Support

Support for our system will be given in the form of a manual on how to operate the system. It will detail the assembly of the system, configuration of the hardware, and operation of the application.

4. Scenario(s)

4.1. Ensuring State of Switchgear

The use of our thermal viewing system is to ensure the mechanical safety switches are open. If a maintenance worker needs to open up a switchgear and work inside, they can use our system to make sure it is depowered. The main problems with the switchgear are the density of electronics and lack of inner lighting. These issues make checking that the equipment is depowered extremely difficult. The operator cannot see the gaps from the window on the door, but our system will fix this. With a thermal image of the mechanical safety switches inside the switchgear, operators on the outside can visually see the open gaps, proving it is depowered and safe to open.

5. Analysis

5.1. Summary of Proposed Improvements

- The proposed system will make operating a switchgear much safer than it currently is. By having a thermal image sensor placed inside the switchgear, the system allows for the operator to not have to open up the back and check if the safety switch being observed is closed.
- The system will also utilize wi-fi which will make the switch observable at longer distances.
- The sensor can be remotely turned on and off, so the system is active only when needed by maintenance personnel. This ensures the system isn't wasting any power.
- We could expand upon this project by making the system use machine learning. This will allow it to automatically classify switches as “open” or “closed”, which will improve the workflow for operators overseeing multiple switchgears.

5.2. Disadvantages and Limitations

Our proposed thermal viewing system will have some limitations which include:

- The size of the system is very limited due to the scant amount of space available within the switchgear.
- All equipment/components used in the system must be able to withstand high temperatures.
- The sensor and accompanying equipment must be shielded to ensure they don't interfere with the dielectrics within the switchgear.
- The locations that the thermal sensor can be mounted are limited due to the space constraints within the switchgear.
- Due to budget constraints, the resolution of the picture won't be very sharp.

5.3. Alternatives

Some alternatives to our proposed thermal viewing system are:

- Placing small flags behind the safety switches and using a flashlight to see inside a window on the front door of the switchgear. If the flag is visible, an operator can conclude the switches are open and the switchgear is depowered.
- Using a "normal" camera with a light source and streaming video of the switches to remote locations.
- A window placed on the backside of the switchgear closer to the mechanical safety switches. With this solution, the operator would need a light source of their own.

5.4. Impact

- There are no ethical concerns because the proposed system is being created to ensure the safety of anyone who works with switchgear. The system is intended to protect people at no cost to any other part of the overall switchgear.
- The environmental impact of our system is minimal. Our only impact comes from power consumption, which isn't high.
- The impact for society would be minimal, as this wouldn't affect the everyday lives of anyone except the operators that work directly with switchgear.

Remote Viewing within a High Voltage Apparatus

Blake Bagley, Julia Garcia, Erica Mathew

Functional System Requirements

REVISION – Draft
24 September 2024

Functional System Requirements

for

Remote Viewing within a High Voltage Apparatus

Prepared by:

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Author Date

Approved by:

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Project Leader Date

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John Lusher, P.E. Date

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T/A Date

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-	9/26/2024	Remote Viewing within High Voltage Apparatus		Draft Release

Table of Contents

List of Tables

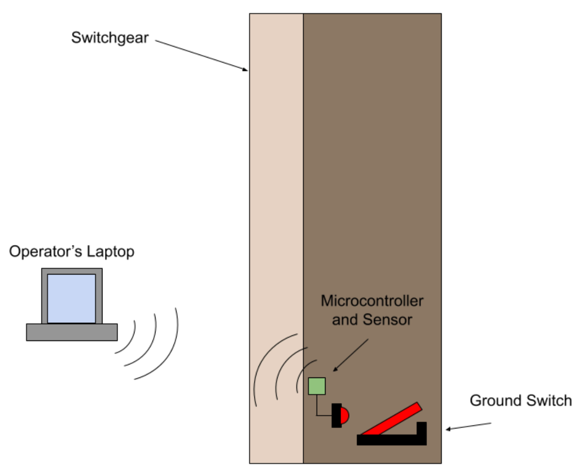
List of Figures

1. Introduction

1.1. Purpose and Scope

As industry demand grows, space inside medium voltage switchgear has become increasingly limited. Manufacturers are required to fit more devices and wires within the same limited space. Additionally, manufacturers are now being asked to include a remote viewing system within the switchgear to monitor a physical ground switch. This ground switch is physically blocked, by wires, from the view of the operator. Our project, *Thermal Remote Viewing System within High Voltage*, provides a real time visual depiction of the ground switch that an operator can view from a safe distance away from the switchgear. We will use a thermal sensor to create an image of the ground switch, which will then be sent to the microcontroller to process the information into a viewable format. The video information will then be sent to a web application for the operator to interface with. Our system will increase safety and efficiency for switchgear operators.

Figure 1. Conceptual Image



1.2. Responsibility and Change Authority

Erica Mathew will make sure all requirements detailed in the Functional System Requirements will be met. Requirements can only be changed if Erica and our sponsors at Powell Industries approve of the changes. Below are the responsibilities of everyone in the team.

Subsystem	**Responsibility**
Thermal Image Sensor	Julia Garcia

Microcontroller	Blake Bagley
Web Application	Erica Mathew

2. Applicable and Reference Documents

2.1. Applicable Documents

The following documents, of the exact issue and revision shown, form a part of this specification to the extent specified herein:

Document Number	**Revision/Release Date**	**Document Title**
IEEE Standard C37.20.2	2015-09-22	IEEE Standard for Metal-Clad Switchgear
IEEE Standard C37.04	2019-05-31	IEEE Standard for Ratings and Requirement for AC High- Voltage Circuit Breakers with a Rated Maximum Voltage Above 1000V
IEEE Standard C37.09	2019-04-11	IEEE Standard Test Procedures for AC High-Voltage Circuit Breakers with Rated Maximum Voltage Above 1000 V
ANSI C37.54	2023	American National Standard for Alternating Current High-Voltage Circuit Breakers Applied in Metal-Enclosed Switchgear—Conformance Test Procedures
NFPA 70E	2024	Standard for Electrical Safety in the Workplace
NFPA 70	2023	National Electrical Code

2.2. Reference Documents

The following documents are reference documents utilized in the development of this specification. These documents do not form a part of this specification and are not controlled by their reference herein.

Document Number	**Revision/Release Date**	**Document Title**
1	Version 1.9	ESP32-S3 Series Datasheet
2	Revision 204	FLIR LEPTON® Engineering Datasheet
3	12/22/2020	GlobTek, Inc. Li-Ion Polymer 3.7 V Battery Pack

2.3. Order of Precedence

In the event of a conflict between the text of this specification and an applicable document cited herein, the text of this specification takes precedence without any exceptions.

All specifications, standards, exhibits, drawings or other documents that are invoked as "applicable" in this specification are incorporated as cited. All documents that are referred to within an applicable report are considered to be for guidance and information only, except ICDs that have their relevant documents considered to be incorporated as cited.

3. Requirements

3.1. System Definition

The Thermal Remote Viewing System within High Voltage is a system specifically designed for remotely monitoring ground switches within a medium voltage switchgear. It allows operators to confirm a vertical tower is properly grounded before opening the switchgear. This system provides a real-time video stream of the ground switches which will be broadcasted to an online website. Our system consists of a thermal image sensor, microcontroller and a website.

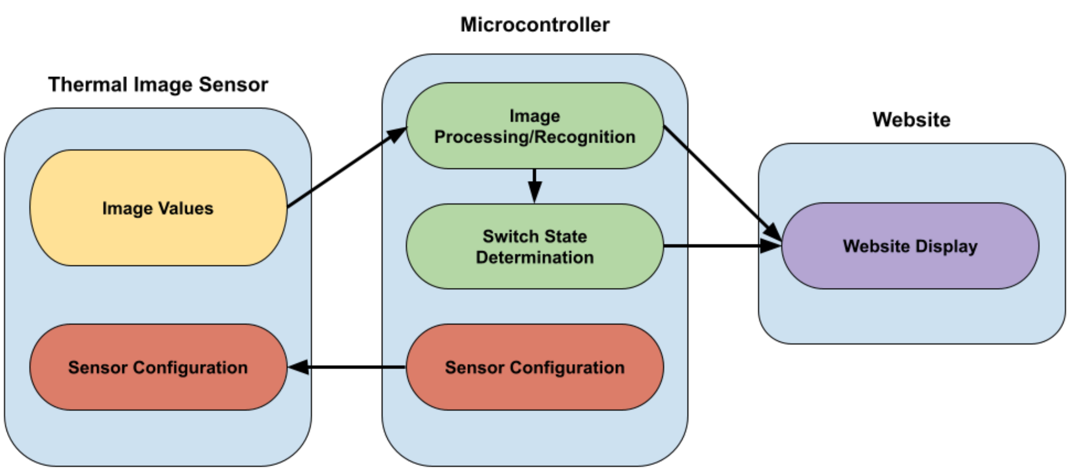


Figure 2. Block Diagram of System

There are three main components to this system. First block represents the first main component which is the thermal image sensor. This sensor will take in IR values and turn them into an image for the microcontroller to process. This sensor will need to be configured to be in the image format that will be used by the microcontroller.

The second block which is the microcontroller will use an algorithm to determine where the switch is located and to determine if the grounding switch is open or closed. The video and switch state will be then sent from the microcontroller to the website to be viewed by the operator.

3.2. Characteristics

3.2.1. Functional / Performance Requirements

3.2.1.1. Connection to Website

The Thermal Remote Viewing System shall allow for multiple microcontrollers and thermal image sensors in different vertical towers to be connected to the website.

Rationale: This will allow for the operator to view multiple vertical towers.

3.2.1.2. Machine Learning Error Rate

The Switch State Determination done by the microcontroller shall not have an error rate exceeding 10%.

Rationale: This will allow for the machine learning of the microcontroller to perform as accurately as needed.

3.2.1.3. Thermal Sensor Node Area

The thermal sensors should take a visual image that covers a minimum viewable area of 6x6 inches.

Rationale: This is a requirement specified by our customer to properly see the gap between contacts in the ground switches.

3.2.1.4. Video Latency

The video output shall be a live video stream with no more than a 5 second delay.

Rationale: This is a requirement specified by our customer to properly view the gap between contacts in the ground switches.

3.2.1.5. Video Resolution

The video output shall have a pixel resolution of 160x120 pixels

Rationale: This is the resolution of the thermal sensor we chose. This will allow for a clear image for the operator to observe.

3.2.2. Physical Characteristics

3.2.2.1. Volume Envelope

The volume envelope of the Remote System shall be less than or equal to 6 inches in height, 6 inches in width, and 6 inches in length.

Rationale: This is a requirement specified by our customer due to constraints of the switchgear the system will be operating in

3.2.2.2. Mounting

The thermal sensor should be mounted facing the ground switches to allow for a complete view. The mounting information shall be captured in the Remote Viewing System within High Voltage ICD.

Rationale: This is a requirement specified by our customer to provide a clear image to the operator.

3.2.2.3. Installation

The installation information for The Thermal Remote Viewing System within High Voltage shall be provided to the customer through a user manual.

3.2.3. Electrical Characteristics

3.2.3.1. Inputs

a. No inputs of the operator shall inhibit the function of The Thermal Remote Viewing System.

Rationale: By design, this should limit the risk of the system becoming damaged.

3.2.3.1.1 Power Consumption

a. The maximum peak power of the system shall not exceed 3 watts.

b. For our class demonstration we will use a battery pack to power our system. If this system were to be adopted into a switchgear, it shall pull power from the switchgear itself.

Rationale: This is specified by the ESP32-S3 Series Datasheet and FLIR LEPTON® Engineering Datasheet.

3.2.3.1.2 Input Voltage Level

The input voltage level for the Search and Rescue System shall be +3.7 VDC to +4.2 VDC.

Rationale: This is specified by GlobTek, Inc. Li-Ion Polymer 3.7 V Battery Pack Datasheet

3.2.3.2. Outputs

3.2.3.2.1 Data Output

The Thermal Remote Viewing System within High Voltage shall include an website interface compatible with the microcontroller to view the ground switch.

Rationale: The Thermal Remote Viewing System within High Voltage information passes directly to the customer's system.

3.2.3.2.2 Raw Video Output

The Thermal Remote Viewing System shall output a RAW14 video for the operator to view on the system's website.

Rationale: This is a requirement specified in the FLIR LEPTON® Engineering Datasheet.

3.2.3.3. Connectors

The Thermal Remote Viewing System within High Voltage shall follow the America National Standard for Electrical Connectors ANSI C119.6-2011.

Rationale: This is a requirement specified by in accordance with our battery

3.2.4. Environmental Requirements

The Thermal Remote Viewing System shall be designed to withstand and operate in the environments and laboratory tests specified in the following section.

Rationale: This is a requirement specified by our customer due to constraints of their system in which the The Thermal Remote Viewing System is integrating.

3.2.4.1. Thermal Resistance

The Thermal Remote Viewing System should be able to properly operate in an environmental temperature up to 80C.

Rationale: This is a requirement specified in the FLIR LEPTON® Engineering Datasheet.

3.2.4.1.1 Dielectrics Test

The Thermal Remote Viewing System shall not compromise the integrity of the dielectrics already within the switchgear

3.2.5. Failure Propagation

If the website doesn't receive video input from the microcontroller after 30 seconds, the website shall display a notice that there is a problem connecting to the microcontroller.

Rationale: This will allow for the user to know if something is wrong with the system.

4. Support Requirements

The Thermal Remote Viewing System shall require internet connection and a computer in order to interact with the website application.

Remote Viewing within a High Voltage Apparatus

Blake Bagley, Julia Garcia, Erica Mathew

INTERFACE CONTROL DOCUMENT

REVISION – Draft

26 September 2024

Interface Control Document
for
Remote Viewing within a High Voltage Apparatus

Prepared by:

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Author Date

Approved by:

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Project Leader Date

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John Lusher II, P.E. Date

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T/A Date

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Table of Contents

List of Tables

List of Figures

1. Overview

This document is provided to detail how the thermal sensor will interface with the microcontroller and how the microcontroller will interface with the website. It will list all inputs, outputs, and how the system manages each. An explanation of the inputs from the thermal sensor to the microcontroller will be provided. Then, an explanation of how that input will be transferred from the microcontroller to the website will follow.

2. References and Definitions

2.1. References

Refer to section 2.2 of the Functional System Requirements document.

2.2. Definitions

mA	Milliamp
mW	Milliwatt
g	Grams
mm	Millimeters
V	Volts
TBD	To Be Determined

3. Physical Interface

3.1. Weight

3.1.1. Entire Printed Circuit Board

Component	Weight	Number of Items	Total Weight
FLIR Lepton 3.5 Thermal Sensor	0.91 g	1	0.91 g
ESP32-S3-WROOM1	TBD	1	TBD
Buck Converter Circuit	TBD	4	TBD

Table 1: Printed Circuit Board Weight

3.2. Dimensions

3.2.1. Dimensions of Entire Printed Circuit Board

Component	**Length**	**Width**	**Height**
FLIR Lepton 3.5 Thermal Sensor	12.7 mm	11.5 mm	6.835 mm
ESP32-S3-WROOM1	25.5 mm	18 mm	3.1 mm
Buck Converter Circuit	TBD	TBD	TBD

Table 2: Printed Circuit Board Dimensions

3.3. Mounting Locations

The thermal sensor will be mounted facing the grounding switch at the back of the switchgear. The sensor must face the grounding switch because the switch is being viewed by the operator. It can only fit in the back due to space constraints within the switchgear.

4. Thermal Interface

The ESP-32 microcontroller will use a heat sink in order to prevent overheating and decreased efficiency. There is only one microcontroller in our system, so only one heat sink is needed. The thermal sensor has safeguards in place to prevent overheating.

5. Electrical Interface

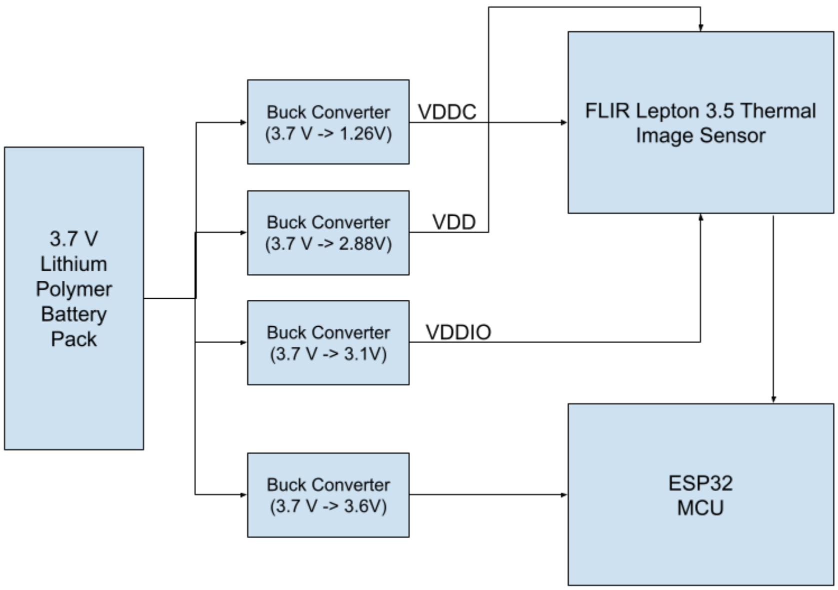

Figure 1: Electrical Interface Diagram

5.1. Primary Input Power

The system will be battery powered using a rechargeable 3.7 V lithium-ion polymer battery. When implemented into the switchgear, the system will be powered by the switchgear itself.

5.2. Voltage and Current Levels

5.2.1. Maximum Values

Component	Voltage [V]	Current [mA]	Power [mW]
FLIR Lepton 3.5 Thermal Sensor	4.8	16	76.8
FLIR Lepton 3.5 Thermal Sensor Core	1.5	110	165
FLIR Lepton 3.5 Thermal Sensor I/O	4.8	310	1488
ESP32-S3-WROOM1	3.6	1500	3600

Table 3: Maximum Voltage, Current and Power Levels

5.2.2. Nominal Values

Component	Voltage [V]	Current [mA]	Power [mW]
FLIR Lepton 3.5 Thermal Sensor	2.8	14	39.2
FLIR Lepton 3.5 Thermal Sensor Core	1.2	84	100.8
FLIR Lepton 3.5 Thermal Sensor I/O	3.1	235	728.5
ESP32-S3-WROOM1	3.3	500	1650

Table 4: Nominal Voltage, Current, and Power Levels

5.3. Data Interfaces

The thermal sensor will send raw video data to the microcontroller through serial pins (SPI), both the sensor and microcontroller are mounted to the PCB.

5.4. User Control Interface

The user control interface is a website that communicates with the microcontroller. The user will login using credentials provided through their companies. Then, the user will be able to select what switchgear vertical tower will be viewed. The user can select the desired video stream from the overview page or the user can use the search bar to find their desired video stream.

6. Communications / Device Interface Protocols

6.1. Wireless Communications

6.1.1. Wi-Fi

The microcontroller has a built-in WiFi module using IEEE 802.11b/g/n standards. This connection will be used to stream live video to the operator’s website.

Remote Viewing within a High Voltage Apparatus

Blake Bagley, Julia Garcia, Erica Mathew

SCHEDULE AND VALIDATION

REVISION – 1
5 December 2024

Schedule and Validation
for
Remote Viewing within High Voltage Apparatus

Schedule:

Validation:

Paragraph #	Test Name	Success Criteria	Methodology	STATUS	Engineers
3.2.3.1.2	Provide Power	Input Voltage reads ~3.7 V, Microcontroller receives voltage, Sensor input VDD receives voltage	Use multimeter to input voltages	PASS	Julia Garcia
3.2.3.1.2	Buck Converters	Output to VDDC reads ~1.26 V, Output to VDD reads ~2.88 V, Output to VDDIO reads ~3.1 V, Output to ESP32 reads ~3.3 V	Use multimeter to measure the output voltages	FAIL	Julia Garcia
3.2.3.2.2	Sensor Sending Video	Signal is going from the output of the thermal sensor and into the input of the microcontroller	Use a oscilloscope to prove signal is present	UNTESTED	Julia Garcia
3.2.1.2	Switch-State Determination Accuracy	Make sure the accuracy of the Switch-State Determination is up to standard	Use photos of the switch in different states	PASS	Blake Bagley
3.2.3.2.2	Receiving Video from Sensor	Video is being received from the camera through the VSPI pins	Checking packet and segment IDs coming in	PASS	Blake Bagley
3.2.1.1	Connection to WiFi	If the ESP32 can make a WiFi connection as an access point or as a station	Searching for ESP32 SSID on a personal laptop.	PASS	Blake Bagley
3.2.1.1	Sending Video to Website	The ESP32 is able to send an image over WiFi	Have the ESP32 send a video to a personal laptop	UNTESTED	Blake Bagley
3.2.1.4	Receiving Video	If no video stream is displayed on website, an error message should be outputted to screen. Video should be of correct vertical tower	Confirm the correct file is linked to its respective MODEL ID (either 001 or 002). 003-005 should display error message.	PASS	Erica Mathew
3.2.1.1	Login-in System	Login with correct credentials and fail with incorrect credentials	Have user create different login credentials to check if they are stored in firebase	PASS	Erica Mathew
3.2.1.1	Search Bar	Search bar redirects user to the proper video stream	Have user type different ID numbers to test search bar functionality	PASS	Erica Mathew
3.2.1.4	Video Display Page	Overview Page that displays multiple video streams. Video streams in overview page are clickable to redirect user to zoomed in video feed on a different page	Send different video live streams and have user try to access all of them	PASS	Erica Mathew

Remote Viewing within a High Voltage Apparatus

Blake Bagley, Julia Garcia, Erica Mathew

SUBSYSTEM REPORTS

REVISION – Draft
5 December 2024

Table of Contents

Subsystem Reports
for
Remote Viewing within a High Voltage Apparatus

Prepared by:

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Author Date

Approved by:

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Project Leader Date

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John Lusher II, P.E. Date

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T/A Date

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-	12/5/2024	Blake Bagley, Julia Garcia, Erica Mathew		Draft Release

List of Figures

1. Introduction

The first subsystem is the thermal sensor and PCB, the power supply is housed on the board along with the microcontroller and the thermal sensor. Below is the subsystem breakdown for our Thermal Remote Viewing System.

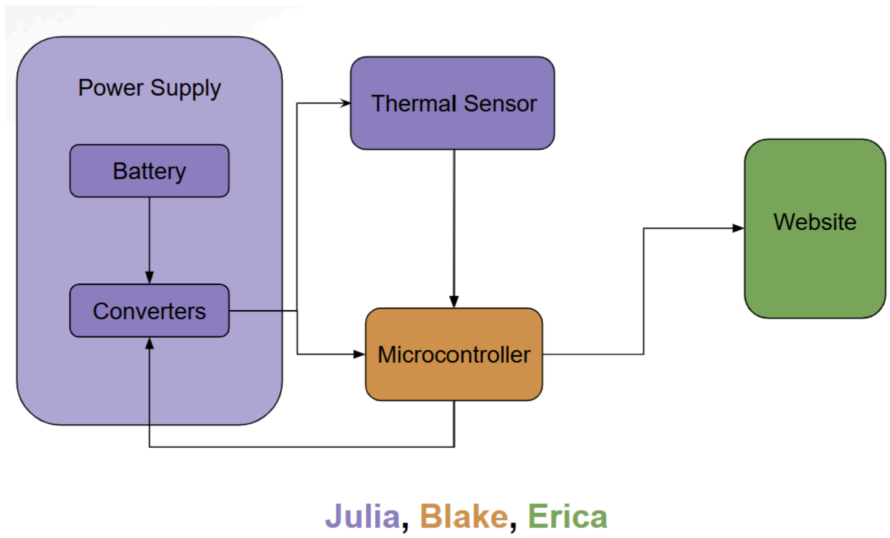

Figure 1: Subsystem Breakdown

2. Thermal Sensor/PCB Subsystem Report (Julia Garcia)

2.1. Subsystem Introduction

The thermal sensor and PCB is the subsystem that contains all the hardware of the system. This includes the power supply, the microcontroller and the camera module. For the power supply, a lithium-ion battery pack is connected to four buck converters to power both the microcontroller and the camera module. The microcontroller will be connected to the camera module through serial communication (SPI). The purpose of this subsystem is to provide power to both major components and ensure data transfer between them.

2.2. Subsystem Details

A block diagram of the subsystems is shown below.

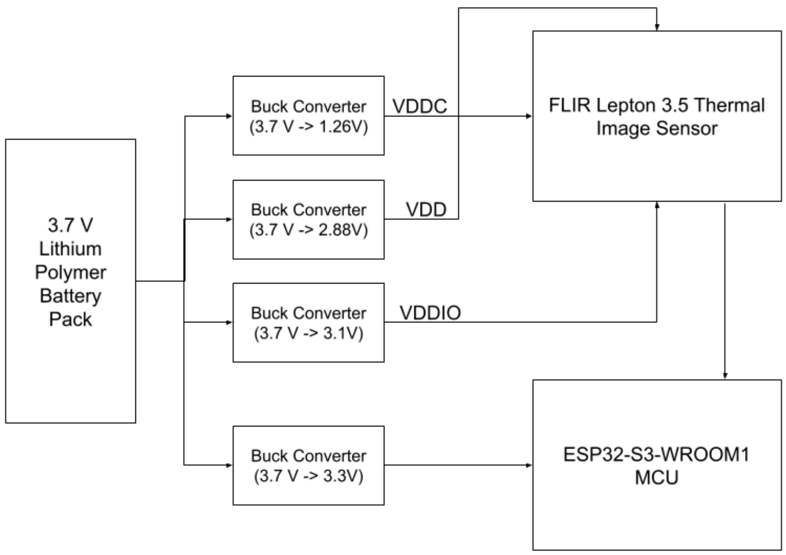

Figure 2: Functional block diagram of the thermal sensor/PCB subsystem

The buck converters are all the same overall design with the component values being changed to provide the correct voltage level for each specific input. The camera module needs three separate power inputs to operate. The core of the camera (VDDC), the sensor itself (VDD), and the input/output ring (VDDIO) all need to be powered separately.

The microcontroller needs pull-down resistors and push-buttons to function and be programmed, while also needing to be powered. The SPI interface between the microcontroller and the camera module requires four pins on each device to be allocated in order for the data to transfer properly.

The layout of all four buck converters is shown in the figure below.

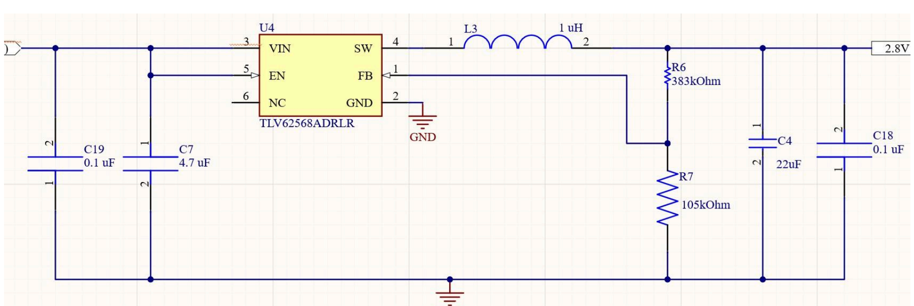

Figure 3: Buck Converter Schematic for VDD input

The connections for the microcontroller are shown in the figure below.

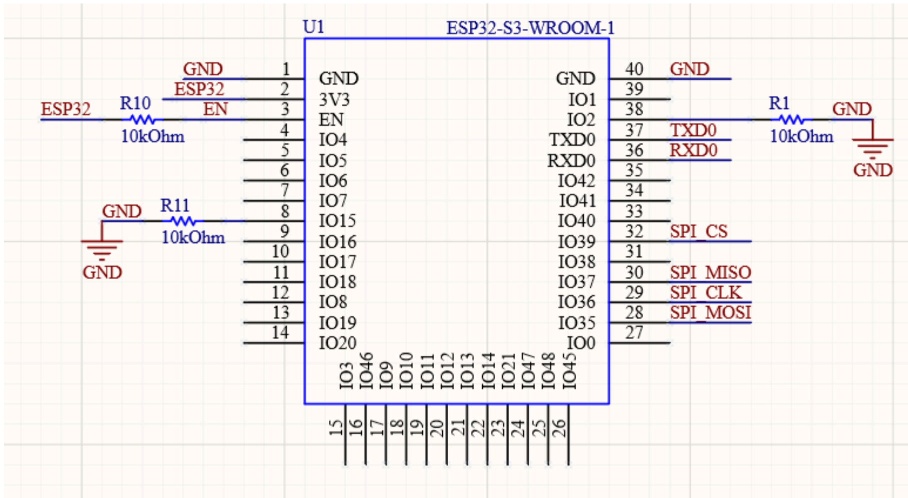

Figure 4: ESP32-WROOM1 Connections

The overall layout of PCB is shown in the figure below.

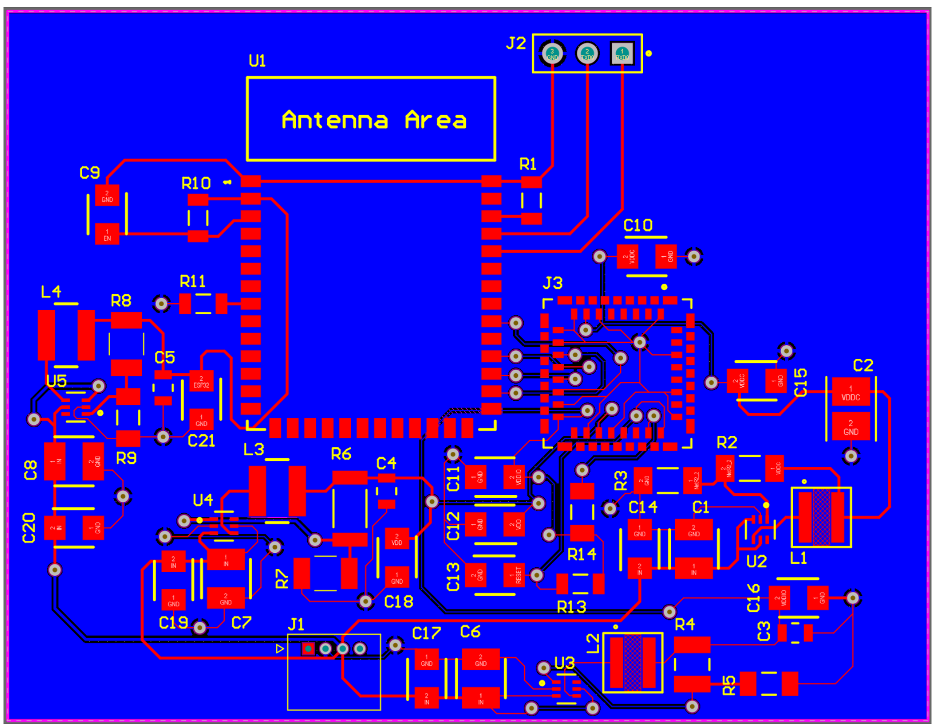

Figure 5: PCB Layout

2.3 Subsystem Validation

To validate the functionality of the PCB, each of the buck converters was tested with a multimeter to ensure the output value was within acceptable limits. The values on the data sheets of the components were nominal values, therefore slightly higher or lower would still power the components. The outputs were also tested with an oscilloscope to see if the DC voltage had an acceptable ripple.

The four figures below show the results of two of the buck converters, the input for the microcontroller and the input for the input/output ring of the camera module. The input for the microcontroller works as intended, while the input for the I/O ring does not.

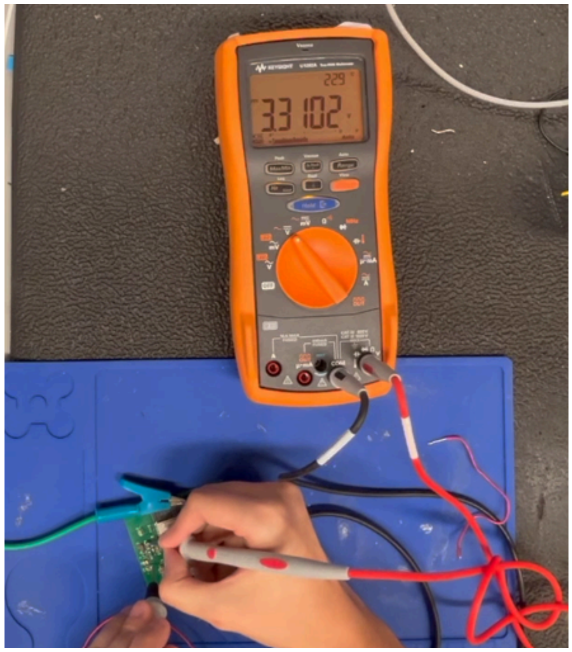

Figure 6: Results of ESP32 buck converter shown by multimeter

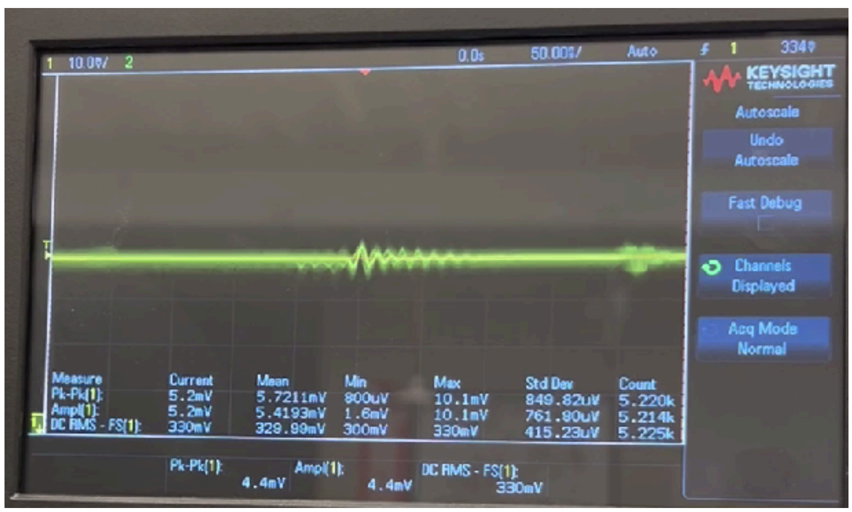

Figure 7: ESP32 buck converter output voltage on oscilloscope

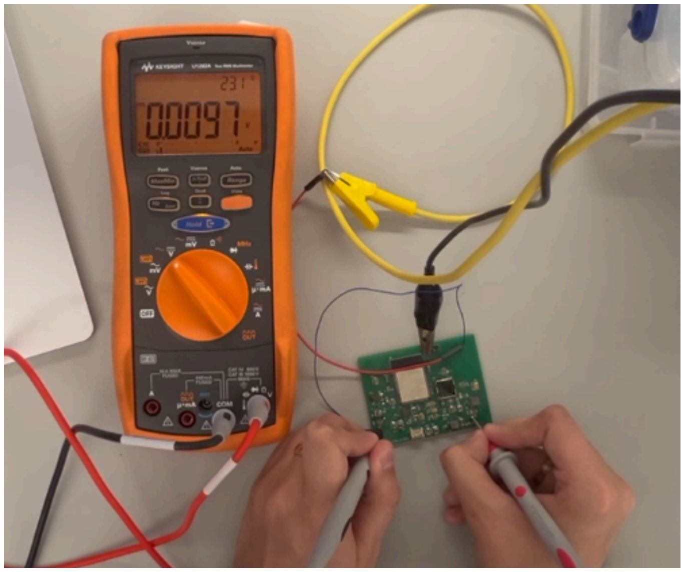

Figure 8: Results of VDDIO buck converter shown by multimeter

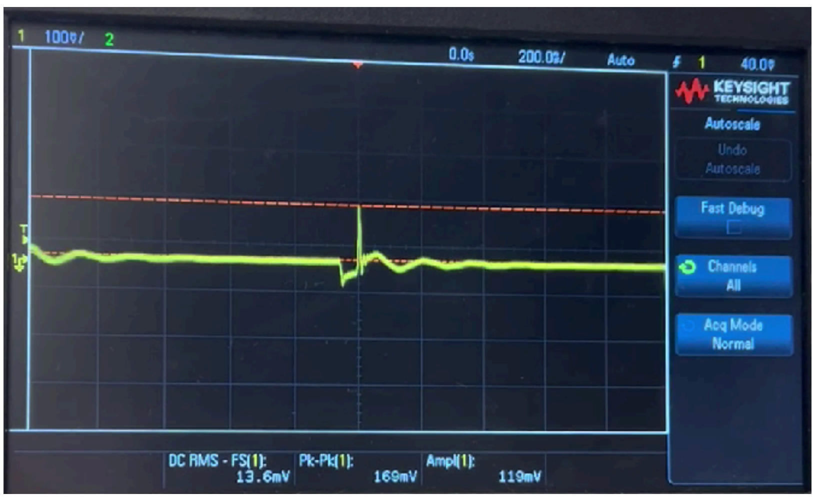

Figure 9: VDDIO buck converter output voltage on oscilloscope

To validate the connections between the microcontroller and the camera module, the connections would be tested by an oscilloscope to show data flow between them. This hasn't been completed because all four buck converters weren't working properly. The camera needs all three inputs to function and two aren't currently working.

2.4 Subsystem Conclusion

The goal of this subsystem is to ensure the two major components can receive power and communicate with each other. The hardware of the system is what provides the video for the microcontroller to send and for the website to receive.

Throughout testing two buck converters consistently functioned properly, the ESP32 input and the VDDC input. The buck converter for the VDD input worked initially, then the pulse-width modulation chip became overheated during the first round of testing, then failed during all subsequent testing. The buck converter for the VDDIO input never functioned properly, the pulse-width modulation chip is faulty and there was no time to order new parts to replace it.

Overall, the design of the buck converters is sound, but the overall functionality was unable to be properly tested.

3. Microcontroller Subsystem Report (Blake Bagley)

3.1. Subsystem Introduction

This subsystem is made up of the microcontroller and the code that will be uploaded to it. As stated previously in this report, the microcontroller has three main jobs: Connect to the operator's laptop through WiFi, take the image data from the thermal image sensor, and process the image to determine if the switch is open or closed.

3.2. Subsystem Details

For the connection to the operator's laptop, the microcontroller is set up as a WiFi access point. This will allow for the operator to choose if they want to connect to a certain microcontroller.

To describe how the microcontroller takes in the data from the thermal imager, we first need to understand how the thermal imager is sending data. The Lepton 3.5 uses SPI communication to send its data. It does this by separating rows of pixel data into packets. Each packet consists of 80 pixels of data. Those packets are then separated into four different segments each containing 60 packets. Through SPI communication, the thermal imager will send one packet per falling edge of the chip select signal. Also, for each segment, the twentieth packet will have the ID of the segment that is currently being read.

With all of this in mind, the following is how the microcontroller takes in the image data. First, the code will continuously read for valid packets until it reads a packet with an ID of zero. Then, it will start to store the packets into memory until the twentieth packet is read. If the segment number is invalid, the memory will be reset and the reading process from before will start again. If not, the segment will finish being read, and the code will restart the process of looking for the next segments until all segments are read and stored. Below is a screenshot of the code snippet described.

```
while(segment[0] != true || segment[1] != true || segment[2] != true || segment[3] != true){

    int segmentIndex = 0;                               //index of current segement
    bool badSegment = false;


    spi_device_transmit(Lepton, &receive);              //read for first row in segment
    if(((int)packet[0] != 15 && (int)packet[0] != 31 && (int)packet[0] != 63 && (int)packet[0] != 127 && (int)packet[0] != 255) && (int)packet[1] == 0){ //checks for discard frames
        memcpy(frame[index], packet, 164 * sizeof(char));       //store first row
        index++;
        segmentIndex++;

        while(segmentIndex < 60)                        //stores the rest of the segment
        {
            spi_device_transmit(Lepton, &receive);      //reads for rows
            if(((int)packet[0] != 15 && (int)packet[0] != 31 && (int)packet[0] != 63 && (int)packet[0] != 127 && (int)packet[0] != 255) && (int)packet[1] < 60){ //checks for discard

                if(((int)packet[1] != segmentIndex && ((int)packet[1] != 0  || segmentIndex != 60)) && !badSegment){
                    printf("BAD FRAME!!! %d != %d\n\n", (int)packet[1], segmentIndex);
                }

                if(segmentIndex == 20){                 //Checks which segment is read
                    printf("SEGMENT ID: %d , %d\n\n", (int)packet[0], (int)packet[1]);

                    if((int)packet[0] == 16){           // Segment 1
                        segment[0] = true;
                    }
                    else if((int)packet[0] == 32){      // Segment 2
                        segment[1] = true;
                    }
                    else if((int)packet[0] == 48){      // Segment 3
                        segment[2] = true;
                    }
                    else if((int)packet[0] == 64){      // Segment 4
                        segment[3] = true;
                    }
                    else{                               // Bad Segment
                        badSegment = true;
                    }
                }

                memcpy(frame[index], packet, 164 * sizeof(char)); //stores rows
                index++;
                segmentIndex++;
            }
        }
        if(badSegment){                                   //resets frame for bad reading
            index = 0;
            memset(segment, false, sizeof(segment));
        }
    }
}
```

Figure 10: Camera Communication Loop

Finally, the code will process the image to determine if the switch that the thermal imager is fixed on is one state or the other. It will do this by reading temperature differences between the entire frame and a smaller area of the frame in which the contact of the switch is located. Firstly, the image data stored isn't normalized at all, so it would be fairly difficult to do math that could read temperature differences. So, the code normalizes the pixel data to range from 0 to 255 using the equation below.

$$T_n = (t_i - t_{min})(\frac{255}{(t_{max} - t_{min})})$$

Figure 11: Normalization Equation

$T_n = normalized\ temperature$

$t_i = current\ temperature$

$t_{max} = maximum\ temperature$

$t_{min} = minimum\ temperature$

Then the code will calculate the average temperatures of both areas, and determine the switch's state on whether the difference in the temperatures is high enough or not. The screenshot below is of the coding snippet.

```
//Converts original frame data to 8-bit numbers
for(int j = 0; j < 240; j += 1){
    for(int i = 4; i < 163; i += 2){
        currHeat = ((float)frame[j][i] * 128) + (float)frame[j][i+1];                  //converts pixel data to one float value

        if(sideCheck == 0){
            Nframe[j/2][(i-4)/2] = (currHeat - minHeat) * (255/(maxHeat-minHeat));         //converts values to range from 0-255 (left side of row)
            side = 1;
        }
        else if(sideCheck == 1){
            Nframe[(j-1)/2][((i-4)/2)+80] = (currHeat - minHeat) * (255/(maxHeat-minHeat)); //converts values to range from 0-255 (right side of row)
            side = 0;
        }
    }
    sideCheck = side;
}

// Average for frame
for(int j = 0; j < 120; j += 1){
    for(int i = 4; i < 160; i += 2){

        rowSum += Nframe[j][i];
    }
}
frameAvg = rowSum/(240 * 80);


// Average for window of check
int pixel = 0;                      //# of pixels in window
for(int j = 24; j < 37 ; j += 1){
    for(int i = 58; i < 72; i += 1){
        checkSum += Nframe[j][i];       //adds all pixel values
        pixel++;
    }
}
checkAvg = checkSum/(pixel);            //calculates average

printf("Frame Average: %f \n", frameAvg);
printf("Check Average: %f \n", checkAvg);

//compares averages to determine switch state
if(checkAvg - frameAvg >  60){
    printf("SWITCH STATE 1 \n");
}
else{
    printf("SWITCH STATE 2 \n");
}
```

Figure 12: Image Processing Code

3.3 Subsystem Validation

To validate the WiFi connection of the microcontroller, I used my own laptop as a device for the microcontroller to connect to. I specifically set the microcontroller's SSID to be "Thermal Camera 1". The snapshots below show that my laptop was able to find and connect to the microcontroller. The second snapshot is from the ESP-IDF command prompt showing the laptop being connected.

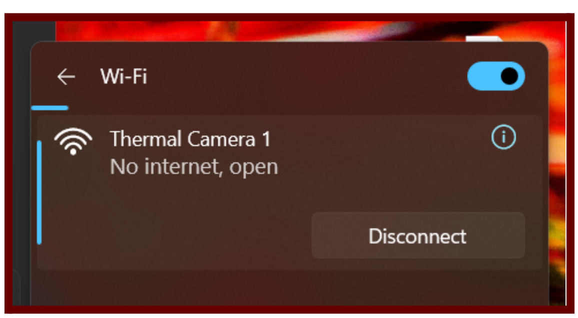

Figure 13: WiFi Connection (Laptop View)

```
I (2035) main_task: Returned from app_main()
I (13075) wifi:new:<1,1>, old:<1,1>, ap:<1,1>, sta:<255,255>, prof:1, snd_ch_cfg:0x0
I (13075) wifi:station: f8:e4:e3:73:03:57 join, AID=1, bgn, 40U
I (14935) wifi:<ba-add>idx:2 (ifx:1, f8:e4:e3:73:03:57), tid:0, ssn:20, winSize:64
```

Figure 14: WiFi Connection (ESP-IDF View)

To validate the communication between the thermal imager and the microcontroller, three tests were performed. The first test was to see if the pixel data was being stored in the correct order. This was done by having the code print the segment ID at the twentieth packet of each segment, and then checking stored values to see if they aligned. The snapshot below shows that the code read through invalid segments until it finally got to the correct ones and stored them. The first number on the left represents the segment ID and the second number represents the packet ID. The segment ID should read in order as 1, 2, 3, and 4. However, when the data is read in, the numbers for the segment ID are shifted by 4 bits. Therefore, in the screenshot, they should read as 16, 32, 48, and 64. It also does a check to see if the packets were stored correctly by printing the ID of the twentieth packet of the stored data.The ID should be 16 if the data is stored correctly.

```
SEGMENT ID: 0 , 20

SEGMENT ID: 0 , 20

SEGMENT ID: 0 , 20

SEGMENT ID: 0 , 20

SEGMENT ID: 0 , 20

SEGMENT ID: 0 , 20

SEGMENT ID: 0 , 20

SEGMENT ID: 0 , 20

SEGMENT ID: 0 , 20

SEGMENT ID: 0 , 20

SEGMENT ID: 16 , 20

SEGMENT ID: 32 , 20

SEGMENT ID: 48 , 20

SEGMENT ID: 64 , 20

ID 0: 16 , 20
```

Figure 15: Segment ID Test

The second test checks if the code will ignore invalid frames. In the previous figure, it shows that the segments whose ID is 0 get skipped until a valid ID of 16, 32, 48, or 64 is read.

The final test is to check temperature reading to make sure they align with the temperature in front of the thermal camera. This was done by putting two different heat readings in front of the thermal camera. One of the temperature readings had nothing in front of the camera. The other had a hand full covering the view of the camera. The first screenshot below shows the first 10 pixel values of the camera when nothing is in front of it. The second screenshot below shows pixel values when a hand is in front of the camera. The screenshots show that a higher pixel intensity is read when a hand is in front of the camera. Therefore, the microcontroller is correctly reading temperature increases and decreases from the camera.

```
PIXEL 0: 115 , 127
PIXEL 1: 115 , 118
PIXEL 2: 115 , 121
PIXEL 3: 115 , 141
PIXEL 4: 115 , 127
PIXEL 5: 115 , 127
PIXEL 6: 115 , 145
PIXEL 7: 115 , 136
PIXEL 8: 115 , 132
PIXEL 9: 115 , 114
```

Figure 16: Room Temperature Test

```
PIXEL 0: 117 , 170
PIXEL 1: 117 , 147
PIXEL 2: 117 , 130
PIXEL 3: 117 , 139
PIXEL 4: 117 , 124
PIXEL 5: 117 , 128
PIXEL 6: 117 , 114
PIXEL 7: 117 , 112
PIXEL 8: 117 , 120
PIXEL 9: 117 , 112
```

Figure 17: Hand Temperature Test

To validate the image processing, I needed to check if the code was reading the temperature differences in the correct regions. The region of check should be located around the top left corner of the camera's sight. To test this, I had half of the camera covered in heat in every direction and checked if the temperature differences aligned with what was interpreted by the code. The screenshots below show the average temperatures of the window of check and the entire frame, and right below that is the determination of the switch's state. These screenshots show that the readings are coming out correctly and the code is making its determination correctly. The high temperature differences are only being read when heat is in the top half of the camera frame and the left half of the camera frame.

```
Frame Average: 11.000000
Check Average: 14.000000
SWITCH STATE 2
I (1497) main_task: Returned from app_main()
```

Figure 18: Nothing in Frame Test

```
Frame Average: 29.000000
Check Average: 51.000000
SWITCH STATE 2
I (1657) main_task: Returned from app_main()
```

Figure 19: Heat in Bottom Half Test

```
Frame Average: 39.000000
Check Average: 43.000000
SWITCH STATE 2
I (1677) main_task: Returned from app_main()
```

Figure 20: Heat in Right Half Test

```
Frame Average: 69.000000
Check Average: 212.000000
SWITCH STATE 1
I (1557) main_task: Returned from app_main()
```

Figure 21: Heat in Top Half Test

```
Frame Average: 60.000000
Check Average: 143.000000
SWITCH STATE 1
I (1537) main_task: Returned from app_main()
```

Figure 22: Heat in Left Half Test

3.4 Subsystem Conclusion

The subsystem works as expected by the testing that has been done in the section above. It shows that the microcontroller is able to make a WiFi connection, correctly read and store the data coming from the thermal imager, and process that data to determine the state of a switch. As far as integration goes, all that is needed to be established is the ability to run the code on the PCB subsystem, and the ability to connect to the website subsystem through WiFi.

4. Web Interface Subsystem Report (Erica Mathew)

4.1. Subsystem Introduction

The web interface subsystem is designed to display a live video stream from a thermal sensor, allowing operators to monitor their switchgear setup more efficiently. The website includes a login/registration page, overview page, map builder page and the video stream page. Below is the website flowchart.

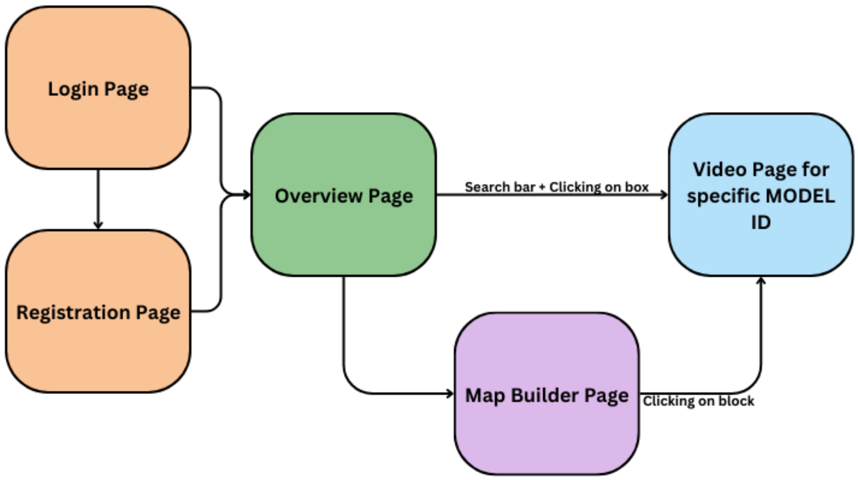

Figure 23: Website flowchart

4.2. Subsystem Details

4.2.1. Login/Registration page

The website opens to the Login Page, prompting users to enter their username and password. If they don't have a profile there is a link directing the user to a registration page. On the registration page the user must enter their email address, password, and a confirmation of their password. The website then checks if the imputed password and password confirmation matches. There are also checks written to validate that the password created is longer than 7 characters and the user provided a valid email address. If all validations pass, an account is created using Firebase Authentication. Firebase stores the user credentials in its local database. After successfully creating a profile, the user is redirected to the overview page.

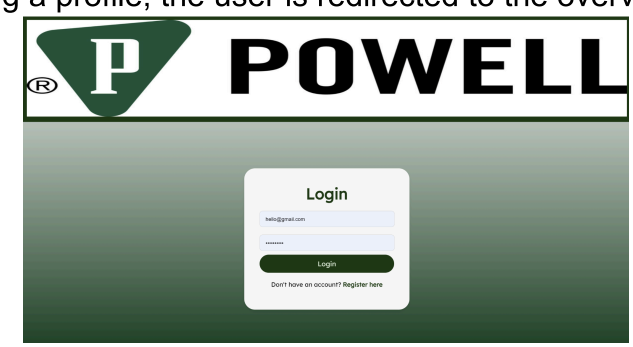

Figure 24: Login Page

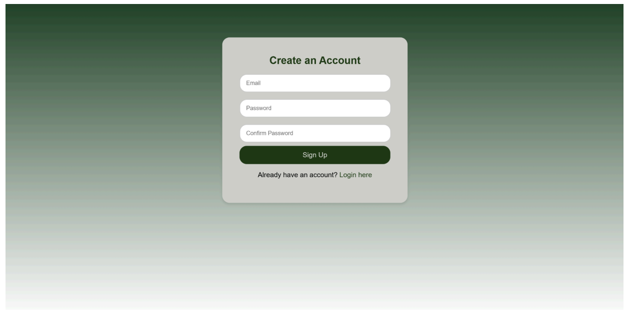

Figure 25: Registration Page

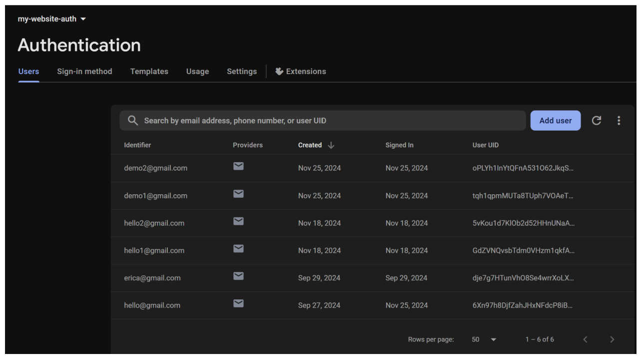

Figure 26: Firebase Authentication storing user credentials

If the user already has a profile they can sign in on the Login page with their email address and password. When the form is submitted, Firebase works to authenticate the user by checking the provided credentials against its database. If authentication fails, an error message is displayed. If authentication is successful, the user is redirected to the overview page.

4.2.2 Overview Page

The Overview page acts as a central hub of the website, allowing users to browse models, search for specific model IDs and navigate to the map builder page. At the top of the page there is a search bar to allow users to type a specific MODEL ID into the field and then press the magnifier icon to search. The search icon consists of a magnifier icon over an invisible search button; this was done to create a sleek appearance throughout the website. The search bar’s event listener handles ‘click’ events from the search button. Then the user’s input is trimmed and converted to uppercase. If the user’s input matches an available model, the user is redirected to the MODEL ID’s video page. If the input does not match, an error message is displayed. The overview page also includes a video grid that allows users to click on blocks that represent MODEL IDs. Clicking a MODEL ID block will direct the user to that specific video stream. At the bottom of the page is a link called ‘Build Your Map’ that will redirect users to the map builder page.

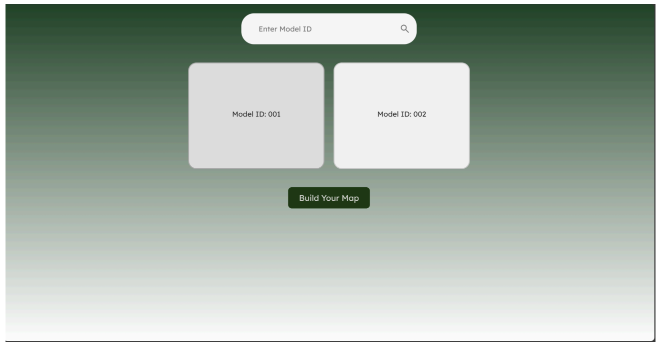

Figure 27: Overview Page

4.2.3. Map Builder Page

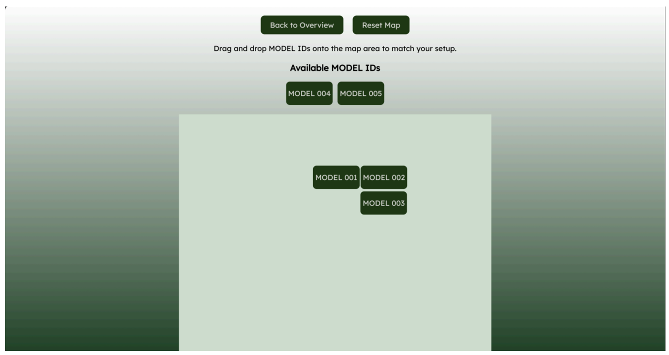

Figure 28: Map Builder Page

This feature was created to allow operators to mimic their physical switchgear setup by dragging and dropping blocks that represent MODEL IDs. By clicking on a block it will direct the user to its specific video stream.

4.2.3.1. Drag and Drop

The drag and drop feature uses the interact.js library to enable smooth dragging. When a block is dragged the position is set to absolute (which allows the block to move freely), additionally the Z-index is changed to a high number that ensures it appears on top of any other element. When the block is dragged from the *model-list* (the available model IDs at the top) into the *map area* (the white box), the block's position is calculated relative to the new container. Once the block stops being dragged, the new position is calculated by finding the difference in the x coordinates (new position - old position) and the difference in the y coordinates to get a new (x,y) coordinate. The distance from the original position to the new position is calculated using the pythagorean theorem and only if the distance is greater than 5 pixels is the movement registered. This is done to prevent unintentional movements and make the blocks move smoother.

4.2.3.2. Saving and Loading

Whenever a block located in the *map-area* is moved, its new location is saved to the browser's local storage. When the page is reloaded, there is a check to see if there is a saved layout; if there is then all blocks are moved to the saved position in the map area.

4.2.3.3. Resetting Map

On the map builder page there is a ‘Reset’ button that allows the user to clear the map area. Upon clicking the button the user is asked for confirmation to clear the page. If confirmation is granted, the saved layout saved within local storage is removed. Additionally all blocks in the map area are moved back into the model list and their position data is cleared.

4.2.3.4. Navigating to Video Page

The blocks have an event listener that detects clicks on a block. There is also a ‘dragging’ boolean that is only set to ‘True’ when the block has been moved more than 5 pixels. When the event listener detects a click and the ‘dragging’ boolean is set to false, the click is processed and the user is redirected to that block's respective video page. This is done to prevent bugs while dragging blocks.

4.2.4. Video Page

For the temporary demo, this website reads from a zip file of 1000 images and displays it one by one to mimic a video stream.

4.2.4.1. Server Side

A websocket server was created using node.js and ws library. The server listens on port 8080 for an incoming client connection. When a connection is made, the server checks the URL of the request to determine which stream it wants. The website has MODEL ID’s 001 and 002 set to read from the image zip file, while MODEL ID’s 003-005 are empty. This was done to show that every block leads to a unique video page. If the client connects to 001 (meaning the user clicked on 001 block), then the server request is for 001 stream. The server then sorts through all the files and ensures they are all jpg, jpeg or png. Once the client connects, the server sends images to the client at a regular interval. The server reads images from the disk and converts them into a JSON string containing base64-encoded image string (which allows it to be sent over websocket as text data). The images are sent in a loop one at a time with a 1 second delay. Both 001 and 002 read from the same zip file to save space, but form their own websocket connection. This was done to show they are independent streams. After integration with the microcontroller, the server will receive live images from the thermal sensor.

4.2.4.2. Client Side

The client side is the browser that displays the images sent by the server. Once it establishes a websocket connection to the server, the JSON string is converted into a javascript object to extract the base64 string. The <img> element in the html file is then being constantly replaced with the new image to mimic a video stream.

The video page has two buttons on the top that allow the user to redirect from the video page to either the overview page or the map builder page.

4.3 Subsystem Validation

4.3.1. Receiving Video

The website was validated to ensure the proper video stream was playing for every MODEL ID. For MODEL ID's with no images (003-005) an error message was displayed to alert users that there is no assigned image file. Both MODEL ID 001 and 002 should link to their respective video page. This was confirmed by both the MODEL ID title at the top of the video page and by checking the console and seeing the connection.

4.3.2. Login System

The Login system was validated to ensure the login page would work with correct credentials and fail with incorrect credentials. This was confirmed by having the user register a new profile, confirm it can be found in Firebase, then log in with the new profile.

4.3.3. Search Bar

The search bar was validated to ensure it would redirect users to the proper video stream. This was tested by having a user type an available MODEL ID and then confirm that they were directed to the correct video page. Additionally, the user typed an incorrect MODEL ID and was given an error message.

4.3.4. Video Display Page

The video display page (overview page) was validated by clicking different MODEL ID blocks and ensuring that the user was directed to the correct video stream.

4.4 Subsystem Conclusion

The goal of the website is to create a simple solution that allows switchgear operators to remotely monitor the state of a physical ground switch within their switchgear. This website allows for simplified monitoring of multiple video streams. Once it is integrated with the microcontroller it should receive image data from a thermal sensor in real time. Below is a walk-through of the website flow.

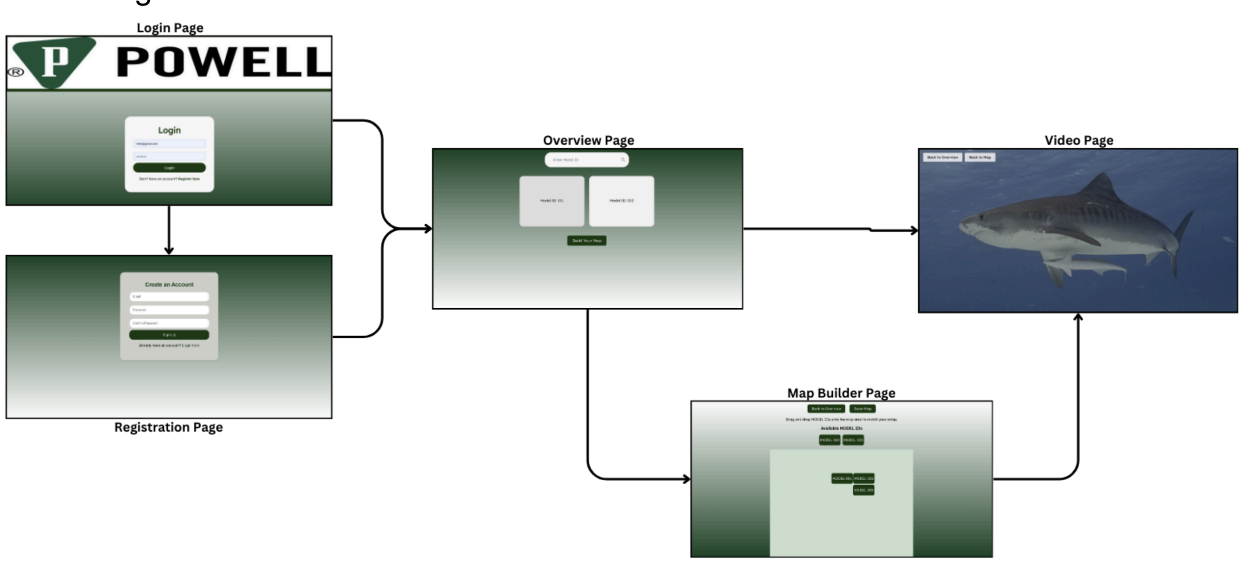

Figure 29: Website Walk-through