Project Final Report
OTheRS

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Acronyms

ADC	Analog to Digital Converter
CAD	Computer Aided Design
CAM	Computer Aided Machining
CAN	Controller Area Network
CDD	Conceptual Design Document
CDR	Critical Design Review
CONOPS	Concept of Operations
COTS	Commercial Off-the-Shelf
DAQ	Data Acquisition System
EAR	Export Administration Regulations
ESD	Electrostatic Discharge
FBD	Functional Block Diagram
FOV	Field of View
FR	Functional Requirement
FPGA	Field Programmable Gate Array
GA	General Atomics
HDL	Hardware Description Language
I2C	Inter-Integrated Circuit
I/O	Input-Output
IP	Image Processing
IR	Infrared Radiation
ITAR	International Traffic in Arms Regulation
ITLL	Integrated Teaching and Learning Laboratory
JIT	Just In Time
LED	Light Emitting Diode
LWIR	Long-wave Infrared Radiation
MCU	Microcontroller Unit
MHz	Megahertz
mm	Millimeter
MOSFET	Metal-Oxide Semiconducting Field-Effect Transistor
MPU	Microprocessor Unit
ORB	Oriented FAST Rotated BRIEF
PCB	Printed Circuit Board
PWM	Pulse Width Modulation
RANSAC	Random Sample Consensus
SDK	Software Development Kit
SPI	Serial Peripheral Interface
TID	Thermal Imaging Device
TRL	Technology Readiness Level
UART	Universal Asynchronous Receiver Transmitter
PID	Proportional Integral Derivative
PCB	Printed Circuit Board
V	Volts
V&V	Verification and Validation

Nomenclature

α	=	Thermal diffusivity ($\frac{m^2}{s}$)
A	=	Amps
A_s	=	Surface area (m^2)
β	=	Volume expansion coefficient
B	=	Planck's law constant
c_p	=	Specific heat at constant pressure ($\frac{kJ}{kgK)}$
δ_x	=	Change in variable x
D	=	Working distance (meters)
$\dot{Q}_{conv}$	=	Heat transfer due to convection (watts)
$\dot{Q}_H$	=	Heat transfer from the hot source (watts)
$\dot{Q}_{rad}$	=	Heat transfer due to radiation (watts)
$\dot{Q}_{reject}$	=	rejected heat transfer (watts)
$\dot{Q}_{req,equil}$	=	required heat transfer for equilibrium condition (watts)
ϵ	=	Emissivity
F	=	Planck's law constant
g	=	gravitational acceleration ($\frac{m}{s^2}$)
H	=	Working height (meters)
$h_{surface}$	=	surface roughness
K_D	=	Derivative gain
k	=	Thermal conductivity ($\frac{W}{mK}$)
K_P	=	proportional gain
K_q	=	Cross couping matrix
λ	=	Wavelength (meters)
L_c	=	Characteristic length (meters)
m	=	mass (kilograms)
ν	=	Kinematic viscosity
Nu	=	Nusselt number
O	=	Planck's law constant
P	=	Power (watts)
Pr	=	Prandtl's number
$R1$	=	Planck's law constant
$R2$	=	Planck's law constant
ρ	=	Density ($\frac{kg}{m^3}$)
R	=	Resistance (ohms)
σ	=	Stefan Boltzman constant ($\frac{Wm}{^\circ K^4}$)
τ	=	Time constant (s^{-1})
θ_h	=	Horizontal mount degree (degrees)
θ_v	=	Vertical mount degree (degrees)

R_a	=	ambient thermal resistance (watts)
R_{th}	=	Thermal resistance (watts)
T	=	Temperature (Degrees kelvin)
T_0	=	Initial temperature (Degrees kelvin)
T_s	=	Surface temperature (Degrees kelvin)
T_∞	=	Ambient temperature (Degrees kelvin)
T_{actual}	=	Actual temperature (Degrees kelvin)
T_{target}	=	Target temperature (Degrees kelvin)
T_{obj}	=	Object temperature (Degrees kelvin)
V_{in}	=	Voltage in (volts)
V_{rms}	=	RMS Voltage in (volts)
V_{supply}	=	Supply voltage in (volts)

1. Project Purpose

Author: Micah Svenson

The OTheRS project seeks to provide proof of concept for an innovative non-contact thermal regulation solution using Long Wave Infrared (LWIR) cameras. This solution seeks to reduces the overall size and resource impact of a thermal regulation system, leaving more room for additional payloads.

Satellites are made up of complex electrical systems that operate in harsh space environments with extreme temperature fluctuations. This makes thermal regulation necessary at all times to maintain mission operation. Current satellite thermal regulation systems provide a robust and simple solution involving a large number of wired thermal sensors, such as thermistors. While this is a reliable and proven solution, there are downsides including complexity in wire management and large numbers of satellite bus inputs. Furthermore, as demand increases for small-sat's and cube-sat's, more compact and efficient thermal regulation systems are needed.

However, the purpose of the OTheRS system lies outside normal applications of IR cameras. As such, there is a scarcity of information on the behavior and accuracy of IR cameras when used on highly reflective material at large skew angles. For this reason, the OTheRS project will focus on quantifying the performance of such a system and making recommendations for future development rather than delivering a satellite ready thermal regulation system.

A replica of a General Atomics Small Satellite Avionics Bay will be constructed using the same materials and dimensions and will produce a representative thermal profile that can be imaged and analyzed. Additionally, the centrally located and enclosed internal electronics stack will be fitted with thermistors to validate thermal data captured by the thermal camera. The system will send thermal data from the camera through a serial output and produce on/off control commands to heaters or other representative indicators to simulate thermal control of the electronics systems. Finally, it should be noted that at this early stage of development it has been determined that mapping temperature from the outer surface of the electronics stack to localized PCB temperatures is out of the scope of this project.

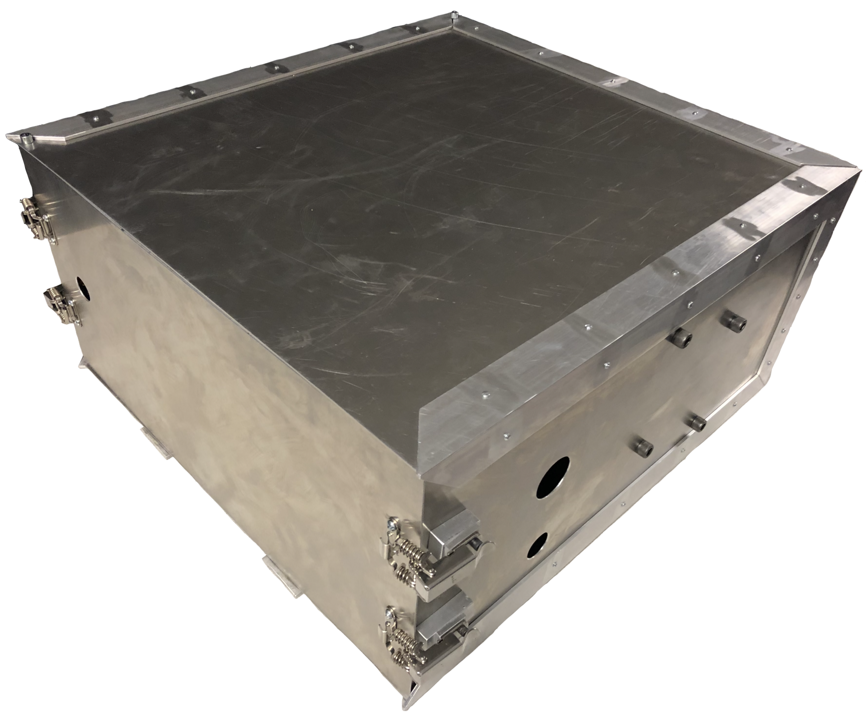

Figure 1: OTheRS Final Test Bed (Avionics Bay)

2. Project Objectives and Functional Requirements

Author: Ryan Bennett, Kendall Worden, Micah Svenson, Pierre Guillaud, Nash Jekot

2.1. Functional Requirements

Below are the Functional Requirements of the OTheRS.

FR 1 OTheRS shall return a thermal data map for multiple components between -30°C and 60°C.
Motivation: This requirement is given by the customer as a primary design driver for the developed system. The thermal map allows thermal control of components that are viewed by the system. This is the primary motive for the project and system as the thermal imaging device(s) are desired to replace the current thermal measuring devices in the spacecraft.
Validation & Verification: Test - Thermal ambient testing will verify if the system can sense this temperature range and resolution. Also, satisfaction of all child requirements will demonstrate the satisfaction of the full functional requirement.

FR 2 OTheRS shall provide regulatory commands when components are outside -20°C to 50°C.
Motivation: This requirement is given by customer as a primary design driver for the developed system. Regulatory commands outside of this range will allow for thermal control of the stack.
Validation & Verification: Test - Regulatory commands can be demonstrated using test cases while the full requirement will need to be satisfied in a thermally controlled and monitored environment. This will also be demonstrated once the child requirements are met.

FR 3 System shall operate on 28V unregulated power provided by the spacecraft.
Motivation: The satellite provides power at this voltage. Therefore, this is a customer defined requirement that allows integration of this system to a mock satellite.
Validation & Verification: Test - Verify system is operational when power is provided by a power supply at the given voltage.

FR 4 OTheRS shall fit within a standard GA nanotray, with dimensions of 18.5cm x 13cm.
Motivation: This is a customer derived requirement to allow for system integration into GA models and tests. This also provides a size requirement to define the available space for the system.
Validation & Verification: Demonstration - The final system can be measured to show the size is within the required dimensions and will be an important consideration when selecting components.

FR 5 OTheRS shall be able to switch a 2.5A load, as needed, to control an externally powered heater or representative indicator.
Motivation: The customer gave this as a desired capability for the system meaning is was customer given and not derived. This is the heater specification given by the customer.
Validation & Verification: Demonstration/Test - An ammeter can be used to verify the output signal meets this requirement and the representative indicator will visually show when the heater will be powered on and off.

FR 6 The thermal imaging device(s) shall image critical stack electronics on at least a single side of the stack.
Motivation: Customer derived as the purpose of this project is to monitor the temperature of the electronics stack in the satellite. Being able to view at least an entire side of the stack will allow for thermal control of the stack.
Validation & Verification: Inspection - An image of the stack can be inspected to verify that this requirement is satisfied. Overlap may be verified using markers that are visible to the camera to allow for easier validation of the requirement.

FR 7 OTheRS shall regulate its own temperature.
Motivation: Thermal regulation of the OTheRS will allow for components and subsystems to function properly in a harsh thermal environment. The thermal environment is already known to be outside the operating bounds of the needed components so thermal control is critical to project success.

Validation & Verification: Test - Testing in a thermal ambient chamber will show if the thermal regulation is successful. Validation of child requirements will also allow for demonstration prior to final testing where components may be damaged by the harsh environment.

FR 8 Test bed shall mimic the GA satellite.
Motivation: This requirement is derived from customer requirements to show feasibility of the system to operate in a mock satellite. This will also show the designed system will function within the satellite which is part of the base idea of the project. Using a mock up of the satellite will allow for testing in a simplified environment without the full constraints of using a satellite that is undergoing testing for launch.
Validation & Verification: Inspection - The test bed can be inspected and compared to the provided CAD file to verify dimensions and other key specifications. Also, materials must be compared to the customer provided information to ensure they match the thermal properties. Design requirements in the Test Bed subsystem can be successfully verified to validate completion of this requirement.

FR 9 OTheRS shall not include ITAR restricted articles.
Motivation: The project is published in public domain so the University requires this as part of the course. Given most of the thermal imaging devices are export controlled under EAR, the requirement only pertains to ITAR as it is more restrictive.
Validation & Verification: Inspection - Checking all parts used in the OTheRS prior to purchasing or installation.

2.2. Requirement Flowdown

2.2.1. Thermal Imaging

DR-IMAG 1 The thermal imaging device(s) shall be sensitive to IR Radiation, measuring between 8.70 to 11.93 microns or -30 to +60 °C.
Motivation: This requirement is a direct flowdown from the parent requirement, FR 1. If the test range is defined by this range, the chosen thermal imaging device(s) must be able to sense the entire range.
Validation & Verification: Inspection - Checking the data sheet will show if the selected device will meet this requirement. It is assumed the camera is made well enough so the team will not have to make modifications to the selected sensor for the sensing range.
Related Requirements: **FR 1** - This requirement flows directly down both logically and technically. If the device cannot sense the entire range then the FR is failed.

DR-IMAG 2 Images of the stack shall be taken at no more than 90 second intervals.
Motivation: During preliminary testing, it was determined that it takes approximately 90 seconds for the surface of the stack to change by 1°C when using power resistors to heat the inside of the stack. This is important to set the minimum capture range so the temperature can be accurately tracked as they change.
Validation & Verification: Demonstration/Inspection - The image capture rate will be defined by the camera or the code to automate the camera. The code can be checked and thus demonstrated using data capture of an object being monitored by other sensors such as a thermocouple. Another technique would be to change the scene objects before the next image is captured which can be visually seen when checking the output of the thermal imaging device(s).
Related Requirements: **FR 1** - This requirement flows down from the first FR as it specifies the thermal data mapping frequency. This is more of a designers choice as the team would like to closely monitor the thermal profile and oversampling is likely for this requirement.

DR-IMAG 3 The thermal imaging device(s) shall be 100 to 146.73 mm from the stack.
Motivation: This is a spatial constraint from the satellite design depending on which sides are monitored and the exact placement of the thermal imaging device(s)
Validation & Verification: Inspection - Measuring the placement of the camera in the test bed.
Related Requirements: **FR 6** - The distance will have an effect on how much of the stack a single thermal imaging device can see. This means the FOV of the device and the distance can be used

to see the overlap. This derives directly from the FR as to view the entire side, there must be total overlap between the thermal imaging devices or a single device must view the entire side.
FR 8 - The distance from the stack is driven by an accurate representation of the customer's satellite. This logically flows down from the ability to recreate or mimic the actual satellite as the accurate representation will also have the same mounting constraints as the satellite.

DR-IMAG 3.1 The field of view (FOV) of the thermal imaging device(s) shall contain at least a single side of stack.
Motivation: Given the distance requirement in the higher level requirement, the FOV of the device(s) must have overlap to provide the entire view of the stack. This is crucial for the parent requirement which states the entire side is to be viewed by the device(s).
Validation & Verification: Inspection/Demonstration - Using calibration points, high emissivity stickers, placed at points where overlap is questionable, the output from the thermal imaging device(s) can be checked. By placing the stickers in a known configuration, the output images can be directly checked to ensure the points show up in one or multiple images. The placement of the points will need to be modified to verify the requirement is met.
Related Requirements: **FR 6** - To view the entire side of the stack, it must be verified that the entire side is contained within the FOV of the device(s). This flows logically out of the FR and into the DR.

2.2.2. Processing

DR-PROC 1 The thermal map shall differentiate between objects in stack based on satellite and test bed configurations.
Motivation: Given there are more than a single object in the stack, the thermal map must be able to show the objects' thermal map separately. This allows for separate control of the objects.
Validation & Verification: Demonstration/Inspection - Test images that have been processed can be visually inspected to validate the thermal map is partitioned into the different objects.
Related Requirements: **FR 1** - This requirement flows from the FR as the FR calls out multiple objects being in the stack. The DR shows how the map will identify the different components in the stack or scene which is a logical flow down from the FR.
FR 2 - Being able to control the objects in the scene means having a thermal profile or data map for the object. By identifying the objects and allocating a certain amount of the data map to the object allows for regulatory commands to be provided for the components or objects individually. This is a direct flow down from the FR.

DR-PROC 1.1 The thermal map shall distinguish between up to 6 objects (trays) in the stack.
Motivation: The customer's satellite design allows for up to 6 tray. This means OTheRS must be able to identify the maximum number of objects in the tray to satisfy the customer's requested capability.
Validation & Verification: Demonstration/Inspection - If the processing software can identify the maximum number of objects or trays in the images, then the requirement is met. This will provide the customer with the ability to test up to the worst case scenario for the satellite configurations.
Related Requirements: **FR 1** - This flowdown from the FR is very similar to the flowdown for DR-PROC 1 but quantifies the maximum number of objects in the images which further specifies the FR.
FR 2 - This flowdown is the same logic behind the flowdown from FR 1. The DR quantifies the maximum number of components or objects that must be monitored and issued regulatory commands if needed.

DR-PROC 2 The thermal imaging device(s) shall be both spatially and thermally calibrated.
Motivation: Calibration is needed to ensure the camera is achieving the highest degree of accuracy with thermal measurement and the camera is viewing the right objects. The calibration will primarily be handled by the processing software and is important to the combination of the images if multiple devices are being used. The metrics have yet to be determined for thermal calibration have yet to be determined due to uncertainties in the project. The metrics are likely to be nailed down during preliminary testing with the initial prototype test bed.

Validation & Verification: Inspection/Test - The spacial calibration can be confirmed visually using calibration points as mention in DR-IMAG 3.1. This is just visual inspection but requires the device(s) to be in the correct orientation. Thermal calibration will be determined in testing once the metrics for calibration are found. The team expects this to be found early in next semester.
Related Requirements: **FR 1** - Calibration is important to the stitching and thus the ability to image multiple components. Thermal calibration also factors in to the accurate measurement of the thermal range as defined in the FR. Both flow directly from the FR but different places in the FR.
FR 2 - Similar to FR 1 flowdown for the DR, the calibration plays an important role into the accuracy of the OTheRS. This means the DR further defines the accuracy of the thermal range and also if the correct object is being controlled with the regulatory command.
FR 6 - Geometric or spacial calibration will define how the image(s) contain(s) the entire side of the stack. This will ensure that once calibrated, the side of the stack will be in the FOV of the device(s). This is important for the repeatability of the testing and validation of the FR meaning that it flows directly out of the FR.

DR-PROC 3 Internal processing shall control the internal thermal regulation of the OTheRS.
Motivation: When testing in the thermal chamber takes place, the OTheRS will likely be out of the sub-components' operational bounds. This means thermal control is needed for the system to ensure it survives full testing testing. For initial testing, the team has assumed that the thermal imaging device(s) are designed well enough to dissipate the correct heat at the high side of the testing range. An important note is that the selected thermal imaging device(s) have built in protection when they are outside their operational bounds.
Validation & Verification: Test - The utilization of test cases will allow for the verification of this requirement. The test cases will be designed to check the controlled response over time to validate the correct response and ability to maintain the needed bounds.
Related Requirements: **FR 7** - The ability to thermally self regulate is called out by the FR. The DR flows from this as the DR calls out how the OTheRS will complete the self regulation and further defines the system that needs to be developed.

DR-PROC 4 Temperature data shall be extracted from the thermal image.
Motivation: Temperature data is what is used to control the stack and objects while also verify the bounds set out by the parent requirements. This is used to define what the thermal data map is and how it is generated.
Validation & Verification: Test/Demonstration - The temperature data can be confirmed via a test and check of the output data. Using truth data points at similar locations as the pixels, a thermal map can be developed from the truth measurements and thus used to confirm the thermal image data.
Related Requirements: **FR 1** - This DR defines the how and the what for the thermal data map that is mentioned in the FR. This logically flows from the FR and helps define the FR further.
FR 2 - The temperature data shows how the need for the regulatory commands is developed. This flows from the FR as it provides a deeper explanation as the generation of the commands and how the commands are determined.

DR-PROC 4.1 Automated image processing shall be completed between image captures as defined in DR-IMAG 2.
Motivation: The processing of the images is crucial so a backlog of images is not developed. This will provide real time data and allow for better control. If the images develop a back log, the objects may overheat and the system will not issue commands as it is not seeing real time images and data.
Validation & Verification: Demonstration - Using the selected components to process similar images to the output of the thermal imaging device(s), accurate run times for the processor can be obtained. If the times for all developed processing functions or modules totals to less than the worst case scenario for the processing, then the requirement will be met.
Related Requirements: Same requirements flowdown as called out in DR-IMAG 2 just flows down to a processing subsystem rather than the thermal imaging device.

2.2.3. Power Management

DR-POW 1 The power management subsystem shall provide power distribution to the subsystems within OTheRS.
Motivation: Components will likely function with different input voltages that are less than the 28V provided by the spacecraft bus. Stepping the power down to the appropriate voltages or power will allow for the OTheRS to function properly and as designed.
Validation & Verification: Demonstration/Test - When the subsystem is given 28V from a power supply, the outputs from the subsystem can be checked with an oscilloscope or voltmeter to verify the correct voltages are being distributed.
Related Requirements: **FR 3** - Power distribution logically flows down from the provided power requirement, the FR. This DR is to provide all components within the OTheRS the correct voltages and powers to the components such that the system functions properly.
FR 5 - The ability to switch the required load will need to allocated view the power management subsystem to ensure the output can switch the required load. This FR will directly affect the power management subsystem which means this subsystem must account for this need and partially drives the design of the power management.

DR-POW 2 Power shall be transferred and distributed using D-Type connectors.
Motivation: This is a desired functionality for the system given by the customer. It is used to simplify the implementation of the system into the final satellite and is consistent with the customer's current design.
Validation & Verification: Inspection - All power connections can be checked to ensure they use this connector type.
Related Requirements: **FR 3, FR 5** - Both the FR flowdown to the DR to ensure the design is consistent. This will allow for plug and play capability with components and ultimately the customers designs.

2.2.4. Control

DR-CONT 1 A control decision shall be communicated by the OTheRS to turn a heater on or a representative indicator.
Motivation: This is customer defined and critical to the thermal control of the stack. Representative indicators can be used to decrease the test bed complexity and possible differences between the customer's desired solutions and the provided system.
Validation & Verification: Demonstration/Test - In the thermal ambient testing, an actual or representative system, can be used to verify OTheRS is sending the correct command for the object or tray. Test cases can also be used to ensure that the controller is functioning as designed prior to increased complexity with testing.
Related Requirements: **FR 2** - Regulatory commands are what must be communicated as determined by the FR and DR. The commands may be as simple as on/off commands which provides further explanation as to what is meant by the FR when regulatory commands is used.
FR 5 - The control of a heater or representative indicator is explained further by the DR meaning it flows out of the FR. This DR explains where the control originates from and also what controlling the heater means. An important note to this flowdown is that the heater is externally powered, thus does not factor into the OTheRS power budget but requires the load to flip the switch on the heater.

DR-CONT 2 A control decision shall be communicated by the OTheRS to turn a component off or a representative indicator.
Motivation: This is customer defined and critical to the thermal control of the stack. Representative indicators can be used to decrease the test bed complexity and possible differences between the customer's desired solutions and the provided system.
Validation & Verification: Demonstration/Test - In the thermal ambient testing, an actual or representative system, can be used to verify OTheRS is sending the correct command for the object or tray. Test cases can also be used to ensure that the controller is functioning as designed prior to increased complexity with testing.

Related Requirements: **FR 2** - Regulatory commands are what must be communicated as determined by the FR and DR. The commands may be as simple as on/off commands which provides further explanation as to what is meant by the FR when regulatory commands is used.

2.2.5. Internal Thermal Regulation

DR-THER 1 The internal temperature of the OTheRS shall be monitored by at least one thermistor.
Motivation: During thermal chamber testing, components within the OTheRS are likely to be out of operational ranges as described earlier. To allow for the thermal regulation of the system to be handled, there must be a source of measurement which thus answered by this DR. It should also be noted in this requirement that the selected thermal imaging device cannot exceed a specified thermal gradient across the sensor meaning more thermistors must be used to verify this limit is not exceeded.
Validation & Verification: Inspection - Verify the components that monitor the temperature of the OTheRS are thermistors. This is likely to happen prior to procurement.
Related Requirements: **FR 7** - The rationale behind the flowdown from the FR to the DR was touched on in the Motivation for the DR. The logical flowdown is that the regulation relies on a sensor on the critical components for control which is what the DR calls out.

DR-THER 2 The minimum operating temperature of the OTheRS shall be determined by the highest minimum operating temperature of other subsystems or components.
Motivation: The minimum bound of operation temperature for the entire system will need to be the highest minimum operating temperature of the selected components that comprise the system. This will ensure that all components that go inside the thermal chamber are maintained within their operating range and thus function in the thermally controlled environment at the testing range.
Validation & Verification: Inspection/Test - The datasheets for all components will need to be inspected after it is decided which components go within the thermal chamber. This will define the inputs for the controller which can thus be initially verified through inspection. The next step would be to provide the controller test cases and verify the response will fit the components' ranges that are within the thermal chamber.
Related Requirements: **FR 7** - The regulation of the OTheRS will primarily be concerned with the minimum range of the components as they are assumed to be designed well enough to dissipate their own heat at the high operational range. This DR flows down from the FR as it defines the minimum range for the thermal regulation of OTheRS. This is both a logical and technical flow as it further defines the FR both qualitatively and quantitatively. It will also aid the design of the controller as it will establish the absolute minimum that the system can handle.

2.2.6. Communication

DR-COM 1 The OTheRS subsystems shall use serial communication to transfer information, signals, etc. with the spacecraft bus.
Motivation: This is a customer derived requirement as communication with the OTheRS and the spacecraft bus is a desired capability. Also regulatory commands may require the use of serial command depending on the component used.
Validation & Verification: Inspection - The output of the OTheRS can be outputted to a computer and the signal can be observed. The signal can also be decoded to determine the information sent and thus confirm the functionality of the communication.
Related Requirements: **FR 2** - This requirement flows down from the FR in a logical sense as it specifies how the commands are communicated. This aids the integration of the system into the customer's product.

DR-COM 1.1 OTheRS shall communicate with RS-232 communication protocol.
Motivation: The customer required either CAN or RS-232 communication protocol as a standard communication with their current product. PAB members recommended against the use of CAN if the customer would not provide support. After speaking with the customer it was determined the OTheRS would use the RS-232 communication protocol as a standard to allow for system

integration.
Validation & Verification: Inspection - Observation of the signals sent from the system can show they are in fact communicated via RS-232. These signals can be directly viewed on a computer for verification.
Related Requirements: **FR 2** - Similar to the higher level requirement, DR-COM 1, this DR will further specify how regulatory commands are communicated with the spacecraft. This means the flowdown from FR to DR is logical while also being a designer's choice. Given the legacy of the protocol along with group member experience with the protocol, the learning curve for implementation will be lessened.

DR-COM 2 OTheRS shall communicate with a heater communication protocol, if any is needed.
Motivation: Depending on the component selected to be or represent the heater, a communication protocol will not be needed. If a protocol is needed, the system will communicate with the device's native protocol to allow for simplified integration.
Validation & Verification: Inspection - If the data sheet of the selected component determines the component has a protocol it can be tested similar to the other communication subsystem requirements. If the data sheet determines this device is "dumb" and does not require a communication protocol, this requirement will be met.
Related Requirements: **FR 2** - This DR specifies what may be accepting the regulatory commands from the OTheRS. This logically flows from the FR as it shows how the commands are communicated with the heaters.

2.2.7. Test Bed

DR-TEST 1 The outer dimensions of the stack in the test bed shall be 246.3mm x 290mm x 318mm.
Motivation: This requirement is derived from customer provided models of the product. This will enable the OTheRS to test in a replicated environment of the satellite and not require the satellite.
Validation & Verification: Demonstration - Verifying the designs in CAD prior to manufacturing will allow for the measurements to be initially verified. The full verification will be measuring the final, assembled stack to check the dimensions are met.
Related Requirements: **FR 8** - This flows from the FR in a technical sense due to it calling out the required size of the designed test bed component. The ability to mimic the satellite will allow for component being viewed by the thermal imaging device(s) to be an accurate representation of the actual product.

DR-TEST 1.1 The interior dimensions of the test bed shall be 261.3mm x 515mm x 547mm.
Motivation: This requirement is derived from customer provided models of the product. This will enable the OTheRS to test in a replicated environment of the satellite and not require the satellite.
Validation & Verification: Demonstration - Verifying the designs in CAD prior to manufacturing will allow for the measurements to be initially verified. The full verification will be measuring the final, assembled test bed structure to check the dimensions are met.
Related Requirements: **FR 8** - This flows from the FR in a technical sense due to it calling out the required size of the designed test bed component. The ability to mimic the satellite will allow for thermal imaging device(s) to be mounted in similar methods to the customer product and provide the correct surrounding environment along with mounting constraints in the customer's product.

DR-TEST 1.1.1 The overall stack surface material shall be 5mm thick.
Motivation: This requirement is derived from customer provided models of the product. This will enable the OTheRS to test in a replicated environment of the satellite and not require the satellite. Also, this will provide similar thermal considerations to the actual test bed and heat flow across the wall.
Validation & Verification:Demonstration - Verifying the designs in CAD prior to manufacturing will allow for the measurements to be initially verified. The full verification will be measuring the final, assembled stack to check the dimensions are met.
Related Requirements: **FR 8** - This flows from the FR in a technical sense due to it calling out the required size of the designed test bed component. The ability to mimic the satellite will allow for

thermal imaging device(s) to view a similar thermal environment and heat flow across the wall to the customer's product.

DR-TEST 2 The stack shall replicate the thermal operating range of electronics contained in the stack, as defined in FR 1.
Motivation: The range of the components within the stack is given by FR 1 meaning the stack must be able to replicate the thermal range of the FR. This will allow for testing the range as defined by the customer.
Validation & Verification: Demonstration/Test - A thermally controlled environment is likely to be used for this thermal range due to the end points of the range. A test or demonstration using just the structure and a reference data system will verify if the stack structure actually reaches the defined range. This will also validate initial finding from thermal changes across the material in an ambient environment.
Related Requirements: **FR 1** - The stack will need to tested at the defined thermal range and specifies why this is the thermal range. This means the DR will flow directly down from the FR. **FR 8** - An accurate representation of the customer satellite will be both structurally and thermally. The thermal representation will be handled by this DR and thus flows out of the FR.

DR-TEST 3 OTheRS shall not be mounted to the outer walls or stack of the test bed.
Motivation: This is a customer derived requirement for how the entire system will be mounted.
Validation & Verification: Inspection - Check the designed CAD models to ensure this requirement is met and upon completion of the final design, verify the mounting is not to the outer walls or the stack.
Related Requirements: This requirement does not flow directly down from any FR as it is a customer defined capability and constraint for the system.

DR-TEST 4 Test bed structure shall replicate material thermal properties of GA's satellite bay.
Motivation: This requirement is derived from customer models and to allow for the structure to replicate the thermal environment of the actual satellite. This requirement will also allow for some variations of the surface material as the intention for the test bed is to allow for variation of parameters.
Validation & Verification: Inspection - Material selection will be important to the V&V of this DR. The assumption will be the data sheet or material properties are constant at the provided values. The values may either be direct from the manufacturer, supplier, or academic research.
Related Requirements: **FR 8** - This DR further defines the ability to recreate the thermal environment of the customer satellite. This further defines the FR and is a technical flowdown from the FR to quantitatively define the thermal replication of the satellite.

2.3. Project Deliverables

The goals of the OTheRS test bed are as follows: First, determine and quantify the ability of the FLIR Lepton IR camera to return spatially and thermally accurate temperature data for an outer face of the GA avionics electronics stack. Second, determine an effective method to reduce surface reflectivity in the FOV of the camera. Third, experimentally determine the extent to which mapping outer surface temperature to internal heat sources is feasible. Fourth, provide proof of basic thermal regulation capabilities. With these goals in mind, the main deliverable for this project is the final test bed apparatus. The test bed replicates the avionics bay of a GA satellite in both dimensions and materials. However, it's design has been altered to create a variable parameter test environment where a variety of test can be conducted that seek to meet the goals stated above. Additional systems have also been designed to assist in the verification and validation of the IR cameras performance as well as mimicking real world satellite conditions. Finally, a comparison between IR cameras and traditional wired sensors will be drawn based on final test bed results.

2.4. CONOPS

Figure 2 depicts the concept of operations for the OTheRS test bed. The aluminum electronics stack is made up of 6 aluminum trays with each containing its own PCB. The PCB's are instrumented with a grid of heating elements in order to facilitate a variety of localized heating tests. The trays are stacked such that the exterior edges are touching on all sides, forming a solid surface on each of the four sides. The rectangular stack is located in the center of a rectangular Avionics bay and IR cameras are mounted to the floor and ceiling of the bay, imaging a single side of the stack. The imaged side of the stack is instrumented with a six by six grid of thermistors on the interior of the stack in order to provide truth measurements for the temperature data returned by the cameras.

The IR cameras are the core of the OTheRS system. Because they are situated outside of a thermally regulated area, they require their own thermal management system to maintain operating temperatures and optimal data accuracy. They are also mounted in fixed positions, but must be calibrated both spatially and thermally to operate correctly. This calibration occurs after images of the stack have been captured. They are sent to an on-board processing unit that processes images using custom built software, which spatially and thermally calibrates the images, corrects skew aberrations due to mounting angles, and stitches the images together to finally provide a cohesive temperature map of the stack face. This temperature data will also be sent to a controller ensure temperatures remain within their operating range. The OTheRS systems will track temperatures on a tray by tray basis and provide heater on/off commands to a representative indicator, such as an LED. This simulates a full control system that would be implemented on a satellite ready system. The temperature data is also sent to a monitoring device via RS-232 serial protocol, which represents the interface between the OTheRS system and the satellite bus in a satellite ready system. Finally, temperature data from the IR camera is compared to truth data obtained from thermistors attached to the internal stack wall. This serves to verify that the camera returns accurate data and allows quantification of camera performance.

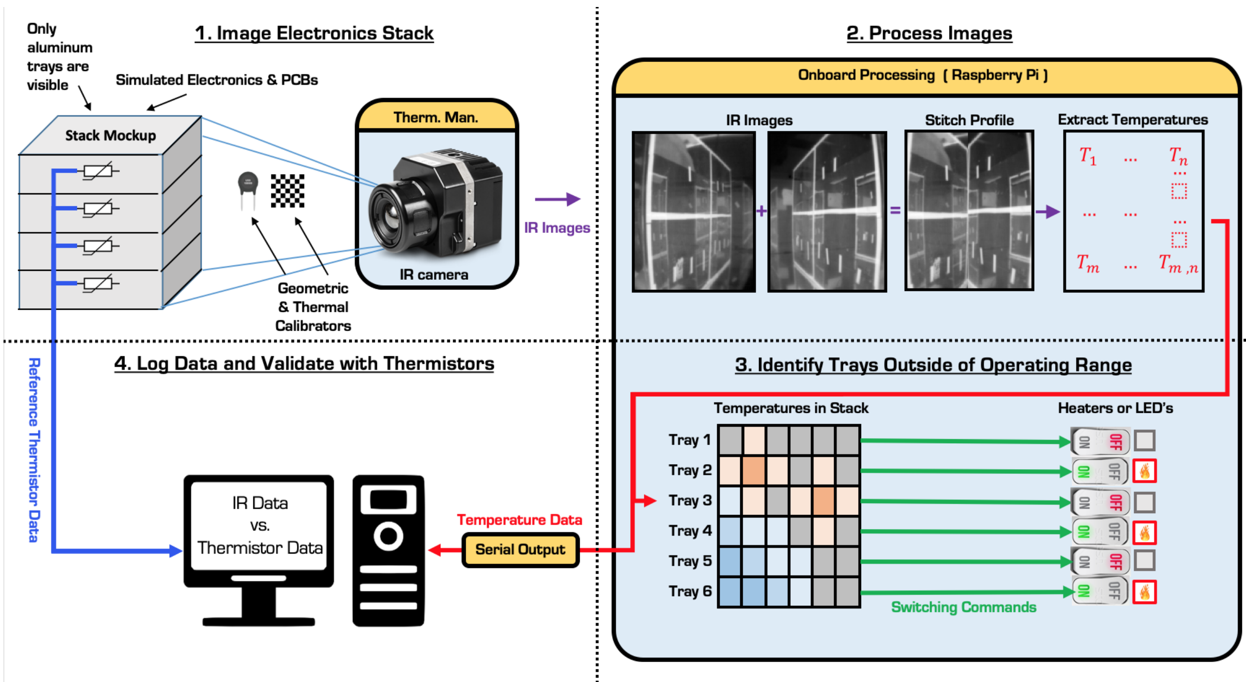

Figure 2: Concept of Operations for the OTheRS Test Bed

2.5. Specific Objectives

There are four objectives for the initial test bed. First, is to determine the ability of the FLIR Lepton camera to return spatially accurate temperature data for an Aluminum face. Second, is to determine the minimum distance at which two internal heat sources can be resolved on the stack face as well as the minimum temperature gradient that can be resolved. Third, is to test initial image processing algorithms with real data to determine their ability to provide coherent data. Fourth, is to determine the affect of an anti-reflective coating or differing surface roughness on the continuity and accuracy of the data.

2.6. Levels of Success

The levels of success for OTheRS are based on the Camera System, Image Processing, the Electronics and Communication system, and the actual Test Bed. At the base level the system needs to sense temperatures between -20° C and 60° C while differentiating between different module trays in the avionics stack. When the temperatures sensed by the camera system are outside of the temperature boundaries OTheRS will send regulatory commands to turn heaters on or off. Finally, the OTheRS test bed will replicate the satellite given by GA. In the mock avionics stack resistors will be used to create a temperature gradient which is also read by thermistors to confirm temperature readings made by the Camera and Image processing systems.

Criteria	**Camera**	**Image Processing**	**Electronic/Comm/Control**	**Test Bed**
Level 1	Camera system will sense temperatures between -30° C and 60° C and will fit within the interior of the given satellite	Software can differentiate between module trays in the stack being monitored while recording their temperature. Software can also facilitate spacial and thermal calibration of the OTheRS system	The control system will command representative indicators based on thermal data from the image processing system and will handle 2.5A. The entire system will also be able to operate on 28V of unregulated power	The test bed will have two different heated objects, whose temperature is read by both the thermal camera and TBD traditional sensors in an ambient air, room temperature environment. This is a minimum to help ensure the camera can differentiate and monitor multiple components
Level 2	Camera system will survive below a temperature of -30°			System operates successfully when tested in thermal chamber between -20° C and 50°C
Level 3		Software can determine temperature of components inside of the Avionics Bay		A range of reflectivity coatings will be tested to determine effect on temperature readings

2.7. Functional Block Diagram

The Functional Block Diagram is shown in Figure **??**. Note that it does not show the entire project's Functional Block Diagram, as it focuses entirely on the the Optical Thermal Regulation System, and not the test bed built to test it. More specifically, it focuses on the the image capture, the image processing, the power regulation, and the internal thermal regulation system, and does not show the reference data system nor the simulation electronics.

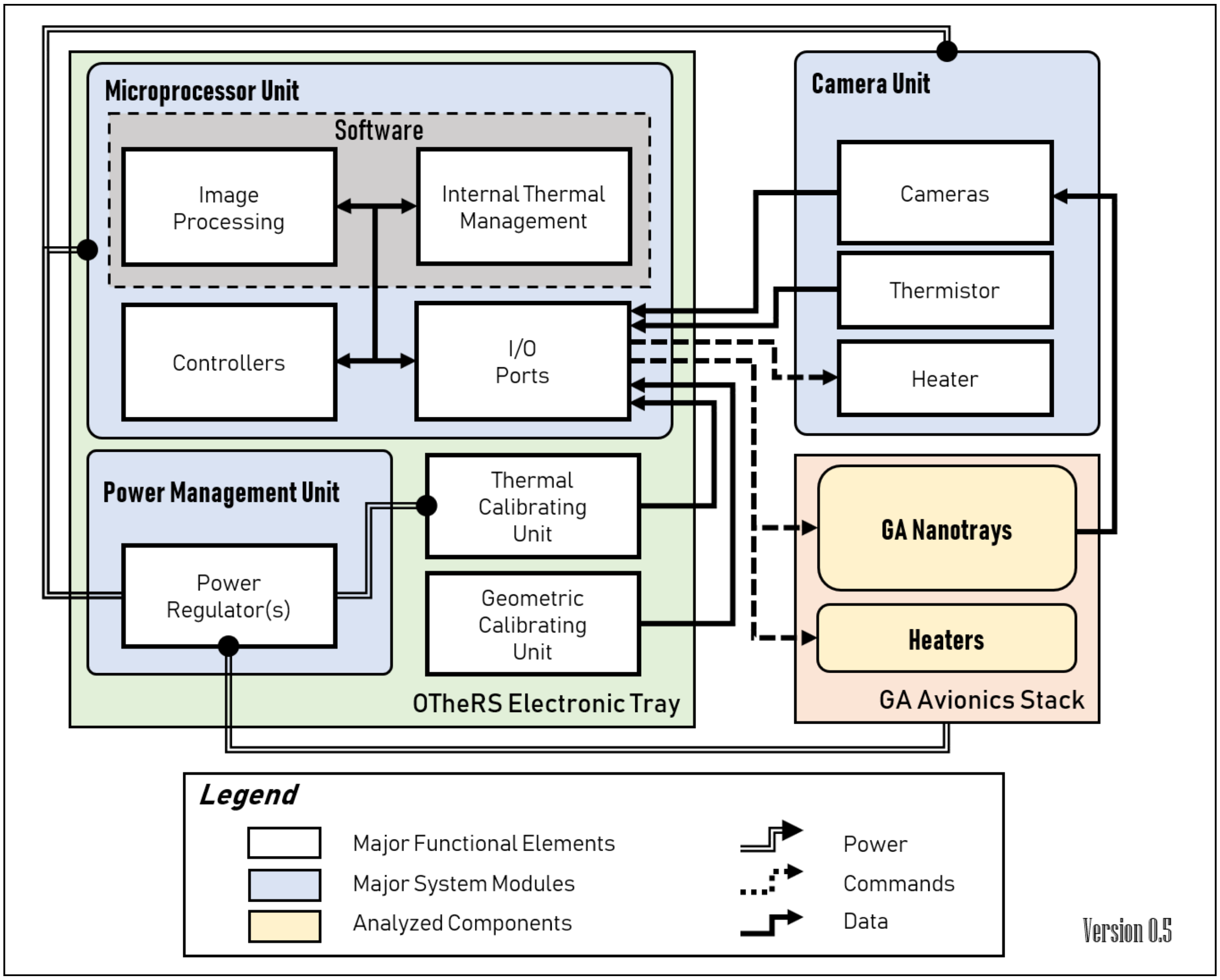

Figure 3: Functional Block Diagram for the OTheRS Test Bed

The thermal data is extracted from the test bed's electronics stack by the two camera units placed inside the replica avionics bay (FR-6).

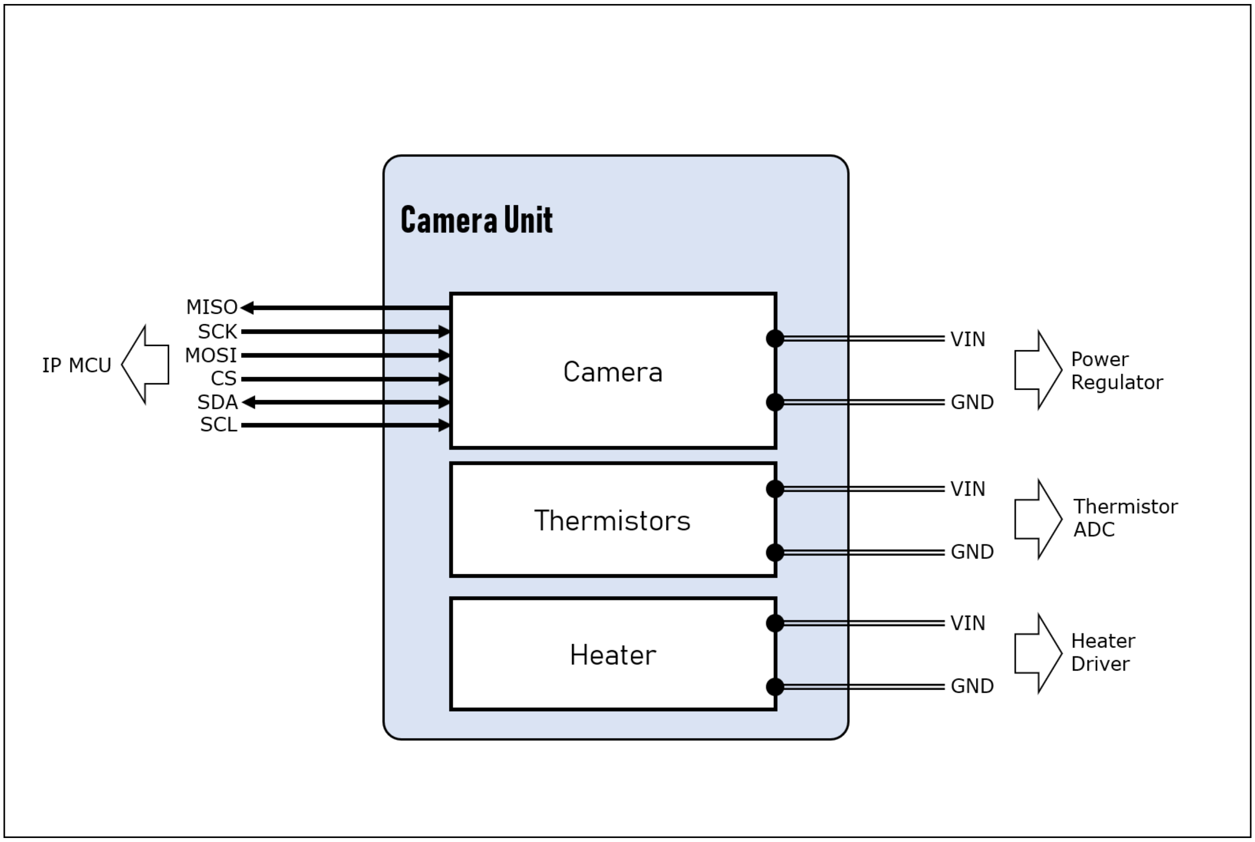

Figure 4: Functional Block Diagram of the OTheRS Camera Unit

The camera unit is composed of three types of components:

1. The camera component consists of a thermal camera and it's corresponding breakout board. The camera component is powered by 3.3V obtained by the power regulator on the OTheRS electronics tray. The camera component communicates directly to the Image Processing Microcontroller through the SPI and I2C communication protocols, acting as the Slave.

2. The thermistor component consists of four thermistors placed on the breakout board around the camera to measure the latter's temperature gradient and determine if it is within operating range (FR-7). The thermistors are connected to a dedicated ADC on the OTheRS electronic tray.

3. The heater component consists of four heaters behind the camera breakout board. The heaters are turned on and off based on results from the thermistor component. The heaters are connected to a dedicated driver on the OTheRS electronic tray.

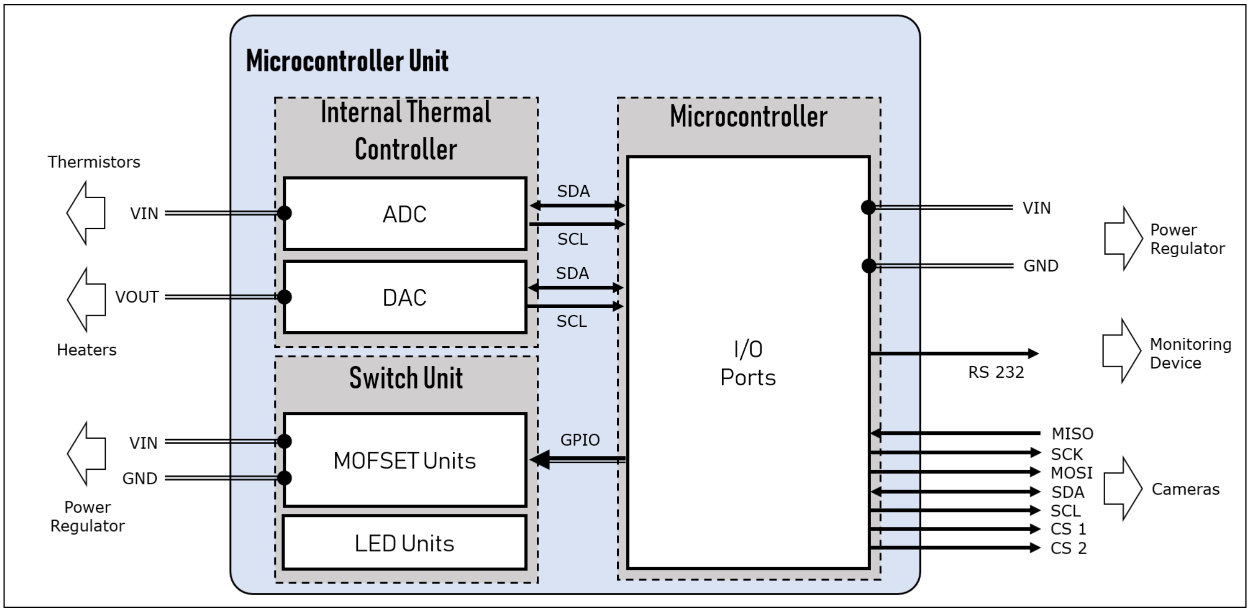

Figure 5: Functional Block Diagram of the OTheRS Microprocessor Units

The Microprocessor Units are composed of different microcontrollers and various controllers:

1. The Image Processing part of the microcontroller handles all data received through the SPI and I2C protocols from the two Camera Units, acting as the Master. This unit runs all the software associated with the image processing (FR-1) and controls whenever to send the image capture command to the Camera Units. The control decision made from the received data is sent to the MOFSETs on the Switch Unit using the GPIO pins present on the microcontroller, and the raw temperature data is be sent through RS-232 to the monitoring device. This unit is powered by 3.3V received from the power regulator.
2. The Internal Regulation part of the microcontroller handles the digital data received from the Internal Thermal Controller, determining if the heaters placed on the Camera Units need to be powered based on the thermistor data received.
3. The Switch Unit receives the output from the Image Processing part of the MCU, and controls an array of LED's to display the parts of the test bed exceeding the temperature range (FR-5) derived from the functional requirements (FR-2) through twelve MOFSETs corresponding to the hot and cold cases of the six test bed trays.
4. The Internal Thermal Controller is composed of both an ADC and a DAC. The ADC is used to transform the voltage received from the thermistors placed on the Camera Unit into a digital form which will be sent through I2C to the Internal Regulation part of the microcontroller. The DAC transforms the digital data received from the same microcontroller into an analog voltage used to power the heaters placed on the Camera Unit.

The Power Management Unit is composed of two DC-DC power regulators which will supply the required 3.3V and 5V necessary to run the electronics, the thermistors, and the heaters, from the received 28V unregulated DC power provided (FR-3).

2.8. Functional Requirements

The functional requirements are listed below with the same numbering system that is used for the entire project. The full explanation of the requirements' Motivation and Validation & Verification can be found in Section 2.1. The list below does not include the FR tag to show that they are Functional Requirements but the numbering is matched for all other portions of the report.

1. OTheRS shall return a thermal data map for multiple components between -30°C and 60°C.

2. OTheRS shall provide regulatory commands when components are outside -20°C to 50°C.
3. System shall operate on 28V unregulated power provided by the spacecraft.
4. OTheRS shall fit within a standard GA nanotray, with dimensions of 18.5cm x 13cm.
5. OTheRS shall be able to switch a 2.5A load, as needed, to control an externally powered heater or representative indicator.
6. The thermal imaging device(s) shall image critical stack electronics on at least a single side of the stack.
7. OTheRS shall regulate its own temperature.
8. Test bed shall mimic the GA satellite.
9. OTheRS shall not include ITAR restricted articles.

3. Design Process and Outcome

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3.1. Trade Studies

When considering the design for the OTheRS, several options were considered. Specifically, the team identified several elements that were pivotal to the project. These elements were the camera type, sensor layout, camera calibration, image processing software, processor, control system, and test bed. Trade studies were conducted on these elements in order to better assess what the design path should be. The following section refers to functional requirements which are clarified in Section 2.1

3.1.1. Camera Type

From the requirements given by the customer, the system will be using an infrared camera to monitor the electronics stack. This type of camera is critical to the design as it will be reading the infrared energy emitted from the stack and converting that into temperature data. The IR camera uses infrared thermography, the study of infrared energy as it is emitted from an object. This energy is then converted into a temperature reading, and then displays this temperature data in an infrared image. Signal processing in an IR camera is outlined in the figure below.

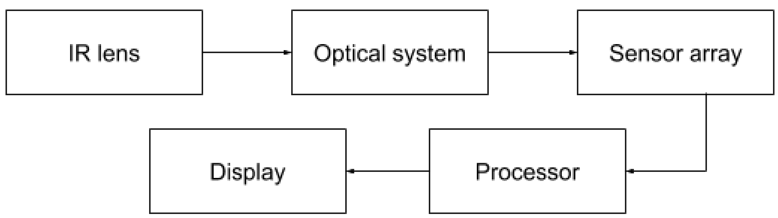


Figure 6: Flow diagram of general infrared camera

The three considered options for the camera type were the FLIR Lepton, Tamarisk Precision, and the FIR MLX90640 camera. The FLIR Lepton is a non-ITAR camera that has an operating temperature between -10°C to +80°C. The thermal sensitivity is 0.05°C. A brief pro and con list for this design option is provided below.

Pros	Cons
Non ITAR	One camera might not be able to image one complete side of the stack due to FOV
LWIR	Smaller thermal sensing range
Comes with a breakout board (to connect other necessary platforms)	
A lot of helpful information in the datasheet	

The second consideration was the Tamarisk Precision. Although this camera has a wider operating temperature range and thermal sensing range, no export information was provided, so it is unknown if this camera is under export controlled or not. The temperature sensing range is -40°C to +80°C and the thermal sensitivity is 0.05°C. The operating temperature range is -20° to +80°C. Below is a pro and con list for this option.

Pros	Cons
LWIR	No information on export control
Wide thermal sensing range	One camera might not be able to image one complete side of the stack due to FOV
	Large in size
	Doesn't come with a breakout board

The last option that was considered was the FIR MLX90640. The sensor is composed of an array of 32x24 of thermopiles. Outputs of all sensors are stored in internal RAM. The FOV for this configuration is 110°x75°. The operating temperature range is -40°C to +85°C. The thermal range is -40°C to +300°C, however the thermal sensitivity is 1.5°C, which is weaker than that of a thermistor (0.1°C). Each individual sensor costs $48.87, however if they are bought as a pack of 10, the cost of each reduces to $45.70. Below is a pro and con list of this design option.

Pros	**Cons**
Non ITAR	Larger FOV
Cheap ($50)	Lower thermal sensitivity
Integrates well with a breakout board	Low resolution

3.1.2. Sensor layout

Another crucial element to design was the layout of the cameras. They had to be placed in such a way that the stack could be viewed. Initially, all four sides of the stack were considered for viewing, this was quickly down-scoped to a single side of the stack in order to remain within budget and practical constraints. The first sensor layout consideration was the implementation of multiple cameras, initial calculation showed that 3 cameras would be needed in order to image a single side of the stack. This was changed to 2 with a diagonal consideration. These calculations are provided below.

In order to see how many cameras are needed to view each side of the stack, the dimensions of the stack were found as well as the distance between the walls and the stack. The dimensions are given below.

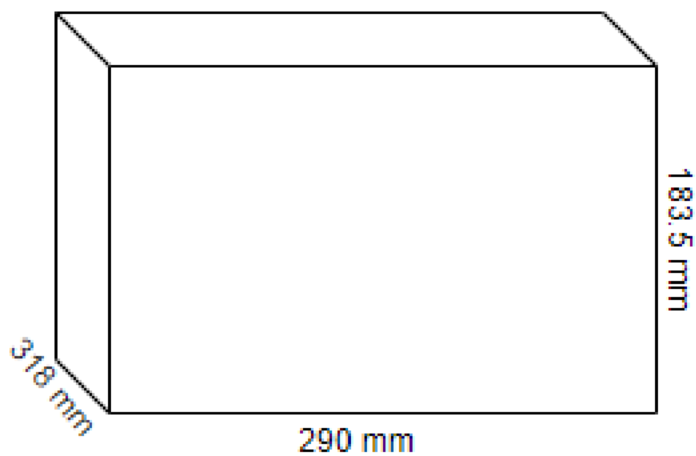
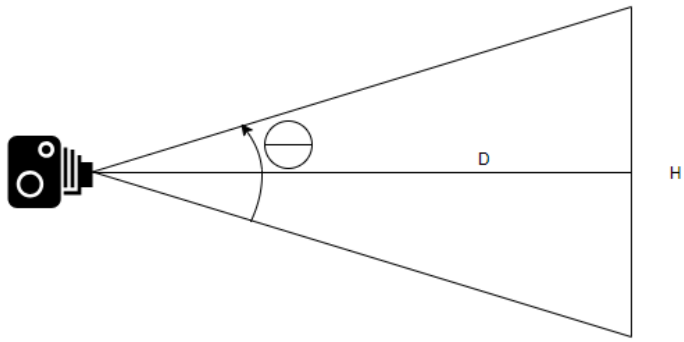


Figure 7: Dimensions of the Avionics Stack

The distance between the stack and the walls where the cameras will be located is 102 or 105 mm. In order to find out how many cameras are needed to capture the entire height of a single side of the stack the following equation was used.

$$tan\frac{\theta_v}{2} = \frac{\frac{H}{2}}{D} \tag{1}$$

This equation is based off of the following diagram.



In this equation θ_v refers to the vertical field of view of the camera, H refers to the height of the stack that will be captured, and D refers to the distance between the camera and the stack. A similar equation was also used to find out how many cameras are needed to capture the width of a single side of the stack.

$$tan\frac{\theta_h}{2} = \frac{\frac{W}{2}}{D} \tag{2}$$

Typical values for the Horizontal and Vertical field of views are $\theta_v = 37°$ and $\theta_h = 51°$. After inserting typical values for the Horizontal and Vertical fields of view of the cameras traded on it was found that 3 cameras would be needed to cover the entire height of the stack, 3 cameras would be needed to cover the width of 290 mm, and 4 cameras would be needed to cover the entire width of 318mm. This means in order to cover the entire stack 30 cameras would be needed. In order to stay within the budget of the project this design decision would be used to only measure one side of the stack in order to have a proof of concept. Another way to to use the multiple cameras is to mount them in the corners of the avionics bay. This increases the distance from the camera to the stack to 146.73 mm. Using the Law of Cosines it was found that only two cameras would be needed to view an entire side of the stack. Which means the entire stack could be covered by 8 FLIR Lepton Cameras.

Pros	Cons
Non-complex	Expensive
Gives Proof of concept	Can only cover a single side of the Stack while staying under budget.

Another design option for the camera layout is to add lenses to the cameras in order to increase their FOV's. In order to find the FOV's needed for a single camera to capture a single side of the stack the following equations were used

$$\theta_v = 2tan^{-1}\frac{\frac{H}{2}}{D} \tag{3}$$

$$\theta_h = 2tan^{-1}\frac{\frac{W}{2}}{D} \tag{4}$$

Where H and W are the the height and width of the satellite respectively. Using a value of 183.5 mm for the height of the stack and 318 for the value of the width of the stack the field of views were found as $\theta_v = 90°$ and $\theta_h = 120°$. This would cause the project to only need fewer cameras for each side of the stack which would allow OTheRS to view the entire stack during testing. However, different complications can come from adding in the lenses. To add the lenses to the micro cameras used in OTheRS a mounting platform would have to be machined for each camera meaning the system wont be made of only COTS parts. Adding lenses will also increase system complexity since the calibration system will have to take the lenses into account when determining temperatures of the stack. In order to ensure this will be a viable solution to the problem much more research will need to be performed on not only how lenses will interface with our chosen camera but also how they will affect temperature readings. Below is a pro and con list of this design option.

Pros	Cons
Inexpensive	Non-COTS Parts will need to be used
Can cover the entire stack	Increased system complexity
Minimizes mass and size of camera system	

Below is a sensor array option that was considered for the thermopile design solution. The thermopile has low resolution and accuracy, but has a FOV of 110°x 75°Which would mean only two sensors would be needed to cover an entire side of the avionics stack. This sensor also has a temperature measurement and operational temperature range which fits the requirements given by GA. The sensor has a price of only $60 per sensor as well and would only require 0.5184W from the electronics system to view the entire avionics stack. The area of each sensor array is also only 676mm^2. A major issue with this sensor is its low resolution which is only about half of the resolution given by the FLIR Lepton and only has an accuracy of 1.5°C. This sensor array also requires a micro controller with 20000 bytes or more of RAM to turn the raw pixel data into temperature data. Therefore modifications on the sensor array would have to be made to increase accuracy and usability in our system. Setting two of these sensor arrays up to view each side of the avionics stack would be extremely cheap but would also cause issues in accuracy.

Pros	Cons
Low cost	Low accuracy and resolution
Only takes two sensor arrays to cover a wall of the stack	Requires 20000 bytes of RAM
Small size and power requirements	

3.1.3. Camera Calibration

In order to ensure that the camera measurements are accurate, the camera must be calibrated. This is accomplished by contrasting the camera surroundings to a known point or points. How the system uses the data point(s) is the calibration methodology. The calibration can only be as accurate as the given data point(s). Therefore, it is also important to consider how these data point(s) are measured in the calibration system. Below gives an overview of some calibration methodologies as well as some different point determination options.

3.1.4. Calibration methodologies

One-Point calibration: The calibration method knows the SI value of a single location on the camera (in the case of OTheRS, this is temperature). The point is used to linearly fit a gradient of expected ideal responses near the single point. This calibration method is particularly powerful because only a single reference point is needed to calibrate the system. This type of system is generally implemented only for systems that are known to vary with a well known linear value, such as an aging thermocouple. The one point calibration can also be used as a drift check to observe when constant values are changing with time. Below lists a simple pro-con list for the one point calibration.

Pros	Cons
Simplicity (only one point is needed)	Low range
Accurate calibration for expected linear data	Only accurate for linearly changing systems

Two-Point Calibration: This calibration method uses the value of two known temperature points to linearly fit a gradient of expected values near the points. This method differs from the one point calibration because the slope is now calculated instead of specified. This is critical because it allows for the correction of both offset and and slope discrepancies. Much like the one point calibration, this method is generally restricted to linearly changing systems. Below lists a simple pro-con list of the two point calibration method.

Pros	Cons
Larger range	Added complexity with more than one data point
Can correct for slope and offset errors	Only accurate for linearly changing systems

Multi-point Curve Fitting Calibration This calibration method uses the value of multiple known temperature points to non-linearly fit a gradient of expected values near the points. This method differs from the other two in that the multi-point calibration will generate a non-linear fit to the points. This is powerful because it allows for the calibration of more complex systems that alter non-linearly. Below is a simple pro-con list of the multi-point calibration.

Pros	Cons
Non-linear systems are an option	Great complexity because of the multitude of points
Less dependency on accuracy of each single point	Tends to deviate at the extremes

3.1.4.1 Point determination

All three of the above methods have a strong dependency on the accuracy of the measured point(s). This section will consider the options of either utilizing a black body radiator or thermistor to get the needed data point(s) for calibration.

Black Body Radiator: The black body radiator as a point determiner essentially heats up an assumed black body to a specific temperature (typically a large temperature) by supplying an electric current for a specific time that is known to heat the object up to a known temperature. The calibration methodologies use this known temperature as an assumed truth value to calibrate the system. A simple pro-con of this point determination method is given below.

Pros	Cons
Very accurate temperature readings	Requires a large power consumption to heat the object to a known value
Useful for calibrating large ranges of temperature differences	Model dependent

Thermistor: In the method of point determination, a thermistor is connected to a known location in the FOV of the camera and feeds the calibration system the temperature of that point. The calibration method then assumes that the received value is accurate for the location and calibrates accordingly. This is beneficial because the thermistor requires a smaller amount of energy to measure a temperature rather than to heat up an object to a specific temperature. Below gives a simple pro-con list of the thermistor point determination method.

Pros	Cons
Power inexpensive	Calibration can only be as accurate as the thermistor
Relatively cheap	Calibration is system dependent

3.1.5. Image Processing Software

The image capturing hardware used for mapping the nanotrays (camera) will require extensive adjacent software components that will locate these objects within the image and extract temperatures to determine possible overheating in the GA electronics bay. When given an image of input, the on-board image processing software will be able to image and map the nanostacks. Once this is completed, extract temperature metadata from the image at verified spatial locations. A temperature range will be determined of the electronics components that conduct heat to the nanotray and plotted vs spacebay. For validation and proof of concept, the image processing software will be calibrated both on its ability to accurately map the stack relative to the thermal camera and based on the temperature data extracted from the image. This will be done based on actual measured locations of electronics bay nanostacks and additional software will need to be implemented to perform a black-body object temperature test to calibrate the temperature calculations of the image processing software. The specific software technologies being considered to perform the on-board image processing and determine temperature data in this trade-off are OpenCV in C++, OpenCV in Python, and Matlab.

SimpleCV in Python and scikit-learn in Python were also considered during research for solving this image processing problem but did not make the final cut. SimpleCV is an older method for image processing, portable to Python, that has been out of community use in scientific applications for some time. This library is Python-only but has weak documentation with little support compared to OpenCV which is currently an industry standard and has a thriving community of support. Scikit-learn is purely a machine learning platform that lacks the required relevant image processing functions and machine learning libraries. Provided in the following subsections were the design considerations for the image processing software.

3.1.5.1 OpenCV in C/C++

OpenCV is an extensive library for computer vision and machine learning applications. These tools, when utilized correctly, make image processing much simpler than in years past. OpenCV is a well-known and powerful library with a strong following of community developers and programmers. This platform was built on optimized code in C/C++ but can be used with Python, Java, and for some tools even MATLAB. For instance, interfacing with Python isn't difficult as the Python OpenCV functions are only wrappers for the original C/C++ optimized code which runs underneath. Therefore, a user can combine the accuracy of running OpenCV in C with an easier programming language such as Python. An example of OpenCV's image processing capabilities can be seen in Figure 8.

Figure 8: Example of OpenCV's technical prowess in image processing

A pros and cons breakdown for using OpenCV and C++ can be seen in Table 3.1.5.1.

Pros	Cons
Open source software	Intense learning curve for new programmers
Extensive optimized libraries for image processing (OpenCV)	Documentation is lacking
Fast runtime of software applications	
Large community of programmers	

3.1.5.2 OpenCV in Python

Python is an open-source and general-purpose programming language that has been extremely popular with developers since its inception. This programming language has a wide variety of uses from back-end web development, data analysis, artificial intelligence, and scientific computing. Python has been praised as a language simple to learn for beginning developers, more so than the core languages of Java and C/C++, while still allowing for the build of powerful software stacks, desktop applications, and much more. Common critiques with Python are that the software built in this language are not easy to maintain and performance overall can be lacking compared to a strictly compiled language like Java or C. A complete list of Pros vs Cons in using OpenCV Python for this project are listed in Table 3.1.5.2.

Pros	Cons
Open source software	Documentation is worse than OpenCV for C++
Code readability	Performance/runtime is lacking compared to that of a compiled language
Ease of software development	
Relatively fast runtime	
Extensive community for support	

As mentioned, Python is a great option when working with OpenCV as Python serves as a wrapper around the original and pre-compiled C code. This way, the optimized C code can be used on the back-end while Python operates on the front-end with benefits such as code simplicity and easier debugging without a drop-off in performance.

3.1.5.3 Matlab

MATLAB is a numerical computing environment and proprietary programming language provided by MathWorks. MATLAB is used extensively in scientific disciplines and academia, notably in aerospace applications. The necessary image processing and machine learning toolboxes are available in external MATLAB libraries for use of this project. Since MATLAB is a commercial product, it is itself an expensive software suite for hobbyists. CU students do possess software licenses to use MATLAB for academic purposes.

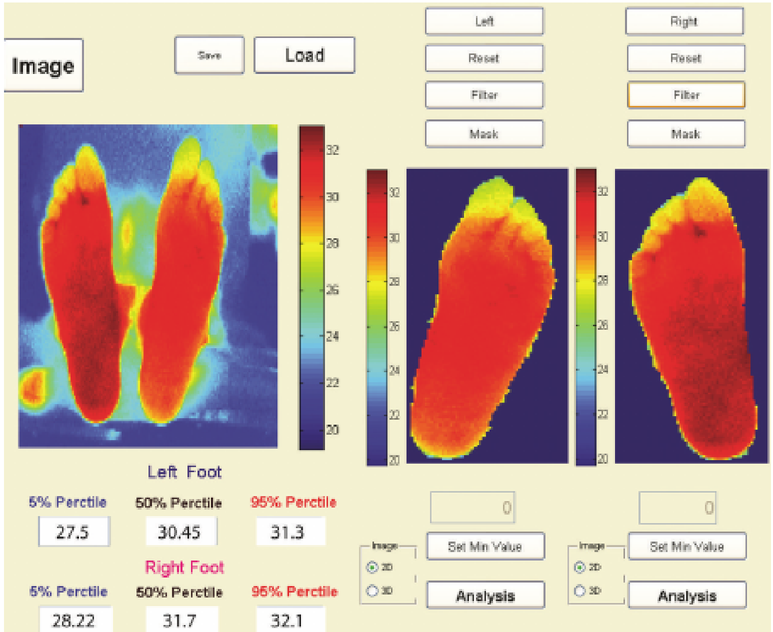


Figure 9: Example of MATLAB's image processing capabilities given a thermal image capture

Pros	Cons
Simple syntax	Slow runtime of software applications
Good documentation and dense community of programmers	Accuracy is lacking in floating point operations, compared to C pre-compiled code
Great library of matrix manipulating functions	Optimized image processing libraries are not extensive
Simulink stand-alone applications	Expensive software suite
OpenCV portability	

3.1.6. Processor

In the OTheRS electronics subsystem, 3 types of computational options were considered. These options were specifically considered because they have a vast heritage in aerospace applications. The OTheRS contemplated the utilization of a microcontroller (MCU), a microprocessing Unit (MPU), and a field-programmable gate array (FPGA), while discarding the options of using a Complex Programmable Logic Device (CPLD) or an Application Specific Integrated Circuit (ASIC) due to their inability to meet processing requirements. Since all three computational considerations have a deep history on satellite applications, all three could accomplish the electrical needs of the system. Because of this, the Trade study will focus heavily on a deeper analysis of available options.

3.1.6.1 Microcontroller:

The microcontroller can be thought of as a small computer on a single integrated circuit. What distinguishes this option from the other two is that the microcontroller has all the peripherals already connected to the unit. These peripherals include the memory, CPU, and I/O ports of the microcontroller. The code instructions for the microcontroller must be programmed in either high-level languages such at C, Python, and Ruby, or in low-level assembly using mnemonics. A simple pro and con list is given below for the microcontroller.

Pros	Cons
Prepackaged peripherals	Cannot process in parallel
Low cost	Programming changes depending on each different MCU
Software flexibility	

3.1.7. *Microprocessor:*

The MPU option is essentially just the computational part of a microcontroller. It is a clock based processor that executes centralized commands to be stored elsewhere. The big difference between the MPU and the MCU, is that the MPU does not have any inherent peripherals such as memory, I/O, timers, and clocks. These differences are highlighted in figure 10 below.

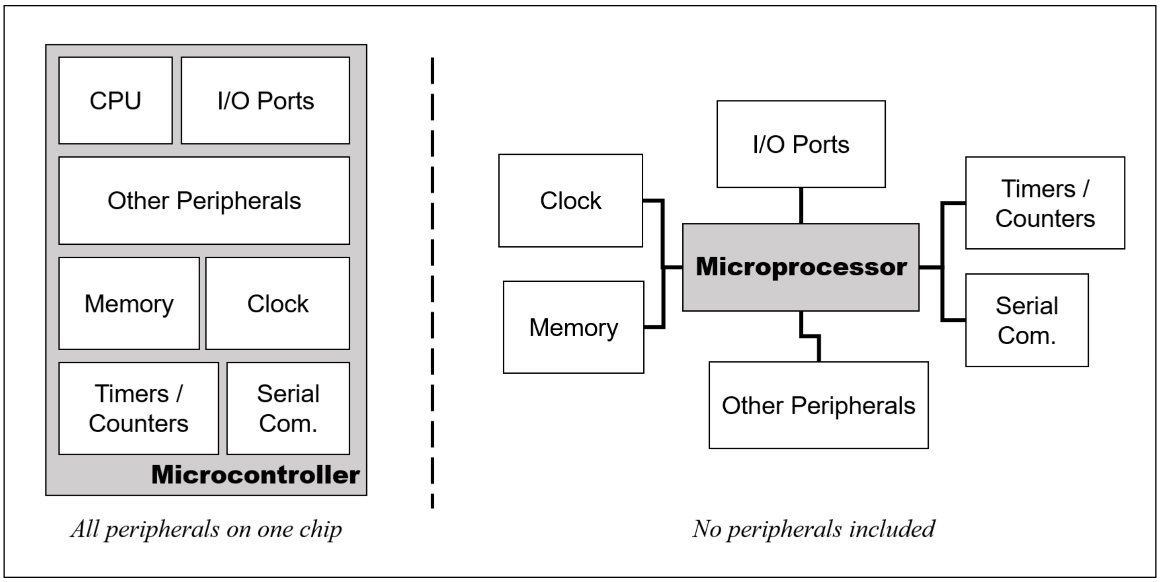


Figure 10: Peripheral difference between MCU and MPU

MPUs can handle both sequential and combinational digital logic. MPUs must execute code from the read-only memory, whereas MCUs generally load programs into RAM for execution. A simple pro and con list is given below for the microprocessing option.

Pros	Cons
Ability to select and choose peripherals on an as needed basis.	Reliance on external memory
High processing efficiency	Relatively higher cost

3.1.7.1 *FPGA:*

FPGAs differ greatly from both MPUs and MCUs. Specifically, FPGAs have hardware flexibility, they are designed for hardware configurations to be fluidly changed. The FPGA is simply in array of logic gates that must be specified. These gates are generally specified by using Hardware description language (HDL). A major difference between FPGAs and MCUs, is that the FPGA is able to process instructions in parallel. Figure 11 below shows the generic architecture for FPGAs.

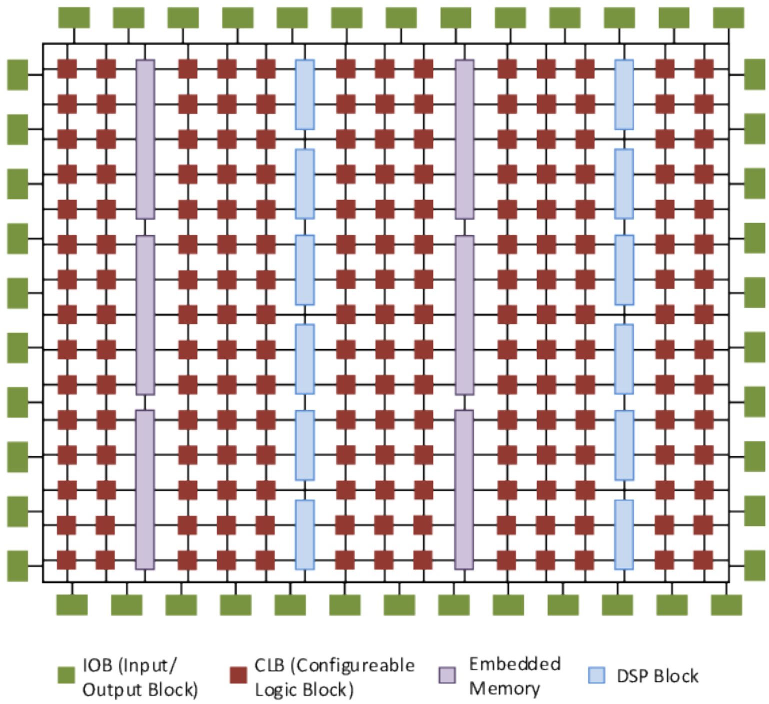


Figure 11: Generic Architecture of a FPGA

A simple pro and con list is given below for the FPGA option.

Pros	Cons
Hardware flexibility	High relative cost
Can process in parallel	Difficult configuration

3.1.8. Control System

Our goal is to maintain the stack electronics between the temperatures specified in **FR 2**. Electronics are some of the most difficult items to keep working in a satellite. If they either get too cold or too hot, they fail. Failed avionics could compromise a satellite's mission. Electronics in a satellite consume electrical power and produce heat ($\dot{Q}_P$). That heat needs to be conducted ($\dot{Q}_{cond}$) or radiated ($\dot{Q}_{rad}$) away in order to stop the components from overheating. Solar and Earth-radiated (albedo) heat loads ($\dot{Q}_{ext}$) also cause periodic increases in heat flux each time the satellite comes around to the daylight side of its orbit. However, electronics that get too cold could also fail. Therefore, we need to be able to control the heat flux into and out of the electronics stack and apply electrical heat ($\dot{Q}_H$) if current heat loads are insufficient to keep the electronics warm. Several thermal control systems have been flown in space. Cutting edge research is ongoing in both active and passive control schemes. Because passive thermal controls frequently rely on a careful balance of environmental factors or complicated hardware and consumables, such as the ice sublimation cooling used on American space suits[?] , these schemes are out of reach for this project. We are therefore left with active thermal control systems where we attempt to drive the heat of the avionics components to a target temperature. The only small satellite active control system currently designated Technology Readiness Level[8] (TRL) 9 by NASA uses electrical heaters[7].

On that basis, trade studies were performed on control schemes which use an electric heater to maintain a minimum temperature for the stack electronics and sufficient heat-sinking to stop potential overheating. Three different control schemes were compared and are listed below.

3.1.8.1 Threshold Based Control

Threshold based control is a form of closed loop control where the heater element is switched fully on or fully off. An upper and lower threshold set the temperatures at which the heater is switched on or off. If the lower threshold is reached, the heater is switched on. If the upper threshold is reached, the heater is switched off, similar to a household thermostat. The primary advantage of this control scheme is its simplicity and easy analysis.

At the coldest tolerable temperature, the heater can be turned on. It then needs to checked that the total heat flux into the electronics stack is positive. This comes down to the equation:

$$\dot{Q}_P + \dot{Q}_H + \dot{Q}_{ext} - \dot{Q}_{rad} - \dot{Q}_{cond} > 0 \tag{5}$$

At the hottest tolerable temperature, the heater will be turned off and it will be insured that the next heat flux into the electronics stack is negative:

$$\dot{Q}_P + \dot{Q}_{ext} - \dot{Q}_{rad} - \dot{Q}_{cond} < 0 \tag{6}$$

With these two points satisfied, it can be assured that the satellite can be kept inside the tolerable temperature range. However, in order to ensure good performance, a larger than necessary heat sink and heater might be utilized. This control method would cause large and rapid swings in temperature - from one end of the acceptable scale to the other. The severe swings by setting tighter threshold temperatures would such be mitigated. However, without changing out the heaters and heat sinks, there would simply be a faster oscillation over a shorter temperature range. This may not be an issue, but in the case of a mechanical switch such as a relay for the heater, this could cause premature failure.

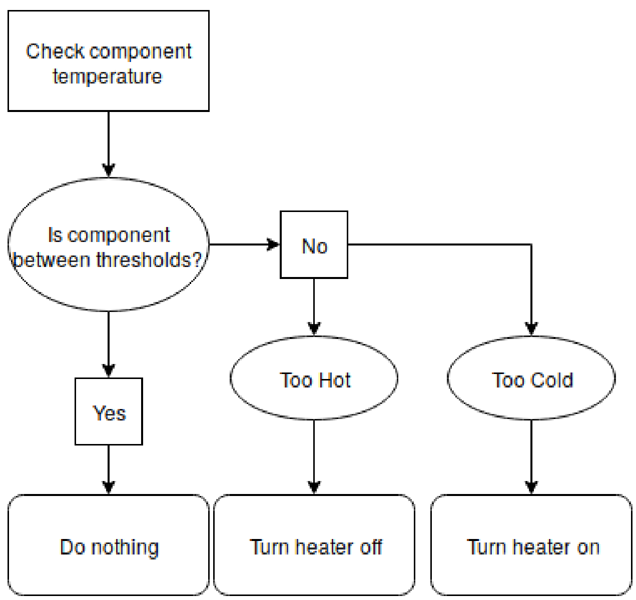


Figure 12: Threshold Based Control Flowchart

Pros	**Cons**
Easy to implement	Causes temperature oscillations
Hardware is simple	Hardware may wear out prematurely
Short implementation time	Constant temperature oscillations may cause premature failures in other components

3.1.8.2 Proportional Control

To stop the temperature oscillations, another option would be to run the heater at some specific power setting in order to try and drive the components to a target temperature. In this case, the aim would be to balance the heat flux in and out of the system in order to maintain steady state.

$$\dot{Q}_P + \dot{Q}_H + \dot{Q}_{ext} - \dot{Q}_{rad} - \dot{Q}_{cond} = 0 \tag{7}$$

In the equation above, $\dot{Q}_H$ would be controlled and the problem turns to controlling this input value. One of the most common ways to control this value is using proportional control, where $\dot{Q}_H$ would be driven according to the rule:

$$\dot{Q}_H = K_P(T_{target} - T_{actual}) \tag{8}$$

K_P is a *gain* value that would be picked either analytically or experimentally. It has units of Watts per degree Kelvin.

This system would give more stable and controllable temperatures. However, electronic switching hardware would be required to arbitrarily modulate $\dot{Q}_H$. This is unlikely to be a relay, like in the threshold based control. Instead, a high frequency Pulse Width Modulation (PWM) signal would probably be used to drive a MOSFET in order to supply the power to the heater. The MOSFET is a solid state switch that can be modulated much faster than a mechanical device with much less wear. This introduces some additional hardware and software complexity, as there would need to be a way to calculate the difference between our goal and actual temperature, use the gain value K_P to determine the appropriate heater wattage, and then create a PWM signal of the appropriate duty cycle in order to produce that wattage from the heater. In addition, K_P may be difficult to determine. The rate of heat loss due to radiation from an object is $\dot{Q}_{rad,out} = \epsilon\sigma T^4$, where ϵ is the object's emissivity, σ is the Boltzmann Constant, and T is the object's temperature. Because T is raised to the fourth power, it may be difficult to use the analytic methods learned in class. Finally, proportional-only control does not damp small oscillations, which may persist and it does not account for environmental biases or improperly set values of K_P. Small errors in temperature setting could persist indefinitely.

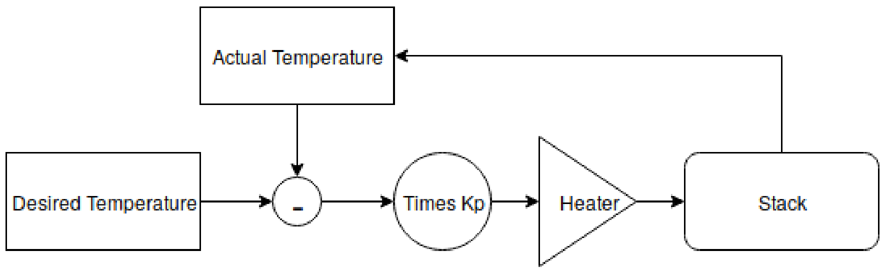


Figure 13: Proportional Based Control Flowchart

Pros	Cons
More stable than threshold control	Still prone to some oscillations and lingering bias
Allows us to set a specific target temperature	Will probably require solid state switching at high frequencies.
	Requires tuning to find a good gain

3.1.8.3 PID Control

A control scheme which solves the values associated with proportional control is proportional-integral-derivative control. The heater modulation law is changed to:

$$\dot{Q}_H(t) = K_P(T_{target}(t) - T_{actual}(t)) + K_I \int_0^t (T_{target}(t) - T_{actual}(t))dt + K_D \frac{d[T_{target}(t) - T_{actual}(t)]}{dt} \tag{9}$$

The new term $K_I \int_0^t (T_{target}(t) - T_{actual}(t))dt$ compensates for lingering error over time by progressively driving the average error to zero. The term $K_D \frac{dT(t)}{dt}$ damps oscillations.

PID control algorithms are common in industry wherever tight and repeatable automatic control is needed. They do not require any different hardware than proportional control scheme. However, they are more difficult to tune because in addition to K_P, the new gain variables K_I and K_D also need to be determined. Because the system response is coupled between all three variables, finding the correct gains by trial and error becomes substantially more difficult. In addition, the implementation must become *stateful*. Temperature at all points in the past would need to be kept track of in order to compute the integral and differential terms properly. However, well tuned PID control can keep a very stable temperature through many different environments.

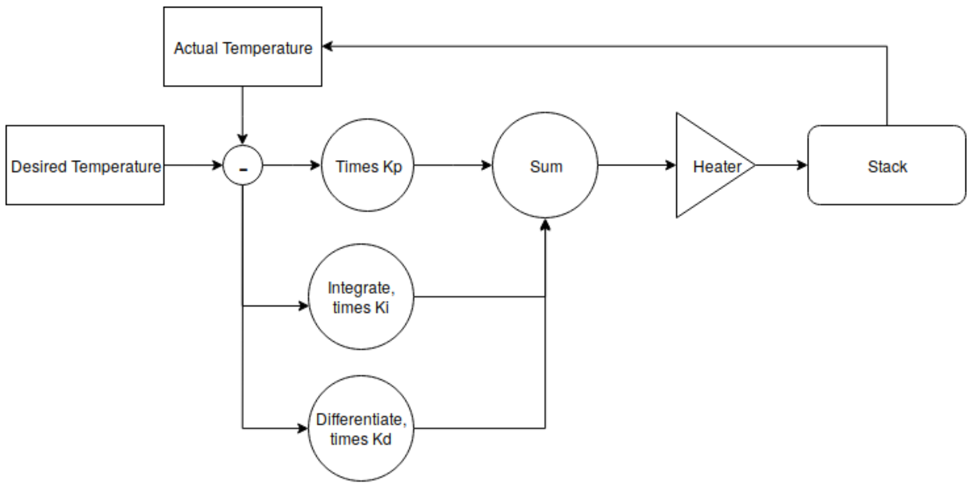


Figure 14: PID Based Control Flowchart

Pros	Cons
Can successfully damp out oscillations and remove bias	Much harder to analyze
Can hold a target temperature	Much harder to tune
No further hardware requirements over proportional control	Software requirements are more complex
	Have to store historical temperature information

Note: Some clarification is needed around the term 'high frequency.' An electrical engineer's idea of high frequency is very different from an aerospace engineer's. In this context, high frequency only means a few hundred Hz. While this is a far from radio frequency signaling, it should be all we need. It is expected that the time scales associated with temperature changes will be in the seconds or tens of seconds. An Arduino Uno generates a PWM signal at $500Hz$. The time scales differ by two or three orders of magnitude. For the goal of avoiding temperature fluctuations and component wear caused by the constant on-off of a heater element, this is sufficient.

3.1.9. Thermal Control

In order to ensure that the various components of OTheRS remain within their operational temperature bounds, the OTheRS design solution must include the ability to measure its own temperature. With this data OTheRS can fulfill requirement **FR 7**. The difference between section **3.6** and **3.7** is that the thermal control section refers to methodology used to accomplish the above task. However, the subsections below follow the same logical control considerations made above in **3.6**.

Sections *3.7.1* to *3.7.3* describe the self-monitoring methods of a multiple camera system, thermistors, or a combination of the two. Furthermore, sections *3.7.4* to *3.7.5* describe heat control techniques such as turning heaters on or off, or switching to low-power state modes. Turning systems on or off may be considered for the final solution, but comes with few benefits or costs. Physical systems were not considered here to keep the scope of the project consistent with customer requests.

3.1.9.1 Multiple Cameras

Using a camera-in-the-loop control system for our own thermal makes sense given our goal of replacing thermistors with thermal cameras. They would provide accurate and presumable, total coverage of our own electronics. However, the cameras themselves are active power consuming components with the associated failure rates and monitoring requirements. We would need to have each camera be monitored by another. That monitoring scheme would place constraints on our possible camera layouts and has the potential to limit our ability to image our primary target: the avionics stack.

Pros	Cons
Increased image fidelity	Increased system complexity
System failure back-up	Increased cost & weight
Increased mounting options	Mounting requirements
	More data handling/processing required

3.1.9.2 Thermistors

Thermistors are the current and proven technology for temperature monitoring of avionics. However, the aim of the project is to replace the thermistors with thermal cameras. While they are cheap and easy to monitor, they require analog to digital conversion electronics and increased number of wires from each component, as well as a separate converter channel or a signal mixer in order to handle a large number of sensors.

Pros	Cons
Lowest cost	Increased wiring complexity
No calibration needed	More data handling/processing required
High data rate	Old tech
Reliable and proven	We are attempting to eliminate thermistors from the design.

3.1.9.3 Combination

Using a combination of thermistors and cameras would not completely eliminate the downsides of each. Some of the cameras would still need to image each other, and others would still need thermistors. However, multiple data sources would increase the robustness of the overall design.

Pros	Cons
Highest system accuracy	Highest wiring complexity
Highest system redundancy	Highest cost and weight
Most data provided	Most extensive mounting requirements

3.1.9.4 Heater Control

In order to respond to thermal information about our own system, a method of thermal control is needed. Only two reliable methods exist without modification of the satellite design. Components can be artificially heated with electrical heaters or the heat production can be stopped by switching components off. Despite limited options, this needs to be considered in order to ensure that the cameras and other electronics keep functioning at peak performance and reliability.

Pros	Cons
Simple to test and calibrate	Increased software implementation difficulty
Cost effective	Increased power away from electronics tray

3.1.9.5 Power-State Control

For processors and components that support it, they could be instead switched to a low-power state. This has the advantage of being better supported by some components than simply cutting power. However, it is not a universal feature and even components that are in standby or sleep modes still consume some amount of power.

Pros	Cons
Provides cooling without turning components on and off	Increased software implementation difficulty
Cost effective	Not all components may support this

3.1.10. Thermal Model

The thermal model refers to the software demonstration of heat transfer between the electronics components due to conduction, convection, & radiation within the electronics bay. Software used for thermal modeling will depend on many factors and some will not be immediately applicable to our project. The three software platforms traded on to perform accurate thermal modeling will be: user-designed heat transfer in a rod, SolidWorks with additional Simulation package, and Thermal Desktop.

3.1.10.1 Heat Transfer in a Rod

The first option is to design a thermal model of heat transfer in a rod, which will be built by the user. This option is by far the simpler model for testing, but will lack sophistication when it comes to validation. Real heat transfer that will take place between components will be three-dimensional, and will require some level of complex modeling.

Pros	**Cons**
Simplest Model	Not as applicable to our application
Introductory model	Inaccurate results for our application
Proof of concept on an accelerated timeline	Only two-dimensional analysis

3.1.10.2 SolidWorks Simulation

This second option is to use SolidWorks, along with Thermal and Flow Simulation toolboxes. Students in the Smead Aerospace curriculum at CU have experience with several simulation environments, but this offers the simplest integration from design to simulation. SolidWorks also has licensing provided by the university and can produce an adequate analysis of the electrical components in question, based on the CAD model provided by GA and further model simplification done by the OTheRS team. SolidWorks and similar software such as ANSYS are powerful modeling tools, but require significant computing power to complete analysis of extensive models.

Pros	**Cons**
Easy to use	Resource intensive
Simple setup (single toolbox)	Moderate learning curve
Great for modeling	Implementation fidelity
3D Analysis	
University-provided license	
Well documented	

3.1.10.3 Thermal Desktop

Pros	**Cons**
Very accurate model	Cost is astronomical
Best meshing available	Complicated software
Well documented	High learning curve
	Resource intensive

The cost of a single thermal desktop license ($40,000) is the biggest detriment to this option and is thus is an easy throw out for the thermal model trade study.

3.1.11. Test Bed

The goal of the Test Bed was to use OTheRS on a fabricated aluminum avionics stack which is being heated up to or cooled beyond the given temperature range. The setup of the Test Bed will match the satellite dimensions given by GA so that it can properly replicate the satellite and show the scatter affects encountered within the actual satellite. The test bed will also incorporate a thermistor system in order to compare the accuracy of OTheRS against the accuracy of more common thermal measurement systems. A replicated fabricated avionics stack will be created in the machine shop complete with fabricated module trays. The avionics stack will then be coated in aluminum to mimic the real avionics stack used by GA. Outside the avionics stack, a metal frame will be used to mount the cameras on. A fabricated nanotray, whose specifications are also given by GA, will be created and have the processor placed within in order to show these components can fit on a standard GA nanotray. All of these parts will be expensive to create and will cause a dip in the budget. Resistors would then be placed inside the fabricated stack in order to heat the stack beyond the temperature range. The resistors will not be able to be precisely controlled but will be able to exceed the temperature range specified by GA. Once the OTheRS senses the temperature go above the specified maximum temperature, it will send a serial command to turn on a light bulb to show the functionality of the system. The recorded temperatures given by the thermistors will be logged onto a computer and will be compared with the temperature taken by OTheRS. This test bed design will demonstrate the viability of the overall system.

Pros	**Cons**
Test Bed Replicates the Satellite	High cost to build
Scatter effects are accounted for	Resistor temperatures cannot be completely controlled
Accuracy of OTheRS and Thermistors can be compared	

Next, a trade study was conducted within each of the above sections in order to figure out a baseline design for the OTheRS.

3.1.12. Camera trade study

Multiple cameras had to be researched in order for OTheRS to decide which would be best for this project. The metrics taken into account to make this decision were cost, size, power, resolution, operating temperature range, thermal sensing range, and HFOV. Table 1 below describes why each metric is weighted as it is.

Table 1: Metric Definitions

Metric	**Weighting**	**Justification**
Cost	0.2	The hard limit of the budget for the entire project is $5,000. Not all this money can go towards the thermal camera, so minimizing the cost of the camera while making sure the camera is still of good quality is ideal.
Size	0.15	There are 102mm between the stack and the outer wall of the shell where the camera will be mounted. The depth of the camera size needs to be minimized in order to maximize the field of view.
Power	0.05	The customer is giving us 28V of input power for the entire system. This must be distributed between the camera and all of the electrical components.
Resolution	0.25	The thermal camera must sense the temperature variation across each electronics tray. In order to do this, it must have a high enough resolution to distinguish between the trays.
Operating Temperature Range	0.1	The customer would like the camera to be operational between -30°C and +60°C. However, the limits of the non ITAR cameras available could constrict this range.
Thermal Sensing Range	0.05	The thermal camera needs to be sensitive to infrared radiation ranging from -30°C to +60°C.
FOV	0.2	We want to minimize the number of cameras per side of the stack while still being able to image the entire side

Table 2 below defines how each metric was broken up in order to get a raw score for each of the cameras involved in the trade study.

Table 2: Scoring Matrix

	Scoring Criteria				
Metric	**1**	**2**	**3**	**4**	**5**
Cost	> $1,000	> $700, < $1,000	> $400, < $700	> $100, < $400	< $100
Power	>28V	>8V, <28V	>5V, <8V	>3V, <5V	<3V
Size	> 30mm	< 30mm, > 25mm	< 25mm, > 20mm	< 20mm, > 15mm	< 15mm
Resolution	<1,000 pixels	<2,000 pixels, >1,000 pixels	<3,000 pixels, >2,000 pixels	<3,000 pixels, >4,000 pixels	>4,000 pixels
Operating Temperature Range	< +10°C to > +20°C	< 0°C to > 30°C	< -10°C to > +40°C	< -20°C to > +50°C	< -30°C to > +60°C
Thermal Sensing Range	< +10°C to > +20°C	< 0°C to > 30°C	< -10°C to > +40°C	< -20°C to > +50°C	< -30°C to > +60°C
FOV	< 30°	> 30°, < 60°	> 60°, < 90°	> 90°, < 120°	>120 °

Table 3 below shows the selected raw scores for each metric for each camera. These values are then multiplied by the corresponding weighting of each metric and summed together to produce the weighted totals at the bottom of the table.

Table 3: Trade Matrix

Metric	**Weighting**	**FLIR Lepton Raw Score**	**Tamarisk Precision Raw Score**	**MLX90640 Raw Score**
Cost	0.2	4	1	5
Size	0.15	5	1	5
Power	0.05	5	4	4
Resolution	0.25	5	5	1
Operating Temperature Range	0.1	3	4	5
Thermal Sensing Range	0.05	3	5	5
FOV	0.2	2	2	4
Weighted Totals	1	**3.9**	**2.6**	**3.75**

From the results of the trade study, it is apparent that the FLIR Lepton camera should be used for the project. General Atomics has provided OTheRS with one FLIR Lepton Breakout Board v1.4. The specific camera that GA is providing will have to be tested to make sure it is in proper working condition because it has been inside of a thermal vacuum chamber during operation.

The FLIR Lepton Breakout Board v1.4 is the fourth model of the FLIR Lepton Longwave Infrared (LWIR) thermal imaging camera. It can detect waves anywhere between 8-14 micrometers. It is meant to be operational in the temperature range of -10°C - +65°C and non-operational in the temperature range of -40°C to +80°C. This camera has a diagonal field of view (FOV) of 63.5 deg and a horizontal FOV of 51 deg. The depth of field is the field between the closest and farthest object in view that are visually sharp. The field for this FLIR Lepton is from 10 cm to infinity. This thermal camera has a thermal sensitivity of 0.050 deg. This will produce a crisper image than a majority of different thermal cameras, as the average sensitivity is 0.1°C with the higher range <0.08°C and the lower range of 0.2°C. A block diagram can be seen in figure 15 below.

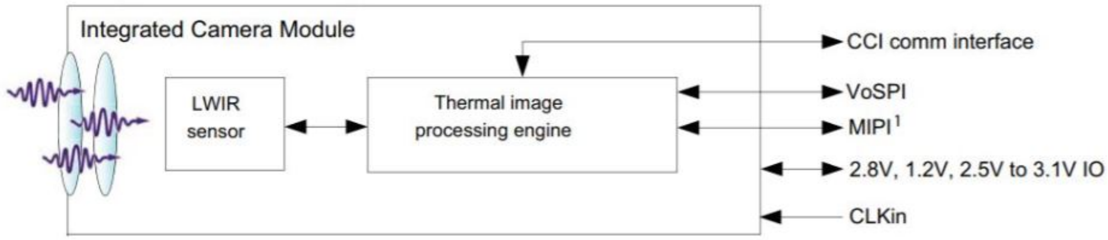


Figure 15: Block diagram of FLIR Lepton camera

3.1.13. Camera Setup trade study

The metrics taken into account for the camera setup include cost, power, system complexity, coverage, and weight. The table below describes the reasoning for each metric.

Table 4: Metric Definitions

Metric	Weighting	Justification
Cost	0.2	The hard limit of the budget for the entire project is $5,000. This money will have to be spread out between all systems in order to ensure every system is properly funded.
Size	0.05	The requirements given by General Atomics were to minimize size and mass of the system. The entire setup that will be chosen must be able to fit in between the walls of the satellite and the given avionics stack. The size metrics given in the following table represent the amount of space taken up by the camera system. Since the cameras used will be relatively small this is a pretty small metric.
Power	0.05	The customer is giving us 28V of input power for the entire system. This must be distributed between the camera system and all of the electrical components. The power metrics given for the following table represent the power that will be used for the camera system on each wall while it is active
Coverage	0.2	At least an entire side of an avionics stack must be covered in order to show a proof of concept of OTheRS. Ideally though the entire avionics stack will be able to be captured by OTheRS to show how using a system similar to OTheRS is more efficient than using thermistors
System Complexity	0.3	The Customer wanted this to mainly be made of COTS parts. If parts need to be machined or different means have to be used to to help increase the coverage of the camera, this will add complications to calibration of the system and can hurt the accuracy. This also defines the experience the team has with optics. This metric is quite high since the team has low formal experience with optics.
Utilizes FLIR Lepton	0.2	The FLIR Lepton won the camera trade study and it will provide precise and accurate results of the temperatures sensed on the stack.

Table 5: Scoring Matrix

	Scoring Criteria				
Metric	**1**	**2**	**3**	**4**	**5**
Cost	> \$4000	> \$2500	> \$1500	> \$1000	< \$500
Coverage	System can only view less than half of a Stack Wall	System can only view half of a Stack Wall	System can only view a single stack wall	System can view at least two stack walls	System can view the entire stack
Size	> 20000mm^2	> 10000mm^2	> 1000mm^2	> 500mm^2	< 500mm^2
Electrical	> 3000mW	> 2000 mW	> 1500mW	> 500mW	< 200mW
Complexity	All Parts must be machined and Group has no experience with the hardware	Mostly non COTS parts used, team has under 20 hours of experience with the hardware	More than half the parts used are COTS. Team has between 20-60 hours with hardware.	Most Parts used are COTS, team has between 60 and 100 hours of experience with the hardware	All Parts used are COTS and Group has over 100 hours of experience with the hardware.
Utilizes the FLIR Lepton	Doesn't Untilize the FLIR Lepton				Utilizes the FLIR Lepton.

The scores for each different setup based on these given metrics are given below.

Table 6: Trade Matrix

Metric	**Weighting**	**Multiple Camera Setup**	**Optical Manipulation**	**MLX Sensor Array**
Cost	0.2	5	4	5
Size	0.05	4	5	4
Power	0.05	4	5	5
Coverage	0.2	3	5	5
Complexity	0.3	5	2	4
Utilizes FLIR Lepton	0.2	5	5	1
Weighted Totals	1	**4.5**	**4**	**3.85**

From this trade study it is clear that using multiple FLIR Leptons would be the best setup to take temperatures of the avionics stack. Using multiple FLIR Leptons will only allow us to take the temperatures of one side of the stack but the temperatures will be precise and accurate which will be able to give a proof of concept to the customer. The FLIR Leptons are \$300 per camera which means that \$600 will be used to purchase both cameras needed to view a single side of the stack. This is cheap enough for the team to still be able to make sure all other systems are adequately funded

3.1.14. Image Processing trade study

A trade study of image processing methodologies was completed to determine which platform between OpenCV Python, OpenCV C++, and Matlab would be best suited for the image processing design requirements. The metrics chosen for this trade study are programming language difficulty, level of documentation (additionally, community support), accuracy of floating point operations, and the libraries of IP functions available. The metric definitions for image processing can be found in Table 7.

Table 7: Metric Definitions

Metric	Weighting	Justification
Programming language difficulty	0.2	The difficulty of programming in a specific language can affect the speed at which software is developed. Experience of the developer also plays a factor as a simple algorithm implemented poorly can lead to inefficient and wasteful code. In the case of programming in C/C++, lazy programming can lead to system memory leaks and further damage. Some languages like Python and MATLAB are high-level and do not require as much tedious work in developing software components.
Runtime	0.3	All image processing will need to be performed on-board and within the electronics bay of the proposed GA system. For this reason, the image processing software requires a true level of runtime sophistication to perform the necessary duties with each image in the time between image captures.
Level of Documentation	0.1	Documentation is a key metric for this trade study, as the image processing software tools available are extensive. A community of like-minded programmers for troubleshooting/debugging support is also helpful when critical software micro-services fail. Community and support available during software development, depends mostly on the programming language of choice.
Accuracy of floating point operations	0.2	Fairly accurate calculations are required to track pixel temperature and when otherwise moving pixel data. This is a key metric for image processing in general which requires high latency and correct calculations to achieve accurate results. Accuracy of floating point operations will factor more into locating electronics components, due to locating and moving pixels in the image RGB stack.
Libraries of IP functions	0.2	The libraries focused on in this trade study are all expansive and require deliberate planning before actual coding takes place. OpenCV can be ported to several different languages including Python, C++, Java. All Python functions use pre-compiled C++ code. Therefore, C++ can be used minimally to develop the underlying image processing, but can be used later on to alter these same functions.

Note that the largest weighting for this trade study is spent on the runtime of the programming language and therefore weighted heavily based on performance relating to image-processing. As an aside, OpenCV Python and C++ both use pre-compiled C code that is highly optimized, while MATLAB has lacking performance when completing simple tasks such as calling external libraries. MATLAB programming language is itself a scripting language, but is compiled to machine code using the JIT compiler. However, performance can be increased many more times in C++ compared to MATLAB vectorized code.

Table 8: Scoring Matrix

	Scoring Criteria				
Metric	**1**	**2**	**3**	**4**	**5**
Programming language difficulty	Software is extremely difficult to use. Team has little experience using this product.	Software is more difficult to use than not. Team has less experience than not in using this software.	Software is fairly easy to use. Team has a decent amount of experience.	Software is easier to use than not. Team has more experience than not in using this software.	Software is extremely easy to use. Team has generous experience using this product.
Runtime	Terrible runtime. Non-ideal case.	Sub-average runtime.	Average runtime.	Better than average runtime. Bordering on ideal.	Impressive runtime. Ideal case, pre-compiled code.
Level of Documentation	Level of documentation and community support is lacking in all regards.	Level of documentation and community support is worse than fair.	Level of documentation and community support is fair.	Level of documentation and community support is better than fair.	Level of documentation and community support is impressive in all regards.
Accuracy of floating point operations	Software lacks the necessary tools to produce any accurate results, even when developed optimally.	Software has necessary tools to produce at-best sub-average accuracy.	Software has necessary tools to produce average accuracy.	Software has necessary tools to produce better than average accuracy.	Software has the tools necessary to produce extremely accurate results when developed optimally.
Library of IP functions	Minimal library of IP functions, nearly no tools required are present. Nearly all components must be custom-made and developed.	Less extensive library of IP functions than not.	Fair library of IP functions. Average amount of custom-made components need be developed.	More extensive library of IP functions than not.	Extensive library of IP functions, all tools required are present. Few custom-made components need be developed.

Table 9: Trade Matrix

Metric	**Weighting**	**OpenCV Python Raw Score (1-5)**	**OpenCV C/C++ Raw Score (1-5)**	**Matlab Raw Score (1-5)**
Programming language difficulty	0.20	4	3	5
Runtime	0.30	5	5	2
Level of Documentation	0.10	3	2	4
Accuracy of floating point operations	0.20	4	4	2
Library of IP functions	0.20	5	5	3
Weighted Totals	1	**4.3**	**4.0**	**3.0**

A few additional justifications follow. Since OpenCV uses the same underlying compiled code in C, OpenCV in Python is at least as-efficient when it comes to run time and accuracy of floating operations when this image processing platform is used. MATLAB, although used extensively in aerospace applications and known well enough by all group numbers, was not chosen as seen by the trade study results. It was determined that on-board image processing would not be able to be handled using MATLAB based on the run time requirements for this specific project application. From this trade study, OpenCV Python is clearly the front-runner image processing platform of choice for this project. Additional development in C/C++ will proceed when the need inevitably arises for custom software components, with a focus on maintaining an optimal-performance software stack.

3.1.15. Processor trade study

Trade studies were conducted to determine which processor, between the MPU, the MCU, and the FPGA, would be used to meet the processing design requirements. The metrics used to make that determination were hardware integration, software experience and complexity, size and weight, power consumption, processing power, and cost.

Table 10: Metric Definitions

Metric	Weighting	Justification
Software Experience and Complexity	0.20	This metric defines how much experience the team has with the software and the software language required to integrate with the specific processor. The desire to create an efficient software to run the image processing and other parts of this project results in a high weight for this metric.
Hardware Integration	0.20	Processors require a variable amount of electronic modifications to be able to run the desired software, changing required cost and workload, and therefore has a high weight.
Power Consumption	0.15	This metric takes into account the fact that satellites have only a limited amount of power,and the processor should not have too large of a power consumption. Processors usually meet that requirement, and this metric will therefore not have the highest weight.
Processing Power	0.20	The processor needs to run the software at the TBD desired rate. This is critical and therefore has higher weight.
Size and Weight	0.15	The size of the system is a design requirement while the customer specified to minimize weight, and will therefore have the higher weight as a metric.
Cost	0.10	The budget of the project is limited, but the price ranges of most processors are well within the budget, and this metric will therefore be weighted at a minimum.

Table 11: Scoring Matrix

	Scoring Criteria				
Metric	**1**	**2**	**3**	**4**	**5**
Software Experience and Complexity	Team has no previous experience with the required software.	Team averages under 20 hours of experience for required software	Team averages between 20 and 60 hours of experience for required software	Team averages between 60 and 100 hours of experience for required software	Team Averages over 100 hours of experience for the required software
Hardware integration	Hardware requires configuration of the specific board to be used as a processor and requires external components to run software.	Hardware requires external components and peripherals to run software.	Hardware comes with some of the components to run software but requires other external peripherals to interface with the rest of the system.	Hardware comes with all the required peripherals to interface with the system, but does not contain the more specific controllers.	Hardware has all necessary components and peripherals already integrated.
Processing power	Processor cannot run software at required frequency.	Processor can run software sequentially to meet image processing rate requirement but requires other hardware to run the internal thermal control software.	Processor can run both the image processing and the internal thermal control sequentially.	Processor can run the image processing in parallel but not while running the internal thermal control software.	Processor can run both the image processing and the thermal control software in parallel.
Power Consumption	Processor requires more than the system's TBD allowed power budget.	Processor operates on average close to the maximum power budget.	Processor can run intensive software without passing power budget	Processor does not need to be constantly supplied with power.	Processor does not require any power.
Size and Weight	Processor cannot fit in a nanotray.	Processor has a fixed size and can fit in a nanotray assuming minimum added peripherals.	Processor has a fixed size and can fit in a nanotray without other parts being affected.	Processor size can be adjusted.	Processor does not require space on the nanotray.
Cost	Average cost (including required components and peripherals) above $500	Average cost (including required components and peripherals) $300-$500	Average cost (including required components and peripherals) $200-$300	Average cost (including required components and peripherals) $100-$200	Average cost (including required components and peripherals) below $100

Table 12: Trade Matrix

Metric	Weighting	MCU Raw Score (1-5)	MPU Raw Score (1-5)	FPGA Raw Score (1-5)
Software Experience and Complexity	0.20	5	5	2
Hardware Integration	0.20	4	3	1
Power Consumption	0.15	3	3	3
Processing Power	0.20	3	3	4
Size and Weight	0.15	3	4	3
Cost	0.10	5	4	3
Weighted Totals	1	**3.80**	**3.65**	**2.60**

By looking at the total score of each processor alternatives, the microcontroller is chosen.

Microcontroller Unit (MCU)

The microcontroller uses coding language (C/assembly) in which the team members are very familiar with, and can easily integrate other languages. Furthermore, the amount of documentation available is quite extensive to integrate the software to the hardware. On one chip, the MCU contains most the peripherals necessary to effectively interface with the system, with the exception of specialized controllers, such as a CAN microchip if CAN is used for communication. The MCU runs its software sequentially, but will be able to run all the softwares required to meet all our requirements. While the MCU's power consumption, cost, size, and weight vary for each specific models, it can on average meet all the specific power budget and size requirements at a low cost.

Microprocessor Unit (MPU)

The microprocessor and microcontroller are very similar in terms of software complexity, requiring the same languages. However, the microprocessor does not possess all the peripherals necessary to run the software and interface with the rest of the system, increasing hardware complexity and cost. The processing power and power consumption are similar to the microcontroller, but often has a bigger size, due to the need to integrate other components independently, instead of having everything built on one chip. This also affects the weight of the processor system.

Field-Programmable Gate Array (FPGA)

The FPGA is not a familiar processor to anyone in the team, requiring languages such as HDL which can require a large amount of extra workload. Furthermore, the FPGA has to be configured to be able to run the desired softwares specifically and does not contain any peripherals required to interface with the rest of the system. The FPGA, however, can run all the softwares in parallel, allowing for faster and more efficient image processing. The power consumption is higher than the MCU and MPU, but can still fit inside the power budget. Similarly, FPGAs tend to be of a higher size and weight than their specialized, already configured counterparts, and are on average at a higher cost.

3.1.16. Control System trade study

Table 13: Metric Definitions

Metric	Weighting	Justification
Mathematical Simplicity	0.4	A complicated system will take up much more of our time to analyze than a simple one, and time is at a premium.
Hardware Simplicity	0.1	Hardware options are fairly fixed. We either can only turn a heater on or off, or we can modulate power as required.
Thermal Stability	0.3	The longevity of satellite components depend, in part, on how well they're treated. Keeping temperatures very constant might be important.
Advance Knowledge Required	0.2	Some control systems have to be carefully tuned, which requires the whole system to be well modeled. Others might be very simple and not require the same amount of modeling and knowledge about the operating environment.

Table 14: Scoring Matrix

	Scoring Criteria				
Metric	**1**	**2**	**3**	**4**	**5**
Mathematical Simplicity	System requires in depth mathematical analysis to function	Performance is very poor without in depth mathematical analysis	Mathematical analysis improves performance	Mathematical analysis adds benefit but the same results can be accomplished without it	No mathematical analysis required
Hardware Simplicity	*unused*	*unused*	Solid state switching at high frequency needed	*unused*	Simple electronic on/off switch used
Thermal Stability	Oscillations likely less than $50K$	Oscillations likely less than $10K$	Oscillations likely less than $2K$	Oscillations likely less than $0.5K$	Oscillations likely less than $0.1K$
Advance Knowledge Required	Must fully characterize system and environment for all possible scenarios	Must fully characterize system, environmental factors can be neglected	Good characterization of system needed for stable performance	Good characterization of system not needed, trial and error can be used instead	No characterization needed

Table 15: Trade Matrix

Metric	Weighting	Threshold Raw Score	Proportional Raw Score	PID Raw Score
Mathematical Simplicity	0.4	5	4	2
Hardware Simplicity	0.1	5	3	3
Thermal Stability	0.3	1	4	5
Advance Knowledge Required	0.2	4	4	2
Weighted Totals	1	**3.6**	**3.9**	**3**

In the subsections below, the baseline design option for each subsystem or critical system component is laid out. These options we chosen based on the trade study results, extensive research, and some back of the envelope calculations based on our functional and design requirements.

3.1.17. Camera baseline design selection

The winning camera choice is the FLIR Lepton camera on the basis of its low power and small size. Depending on optical designs, it may be necessary to utilize multiple cameras in order to image the entire stack area. The space inside the satellite bus is limited and the field of view of one Lepton camera is too narrow to view the entire stack from inside the satellite. The camera choice is still contested as other infrared sensors have wider fields of view, but have other drawbacks such as lower resolution and accuracy. Our trade studies identified that multiple MLX90640 thermopile sensors give more effective coverage of the stack, but would limit the accuracy and resolution of the thermal profile. The final selection is the FLIR lepton 3.5.

3.1.18. Camera Layout and Test Bed baseline design selection

The baseline test bed is designed to replicate the avionics stack of the satellite. The mock avionics stack will be made up of stacked trays using approved substitute material as the GA satellite bay. The exact dimensions of the outer walls will depend on the final camera configurations we select for our test. The baseline Camera Layout will use 2 FLIR Lepton's to take the temperature of a single wall of a fabricated avionics stack. This is the most accurate setup due to the high resolution and thermal sensitivity of the FLIR Lepton.

3.1.19. Camera Calibration baseline design selection

For the purposes of OTheRS, a two point calibration system with one of the points coming from a black body radiator and the other point measured from a thermistor is sufficient. The linear thermal slope is unknown so one point calibration is not sufficient. Multi-point fitting would be too large to implement because of the limited require space near the stack. This leaves two-point calibration as the most viable method. As far as point determination, two thermistors would be ideal, however, by using two thermistors, it cannot be ensured that the required range of -30°C to 60°C is accurately captured by the two measured points. Thus, the optimal selection for point determination is one thermistor that measures a point near the stack that is expected to remain relatively thermally constant. The other point shall be assumed from a black body radiator that heats up to a temperature that is sufficiently far from thermistor measurement to increase the effective range of the calibration.

3.1.20. Image Processing baseline design selection

The image processing subsystem will involve the programming required to capture images via the camera, identify the stack's physical dimensions/positions, and extract temperature data of these components. This subsystem will interface with the camera and control systems, while being used in benchmark form during the test bed analysis. With the temperature data in hand, the control system will know which heaters to turn on/off in order to manage the thermal needs of the OTheRS. Regardless of camera choice, we will need to extract information from the images. If we use multiple cameras, we will likely need to perform advanced image processing in order to merge the images and create the thermal map. We chose the OpenCV image processing framework in Python on the basis of easy language constructs and the plethora of IP functions/paradigms available through OpenCV. This software stack will combine the optimized and high-performance pre-compiled C code available as the foundation of OpenCV with the easy

3.1.21. Processor baseline design selection

The Camera(s) will be connected to a microcontroller chip to process the images and relay data. The microcontroller will then control the temperatures of the electronics in the test bed stack switching electrical heaters according to proportional control law, or it will pretend to do so using LEDs as an indication of heater power. We will process and output data over a serial link as required in order to build a 'thermal map' of the avionics stack. The specific selected processor is the Raspberry Pi 3.

3.1.22. Control System baseline design selection

If full power heaters are used, they will be switched according to proportional control law. This provides an optimum between stability and implementation difficulty. A MOSFET, or other similar transistor, will be used to switch up to $2.5A$ at high frequency using PWM modulation. If indicator LEDs are used, then the transistors will switch those.

3.1.23. Thermistors baseline design selection

For performance comparisons, thermistors will be used, which have an accuracy of $0.1°C$, which is industry standard. This requirement derives from the basic functionality requirement that our system be self-monitoring and self regulating. The test bed will focus on accuracy rather than a flight ready system.

3.2. Final Design

3.2.1. Structure and Test Bed

The final SolidWorks model can be seen in figure 16. The final setup of the test bed is designed so that the electronics stack can be accessed and removed from the outer avionics bay. To do this, there is one wall of the outer avionics bay that is held on to the rest of the structure by four latches, while the rest of the bay is held together by aluminum angles. In order to assure repeatability for the location of the electronics stack within the avionics bay, standoffs have been attached to two of the avionics bay walls.

The electronics stack contains six trays, a stack lid, an offset plate, and a removable face. This face that will be added in front of the trays so that the FLIR Leptons can image a smooth side of the electronics stack. Multiple copies of this face are manufactured so as for the ability to test many surface coatings.

Camera mounts consisting of a 3D printed 60° offset wedge mounted onto a thin rod are placed in corners of the avionics bay so that together, both cameras can view an entire face of the electronics stack.

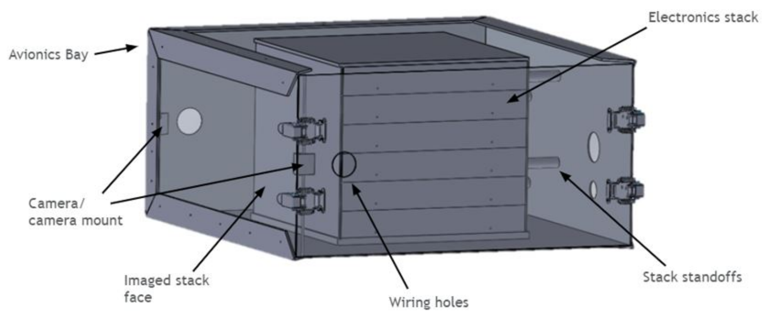


Figure 16: SolidWorks model of final test bed

3.2.2. Thermal Camera & Image Processing

Two FLIR Leptons were used to capture the entire side of the stack by taking advantage of the FOV overlap between the images. These cameras are placed on either side of stack and given a horizontal offset of 60^o. The Raspberry Pi serves as the main computer and decision-making entity for the OTheRS system. Both FLIR Lepton cameras communicate over I^2C and SPI with the Raspberry Pi. The radiometric feature available through the FLIR SDK software allows for absolute temperature measurements at each pixel location in the images. Image processing allows for obtaining temperature and image data from the thermal cameras for analysis onboard the Raspberry Pi. This is accomplished by running modified FLIR Lepton software for capturing still frames size of 160x120 pixels. Output from the image capture software module is two thermal images and two text files of temperature data on every pass. This functionality is captured in the image processing software flowchart in Figure 17.

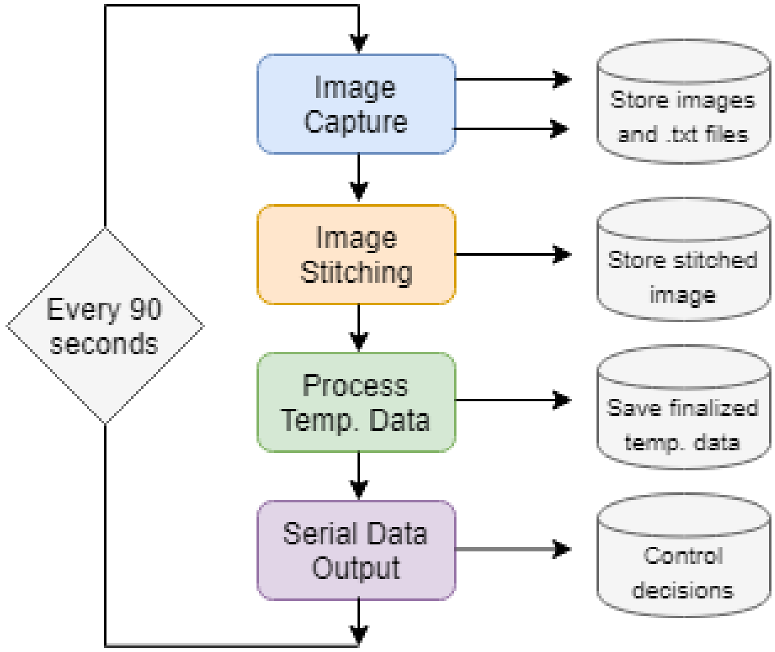


Figure 17: Image Processing software flowchart

To ensure proper camera placement, the thermal cameras will be calibrated with respect to space. In order for the cameras to be spatially calibrated, the images input to the image processing subsystem are stitched together to develop a single output representative of the stack face. The final image stitching software module takes advantage of the simplified geometry of the test bed structure to combine both images without compromising the corresponding temperature data. This stitched image will be saved onboard the Raspberry Pi external storage, available to the customer for further post-processing. The next software task to complete after image stitching is temperature data processing. Extracted temperature data from the camera is collected in Kelvin but then converted to Celsius at this step. This software script pulls in pre-determined geometric data for the coordinates of each tray in the stack. Within each tray, the corresponding tiles are also located using similar pre-determined coordinates. With this data in hand, the maximum, minimum, and mean temperatures for the pixels within each tile are calculated. From the mean temperature tile data, control decisions are selected to determine which regulatory commands to send to the Host computer from the OTheRS system. These control decisions are communicated from the Raspberry Pi computer to the Host computer over serial data protocol RS-232 as specified by the customer. This workflow of software completes image processing on-board the Raspberry Pi.

3.2.3. Capturing Still Images from the Lepton

The Leptons present a 27 frame per second video stream interface over a 8 to 20MHz SPI bus, with tight timing requirements on the master device. Each video frame is split into four segments, each consisting of 60 packets of 164 bytes, for 80 pixels per packet, plus synchronization information. While each packet is numbered sequentially (0 through 59), the numbers relating to each segment are only valid on the 20th packet of each segment. Each segment represents a grid two packets wide and 30 packets high. Each packet needs to be clocked out of the Lepton by the Raspberry Pi in a quarter of a frame, or within 9.26 milliseconds. This is equivalent to a data rate of just over a megabyte per second, a demanding speed for an embedded computer.

For this purpose, a custom built piece of software, `raw_capture`, was written in C in order to interface with the SPI controller on the Raspbery Pi and capture a still image from the camera. In order to capture the image, the Lepton first has to be initialized and a stable video stream has to be established. Once the stream is established, packets can be parsed from the incoming video stream, but cannot yet be written into a frame buffer. The packets must be reassembled into segments before the segments themselves can be ordered, as the segment number is only transmitted halfway through each segment.

3.2.4. *Electrical Design Software*

Four large PCBs were produced over the course of this project. They were the Raspberry Pi's breakout board, the Reference Data System board, and Simulation Electronics driver board and heater boards. All electrical designs were produced in KiCad version 5, a free and open source electrical design suite. For the majority of components, libraries containing the schematic symbols for the selected integrated circuits are already available, and the components are placed in KiCad's schematic editor and routed together. The schematic symbols are then associated with footprints, which represent the physical layout of each component on the PCB. The symbol connections, footprints, and associations are loaded into the PCB layout design editor and arranged appropriately before traces are routed between each component. Once components are placed and routed and the design is satisfactory, CAM files are generated, exported, and sent to the manufacturing centers.

3.2.5. *Reference Data System*

In order to quantify the accuracy of the cameras' temperature outputs, a system to provide reference temperatures on the inside of the face being imaged. This system is based on an Arduino Uno development board and a custom PCB designed using the methods in the previous section.

A total of 36 thermistors were used, for a total of 6 thermistors placed equidistantly on each tray. In order to accommodate all thermistors, five ADCs with 8 channels each are present on the custom PCB. The full thermistors placement is as shown:

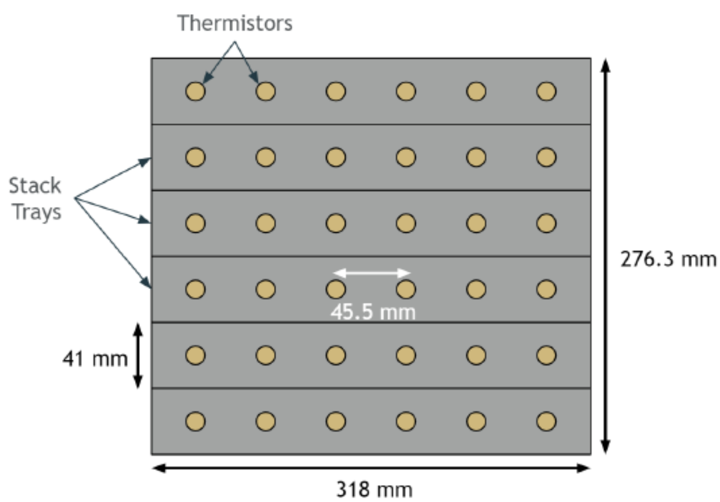


Figure 18: Thermistors placement

NTCLE413-428 $10k\Omega$ 1% tolerance thermistors were selected as the primary measurement device as they are well characterized and highly available. These were arranged in a resistor-divider configuration with $18k\Omega$ 1% pull-up resistors in order to produce a voltage that varies based on temperature. The precise value of this resistor was chosen in order to give the maximum voltage range over the temperatures listed in **FR 1**. This voltage was connected directly to one of the input channels of a Texas Instruments ADC128D818 I2C analog to digital converter (ADC).

This chip converts the analog voltage to a twelve bit digital measurement that the Arduino Uno can process. This chip was chosen primarily for its use of the I2C protocol, which allowed for multiple ADCs to use the same data bus, greatly simplifying circuit layout, as well as easing software integration.

The custom PCB design is as follow:

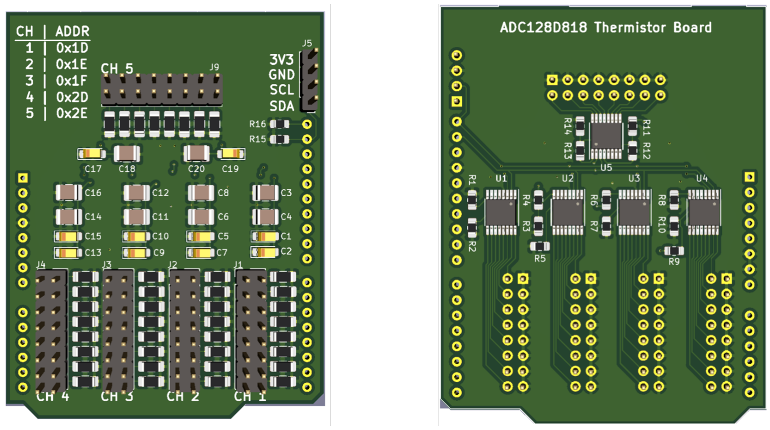


Figure 19: Front (left) and Back (right) of reference data PCB

Visible are the five ADCs on the back of the PCB and all the pins for connecting the thermistors and the pins connecting the microcontroller on the front.

The software uses the Arduino development platform to act as a intermediary between the thermistor ADC system and the monitor software. The ADC registers consisting of the resistance values read are continuously inputted to the software and serially communicated on at a 9600 baud rate. To convert the input resistances to temperatures the following equation is used:

$$T = [\frac{1}{T_{25}} + \frac{1}{B_{25}} ln(\frac{R_{TH}}{R_{25}})]^{-1} \tag{10}$$

The full system can be visualized by the following diagram:

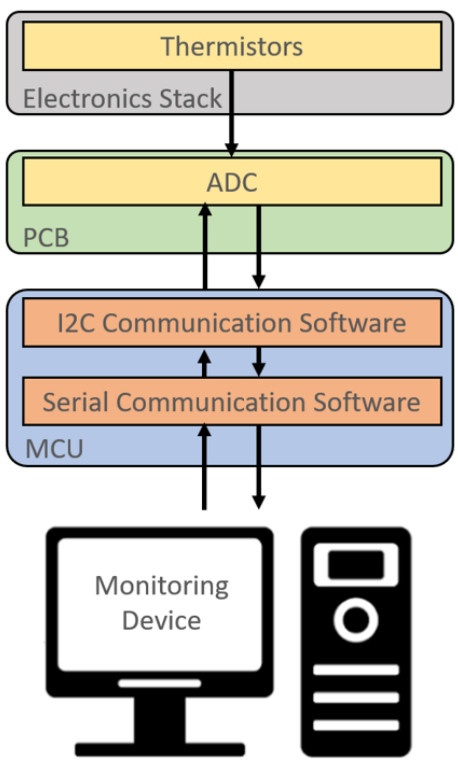


Figure 20: Diagram of the reference data system

3.2.6. Simulation Electronics

The simulations electronics system provides a method of distributing heat within the avionics stack, in place of actual flight processors. It is comprised of PCBs that take up the area of the avionics stack with grids of power resistors, and a microcontroller based PCB with twelve MOSFETs to modulate power between the power resistors. The power channels can routed to individual resistors using plugs located on the back of each PCB tray. The microcontroller selected is an Arduino Uno development board with the custom PCB mounted on top. The PWM signals are generated using PCA9865 PWM controller from NXP Semiconductor.

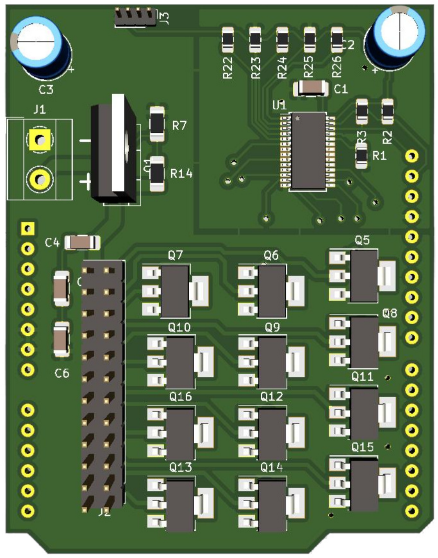


Figure 21: The Heater Driver PCB, showing PWM controller (top right) and MOSFETs (bottom right). The power resistors are shown in figure 30

3.2.7. Raspberry Pi Breakout Board

In order to accommodate all the systems required for operating the two Lepton cameras and their thermal control systems in a well integrated manner, a PCB was designed for the Raspberry Pi. The principal elements of this PCB are pin headers for both Lepton cameras, as well as a temperature measurement system and a heater system which borrowed designs from both the Reference Data System and the Simulation Electronics and adapted them for software control from the Raspberry Pi's Linux environment.

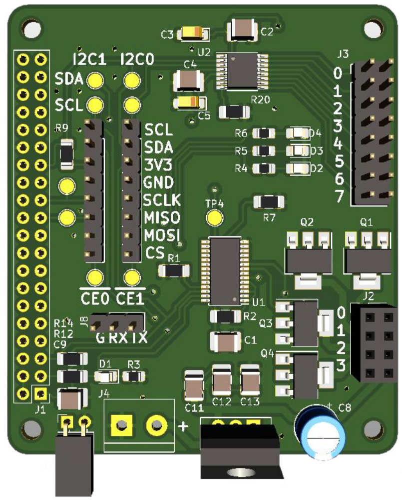


Figure 22: The breakout board for the Raspberry Pi, showing headers for the FLIR Leptons (center left), thermistor ports (top right), and MOSFETs (bottom right). Figure 43 shows a photo of the completed and assembled PCB

.

3.2.8. System Integration

A graphical user interface is used in order to visualize all the thermal data inputs, control the tests, and save all the necessary data for post-processing and testing validation. This monitor software receives serially the temperatures outputted from the image processing Raspberry Pi and from the reference data Arduino and sends serially pulse-wave modulation values and commands to the simulation electronics Arduino.

The GUI itself consists of three windows: one, the main window, for visualizing and saving the serial inputted temperatures, another, the test window, for troubleshooting the serial and I2C communications, and a final one, the configuration window, to select which data points to visualize and control the simulation electronics heaters.

The main window is as follow:

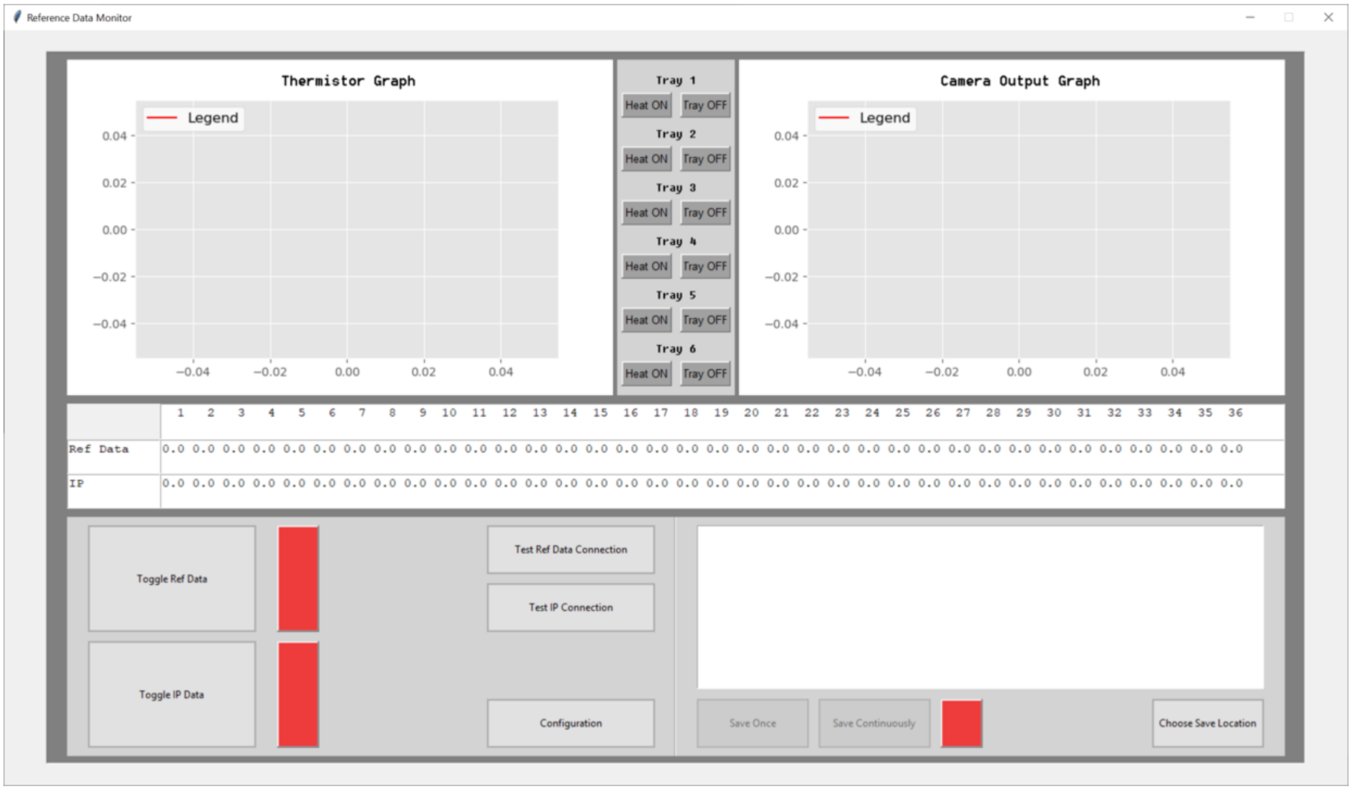


Figure 23: Main GUI Window

The two graphs display the latest 60 seconds worth of data received at user determined grid locations, configured in the configuration window. Beneath the graphs, the table displays all the received data. The serial ports can be opened and closed through two toggle buttons, with their status displayed on adjacent visual indicators. The data can be saved by selecting a save location and either saving continuously or saving once. Any text added to the text box above the save buttons will be added as a comment to the save files. Finally, the configuration window and troubleshoot windows can be accessed from the main window.

The configuration window is as follow:

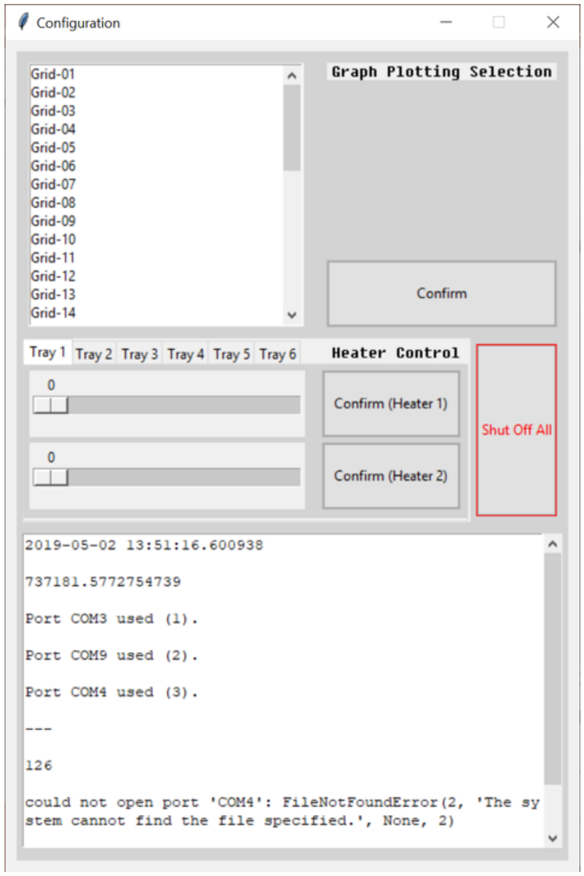


Figure 24: Configuration GUI Window

The first part of the configuration window, a list of grid location, is used to select which temperatures are displayed on the main window graphs. The second part enables the user to select which simulation electronics heater to control and select the percent of the Pulse-Wave Modulation signal for the latter, therefore choosing the power input of the resistors. Finally, the last part of the configuration window is simply a text box that displays all the errors and events encountered during the testing, along with the lines of code associated with them.

The troubleshoot/test window is as follow:

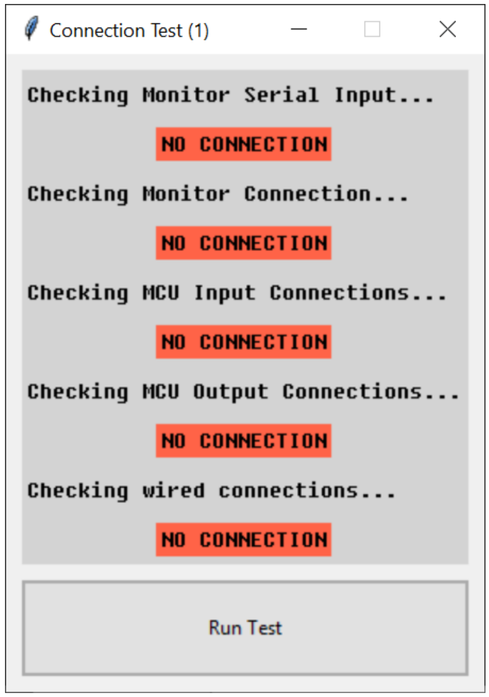


Figure 25: Troubleshoot GUI Window

The troubleshoot window simply consists of visual indicators to display which serial and I2C tests succeeded and failed, and a button to rerun the tests.

3.2.9. Thermal Model

The goal of performing a thermal simulation of the OTheRS test bed was to further quantify the performance of the camera solution in comparison to the chosen thermistor truth data system. The SolidWorks simulation environment was chosen for several reasons, including its compatibility with the mechanical design of the system, extensive documentation, and access to students both on and off campus. While ANSYS is considered a better simulation software, familiarity with the SolidWorks environment allowed for the overall learning curve to be smaller and was a factor in the software choice. In order to complete simulation calculations in such a manner that allowed for the parameters of the test bed to be adjusted, several simplifications and assumptions were applied with the goal of reducing the computational cost of the model without sacrificing result fidelity. Simplifications, along with justification, from the final OTheRS test bed are as follows.

1. Remove hole features from the model to significantly reduce number of mesh nodes.
2. Remove L-bracket PCB mounts from tray model because heat transfer through them can be modeled as PCB contact to the stack itself.
3. Remove ledge "stacking" design from tray model, reducing number of vertices in model.
4. Remove bay L-brackets, door hinges, and stack standoffs because these do not affect the stack wall surface temperature.
5. Suppress or remove unpowered heaters to reduce number of mesh nodes.

As an example, Figure 26 below is a side by side comparison of the tray model used for computations versus the tray model manufactured and tested with.

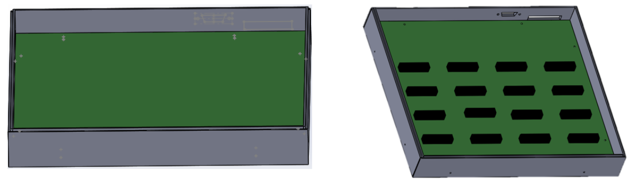


Figure 26: Simulation Tray versus Test bed Tray

In addition to these simplifications, certain assumptions were applied during the creation of the simplified model, again with the goal of reducing the model complexity - these again are as follows.

1. Thermal conductivity set to nominal 1.42 [W/m-K], as listed on thermal grease packaging.
2. Convecting flow does not occur past PCB-to-stack boundary.
3. Body at uniform temperature when testing begins.
4. Power supply to heaters is constant.
5. Heat transfer is symmetric along body centerline when heater configuration is also symmetric.
6. Ambient air temperature outside of the satellite bay does not change with time.

The process of building the model is fairly straightforward, where definitions of heat paths between objects and the ambient environment being the only requirement. Surface-to-surface radiation is used inside the avionics stack and satellite bay and surface-to-ambient radiation occurs on the outer surfaces of the bay. Conduction occurs between stack walls, the heater to the PCB, PCB to the walls, and stack to satellite bay. Finally, convection is modeled off of the heater, PCB, stack walls, and bay walls (both inside and outside to ambient). Common value ranges are provided in Table 16. ϵ represents emmissivity, U represents convection coefficient, and k represents thermal conductivity

Heat Transfer Coefficient	**Value [Units]**
ϵ_{heater}	.92
ϵ_{PCB}	.9
ϵ_{Al}	.1
U	0-10 [W/m^2 K]
k	1.42 [W/m K]

Table 16: Heat transfer values used in the thermal model

3.2.10. Miscellaneous Designs

As per Functional requirement 3, the OTheRS system must function off of 28 volts of unregulated power. The Raspberry Pi however, only needs 5 volts to power. Because of this, voltage regulation is necessary to run the Raspberry Pi. A Buck converter was utilized to step down the voltage. Figure 27 below is a picture of the buck converter.

Figure 27: MP1584EN Buck Converter

A circuit was designed around this buck converter to step down the 28 volts to 5 volts from a given power supply. Figure 28 shows the completed circuit with the buck converter.

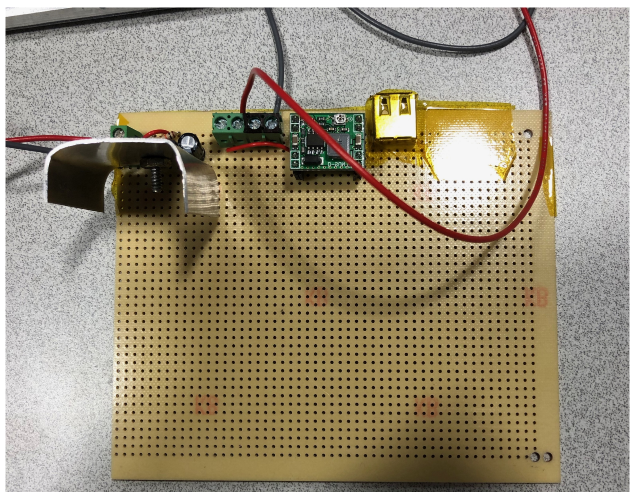


Figure 28: Completed Voltage Regulation Circuit

4. Manufacturing

Author: Emma Cooper, Jacob Killelea, Justin Alvey

4.1. Mechanical

4.1.1. Individual Electronic Tray

The walls of each of the six trays composing the electronics stack is constructed out of a piece of of 6061-T6 Aluminum. Ledges are cut into each piece as a way to adhere all six trays stacked on top of each other. These ledges can be seen in figures 29 and 30. Two small L-brackets are screwed onto each wall of the four tray walls. The purpose of these is to hold the PCB in place, which then in turn holds all four tray walls together. These L-bracket mounts can be seen in figures 29 and 31. Each of the six back tray walls contains a rectangular and a trapezoidal hole in order for easy connections to the internal electronics. All tray walls are machined using the CNC in the Aerospace machine shop.

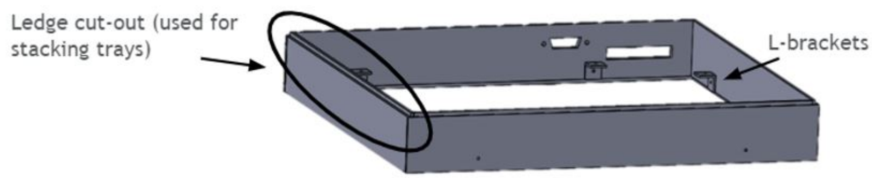


Figure 29: SolidWorks model single tray

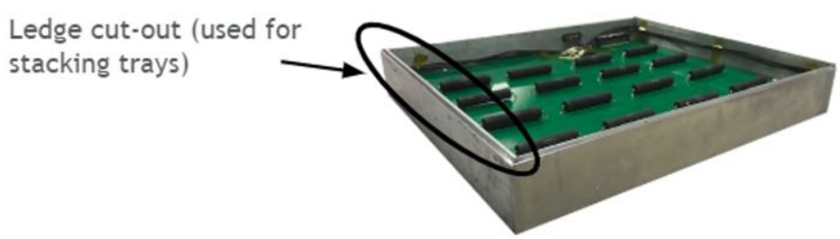


Figure 30: Actual single tray

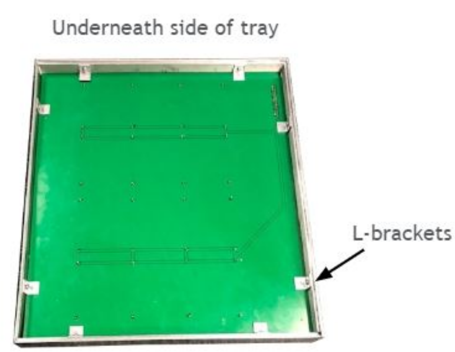


Figure 31: Underneath side of a single tray

4.1.2. Electronics Stack

The assembled electronics stack consists of all six trays stacked on top of one another as well as a lid, an offset plate in order to replicate the customer satellite, and a removable face that is to be imaged. Both the lid and the offset plate are designed to have grooves so that the ledges cut into the trays can easily fit into these pieces. The stack lid, offset plate, and the four removable faces are manufactured with the CNC mill in the Aerospace machine shop.

Four separate aluminum faces are fabricated so that they can slide onto the front of the electronics stack in order for the cameras to have a smooth face to image. The plate is held in place by additional grooves cut into the offset plate and stack lid. Four copies of this piece were made in order to be able to test multiple surface coatings.

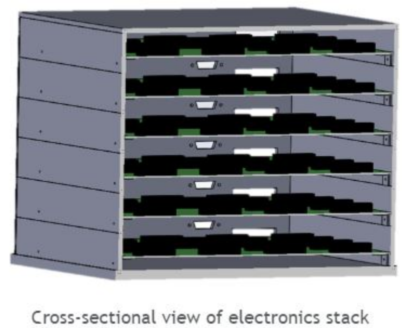


Figure 32: SolidWorks model of assembled electronics stack, inside look

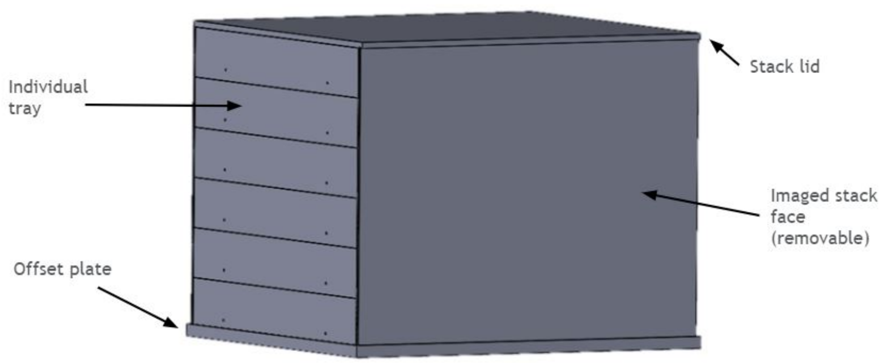


Figure 33: SolidWorks model of assembled electronics stack

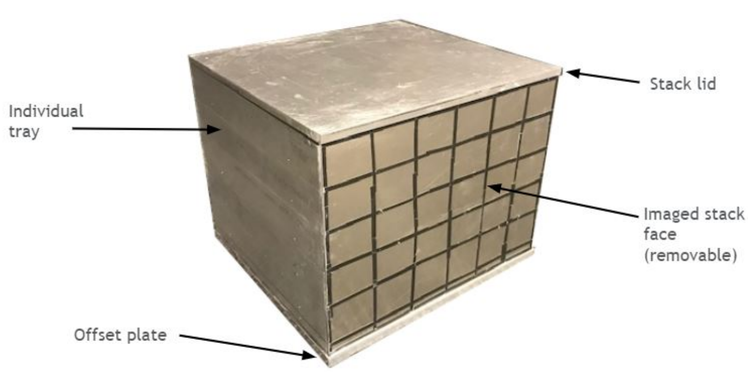


Figure 34: Actual electronics stack assembled

4.1.3. Camera Mounts

Each of the two FLIR Lepton cameras needs to be positioned in a way to see as much as possible of the imaged face of the electronics stack. The optimal configuration for this is to have the cameras on opposite sides of the imaged face of the stack angled in at 60°. Each camera also needs to have a vertical placement that is exactly half way in between the top and bottom edge of the imaged face of the stack.

Two camera mounts were 3D printed using black resin. Each mount takes the shape of a triangular wedge with the necessary 60° angle. Two small protrusions on the camera mounts allow for the camera breakout board to be securely screwed onto the mount.

In order to account for the necessary vertical placement of the cameras, two rods are placed in opposite corners facing the imaged face of the electronics stack. Two shaft collars (seen in figure 37 are used per rod in order to hold the camera mount in the correct location.

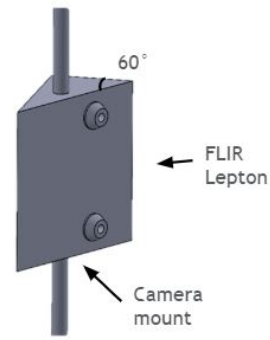


Figure 35: SolidWorks model of camera mount

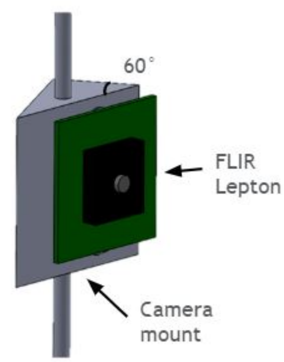


Figure 36: SolidWorks model of camera mount with FLIR Lepton

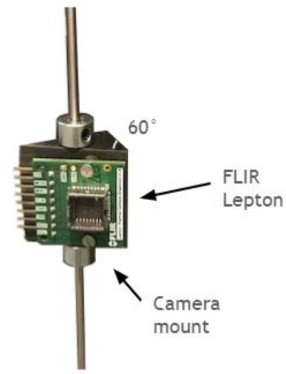


Figure 37: Actual camera mount with FLIR Lepton

4.1.4. Outer Avionics Bay

The outer avionics bay consists of five aluminum walls held together by aluminum angles. The sixth wall of the outer bay is held on by four clamps. This is so that it can be removed in order to allow access to the inside of the test bed. In order to minimize alignment error, holes were machined into the aluminum angles using the CNC, however, the corresponding holes were not drilled into the walls via CNC. Building from the bottom of the bay and moving up, a center punch was used to mark locations on the bay walls that corresponded to the drill holes in the aluminum angles. These locations were then drilled with a hand drill.

There are four wire holes cut into the sides of the outer avionics bay. Two of these holes are to allow for the wires from the two cameras to leave the test bed and the other two holes allow for the wires necessary for the electronics stack to leave the test bed.

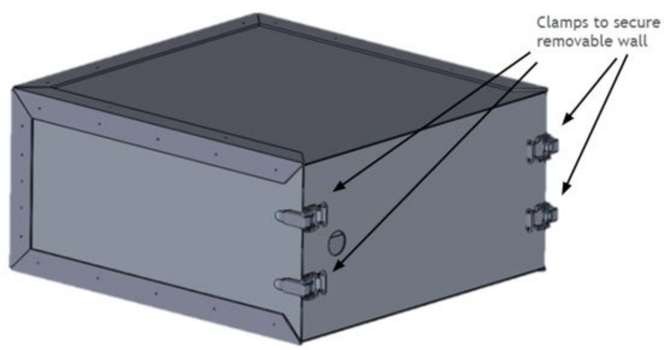


Figure 38: SolidWorks model of outer avionics bay

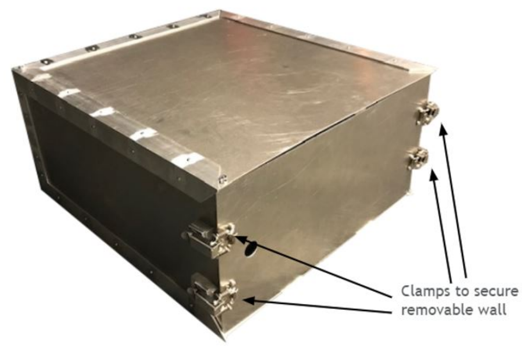


Figure 39: Actual outer avionics bay

4.1.5. Final Test Bed Assembly

The final test bed is designed so that the electronics stack can be accessed and removed. However, the electronics stack needs to be placed back inside the test bed in the same exact location each time it is removed. In order to ensure this location accuracy, standoffs (seen in figures 40 and 42) were created using the lathe in the Aerospace machine shop. Each standoff is dimensioned so that the electronics stack will sit in the center of the test bed. These standoffs are screwed onto two adjacent walls of the outer avionics bay.

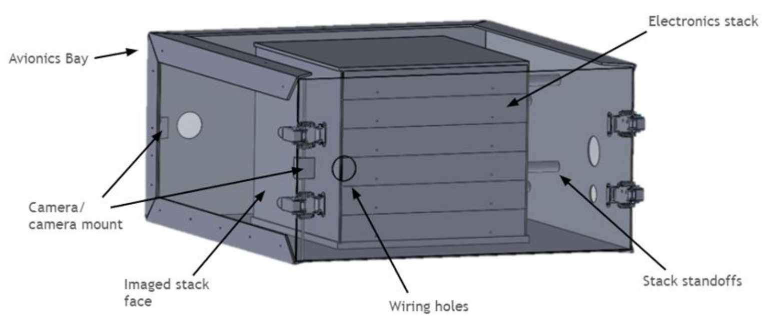


Figure 40: SolidWorks model of final test bed

Figure 41: Actual final test bed

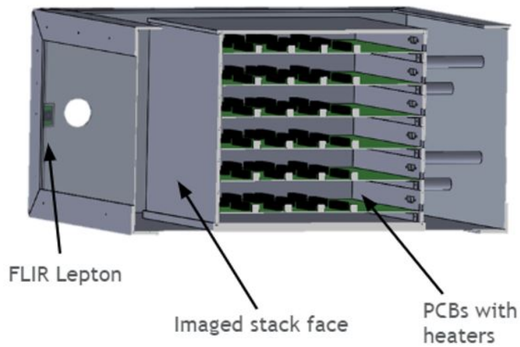


Figure 42: SolidWorks model of final test bed, sectional view

4.1.6. Challenges Faced

After initially machining all parts, components were assembled into the final test bed configuration. This however showed a handful of issues that needed to be addressed. There was not enough tension in the latch that was holding on the removable wall of the outer avionics bay. To fix this, a small offset block was added to the outside of the bay to increase the distance between the latch and the catch for the latch. The grooves in the electronics stack lid and in the offset plate had to be widened slightly to acquire a better fit with the electronic stack trays.

The biggest issue, however, was that there was a machining error with the electronic stack trays in that three out of the four sides of each tray was approximately 3mm to tall. With this error adding up across all six trays, the electronics stack was significantly too tall to fit inside of the outer avionics bay. It was decided that the bottom tray should be cut down enough so as to not have each other tray trimmed down in order to fit. This however eliminated the electronic functionality of this bottom tray.

4.2. Electrical

4.2.1. Printed Circuit Boards

Two different PCB manufacturing centers were using during the course of the year. The first is the Advanced Electronics Center in the Integrated Teaching and Learning Laboratory (ITLL) here at CU Boulder. The ITLL has the tools necessary to CNC mill bare copper PCBs with through-hole plating, with tolerances adequate for the small dimensions of most modern electronics. Initial PCB prototypes were produced here and used for both the Reference Data System PCB and Simulation Electronics' MOSFET driver PCB.

However, errors in the export of some design files meant that holes for important connectors were drilled undersized and both boards required additional work before being functional. In the case of the Reference Data System, every hole on every connector for the thermistors were drilled undersized and the connectors could only be soldered into the top of the board instead of through the PCB, as intended. This had a severe effect on the quality of the final design and it was ultimately decided that the workmanship of this version was unsatisfactory.

On the Simulation Electronics' MOSFET driver PCB, few enough holes were mis-drilled that they could later be drilled out and the proper connectors inserted. However, the process of re-drilling the holes destroyed the through hole plating on these holes and consequently, the connectors only had electrical contact with the underside of the PCB. This required additional work to rectify by prying up the plastic housing on the connectors and soldering the top side of the pins to the upper surface of the PCB, but the final product was serviceable.

Future boards were ordered from Shenzhen JLC Electronics Co., Ltd. (JLCPCB), in Shenzhen, China. These boards are produced with a photolithographic acid etch process, and have tighter tolerances than those made at the ITLL. Instead of bare copper, they also feature a solder mask to reduce assembly errors and a silkscreen layer for information such as component names, pin numbers, and device addresses to be printed on. In comparison to the ITLL boards, the same holes that were previously under-drilled were now found to be slightly oversized, but this introduced no extra difficulties. The PCBs produced here include the Raspberry Pi's breakout board, a version of the Reference Data System PCB, and the Simulation Electronics PCB that housed the power resistors.

4.2.2. *PCB Assembly*

Initial assembly of the Reference Data System and Simulation Electronics' MOSFET driver PCB were conducted in Trudy Schwartz's lab in the Aerospace Engineering wing. However, when the initial version of the Reference Data System was determined to be unsatisfactory, the board was taken to the ITLL, where components were salvaged and placed on a PCB from JLCPCB using the hot air reflow method. This method was also used on the Raspberry Pi's breakout board. The hot air reflow method provided modest time savings when compared to a normal soldering iron, but an appreciable reduction in solder joint defect rate was observed.

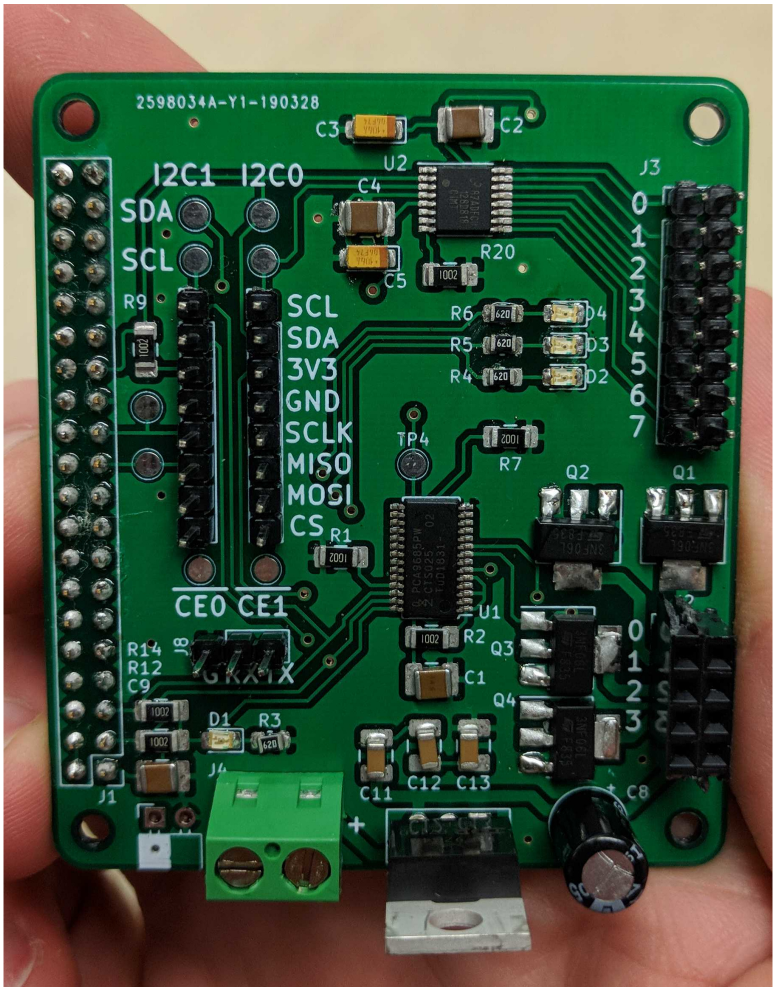


Figure 43: The completed Raspberry Pi breakout board. Top IC: ADC, Middle IC: PWM Generator, Bottom Right: MOSFETS. A render of the PCB design is show in Figure 22.

4.3. Software

4.3.1. *Developing raw_capture*

Initial attempts at this software attempted to short circuit the approach specified in the datasheet by placing video lines into a frame buffer as soon as they are available, but this process introduced a variety of small errors. Because the Lepton did not always send video segments in order and synchronization data only comes in the middle of each video segment, several video lines could be placed into the wrong location in the frame buffer before the synchronization message resets the location of the segment and the rest of the lines are written elsewhere. This caused pictures to frequently have errors or repeating sections in the image.

This was resolved by representing image transmission elements in data structures that matched the protocol described in the datasheet so that image data reorganization and error checking could be accomplished, as well as an extensive testing regime. Without a way to synthesize a realistic data stream from the cameras, every step of development required significant time working in an ESD safe area, making incremental changes to the code and observing software stability and image quality results.

4.3.2. Developing stitch.py

Image stitching is the process of modifying the perspective of input images and blending them, so that photographs can be aligned seamlessly. For OTheRS, the main purpose is to satisfy spatial calibration by combining both cameras input images into a single panoramic image. OpenCV is a popular, open-source computer vision and machine learning platform available for common image processing strategies. This library contains a StitchAPI for image stitching which involves finding commonalities between input images, estimate transformation matrix for stitching, and then applying a warping transformation to complete the stitch. An example of the OpenCV image stitching prowess is shown in Figure 44.

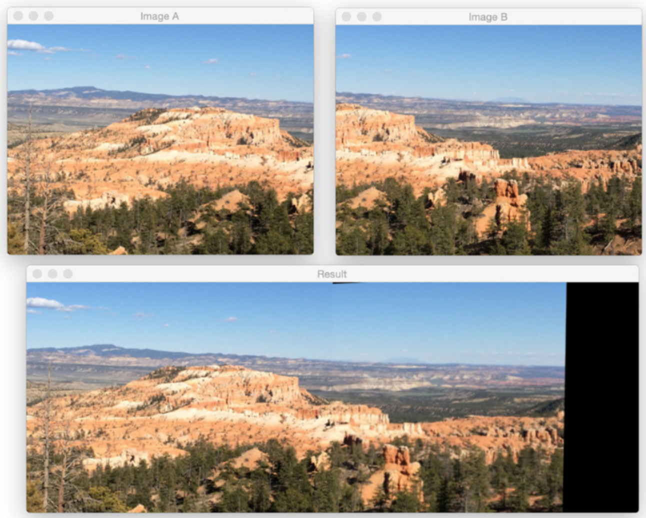


Figure 44: OpenCV library image stitching example

The OpenCV library was first explored as a method for transforming both thermal images into a final stitch in order to capture a single side of the stack. However, for the purposes of OTheRS, the StitchAPI available through OpenCV proved unsuccessful. The OTheRS image processing system requires a minimum number of at least 10 matches between the two images to complete the overlap. With so few pixels to work with (160x120) per image, the StitchAPI did not produce enough quality matches. The StitchAPI requires images of size at least 600X400 pixels. An example output from the OpenCV StitchAPI with two thermal images at input is shown in Figure 45.

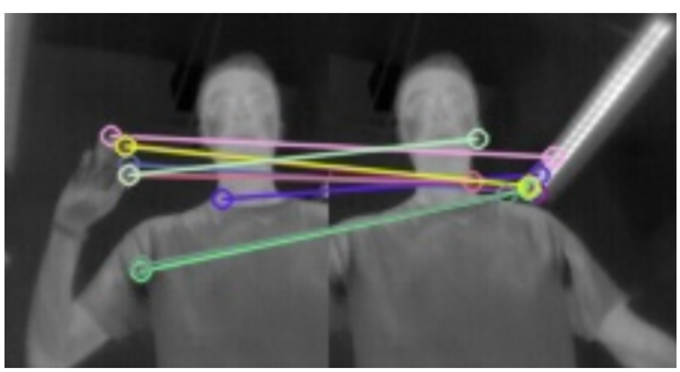


Figure 45: A thermal image example output from OpenCV image stitching method. Proposed matches are in color. Note the incorrect matches between the two images.

With unfruitful test results for this project application, the OpenCV image stitching algorithm proved useless. Instead, a simplified geometry was developed for the aluminum stack face in order to expedite the image stitching software process. Emissive tape was arranged on the aluminum stack face to outline the edges of the stack and a 6x5 grid of tiles. A custom image stitching software application was developed to take advantage of this simplified geometry. The software flowchart for image stitching is shown in Figure 46.

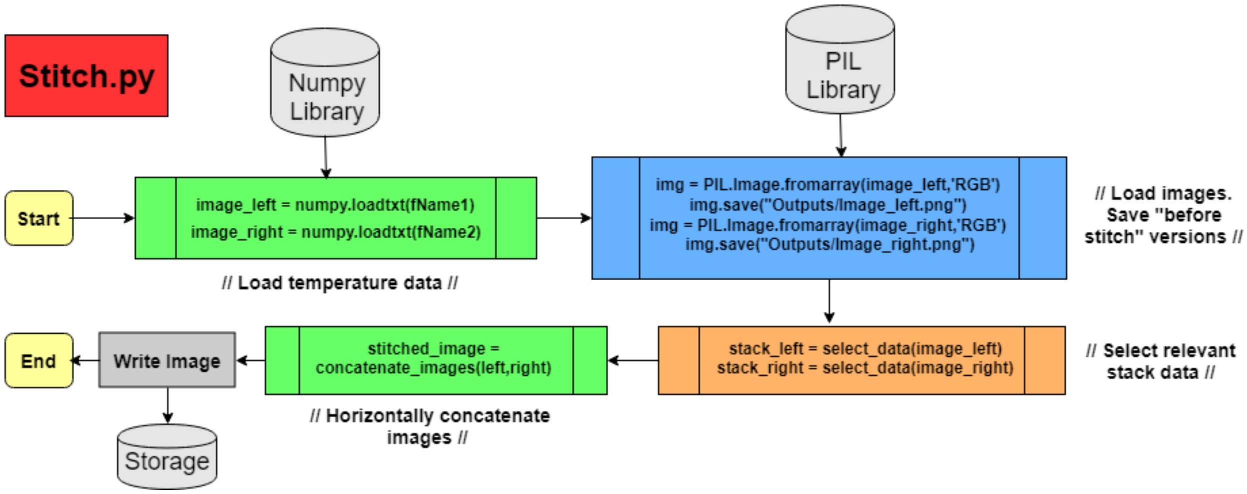


Figure 46: Software flowchart for Stitch.py

The software starts by reading in the associated temperature and image data from raw_capture for processing. Images at the start of this script are saved to provide a "before" version of the images once the image stitching is complete. From each image, the relevant data representative of the stack face is selected and the non-essential data removed. The remaining data is rotated to line up horizontally. With each image providing data from half of the stack, the concatenate_images() function is called to horizontally stitch the two images together. This custom stitching software's main purpose is not to find similarities between the two images, but the vertical line where the left image stops and the right image starts. With this vertical line serving as stitching axis, the two images are combined horizontally. To finish the script and verify spacial calibration, the stitched image is written to a file and saved on-board the Raspberry Pi. Python libraries used in this stitch.py script include Num.py which is used for numerical processing/matrix math and PIL which is the Python Imaging Library.

4.3.3. Developing tile.py

The pixel temperature data obtained from the FLIR Lepton thermal cameras need to be processed in order to determine tray temperatures. From the tray temperatures within the images, control decisions can be made to simulate regulatory commands. The purpose of the tile.py script is to locate the 5 tray elements within the thermal image through hard-coded object detection. Within each tray element, the 6 tiles are located through a similar hard-coded object detection procedure. This hard-coded procedure is possible by keeping the thermal cameras in the same configuration and position relative to the stack. After initial testing of the cameras in the final test bed, the tile positions were located using a Java image processing library known as ImageJ. Each tile has a unique geometric positioning within the image, which was selected manually using ImageJ and independent of the on-board Raspberry Pi software. The bounding coordinates for each tile and the interior data points are saved in a CSV file for loading into Python. A software flowchart describing this script is shown in Figure 47.

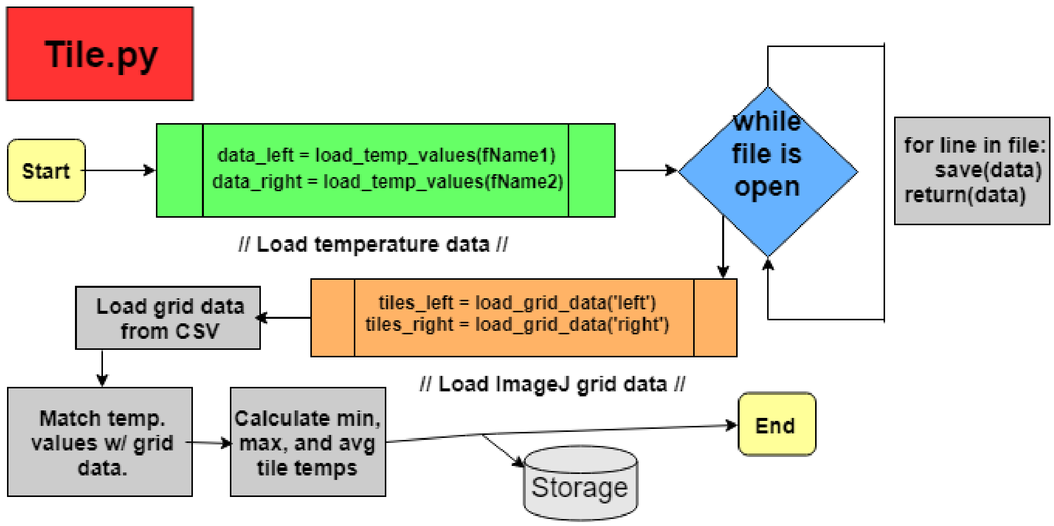


Figure 47: Software flowchart for Tile.py

The data representative of each tile is matched with the temperature data for this region. A for loop accomplishes this task. Each tray is iterated using a for loop to look at the individual tiles. Each tile is then iterated through to look at every pixel within the tile. The maximum, minimum, and mean temperatures are calculated for each tile in the stack grid geometry. With these processed temperatures data in hand, control decisions can be determined for communicating to the simulation electronics.

4.3.4. Developing control.py

A control script is written to determine which regulatory commands to send after determining tray temperatures. As output from the tile.py script, the mean temperatures for the tiles are sorted through and compared against the temperature limits as defined by the customer. When a majority of tiles in a tray are found to exceed the upper-bound temperature limit of 50^oC, the simulated tray electronics are switched off to ensure survivability. Likewise, if a majority of tiles in a tray are found to be colder than the lower-bound temperature limit of -20^oC, the heaters are switched on. If a tray is found to be within the operational temperature range, most notably less than 50^{o}C and above -20^{o}C, the simulation electronics will remain unchanged. This functionality is accomplished in the control.py script. A flowchart for this script is shown in Figure 48.

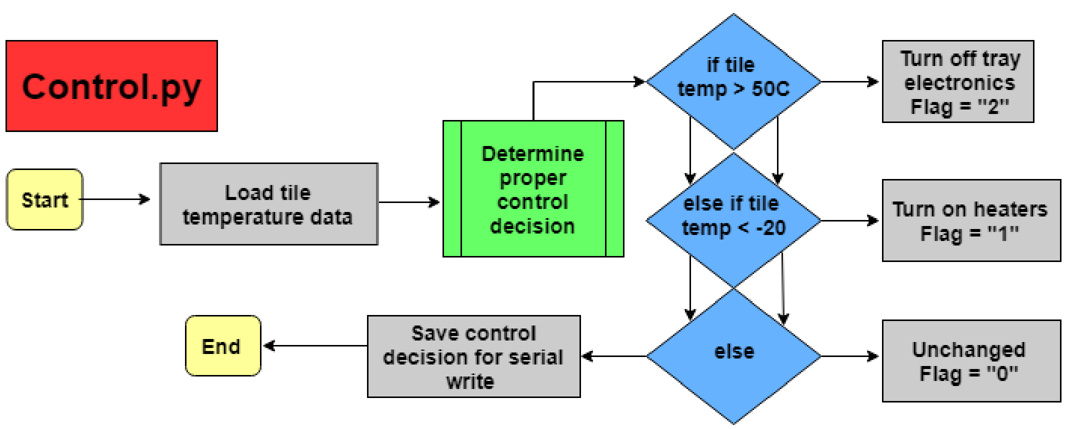


Figure 48: Software flowchart for Control.py

The tile.py temperature data is loaded, the proper control decision is then determined, control decision is saved, and the script is finished. The control decision flags are as follows: 0.) Unchanged - tray is within operational temperature range, 1.) Turn on heaters - tray is too cold, 2.) Turn off tray - tray is too hot and incorporating coolers was beyond the scope of the OTheRS project. After this script, the serial.py script is called to export these control decisions from the Raspberry Pi of the OTheRS system to the Host computer.

4.3.5. Developing serial.py

The main purpose of the serial.py script is to communicate over asynchronous RS-232 protocol the regulatory commands for the simulation electronics with a Host computer. A comparison is made on the host computer between the temperature data from image processing and the thermistor reference data system. The RS-232 protocol was specified by the customer for sending regulatory commands. A software flowchart describing this serial.py script is shown in Figure 49.

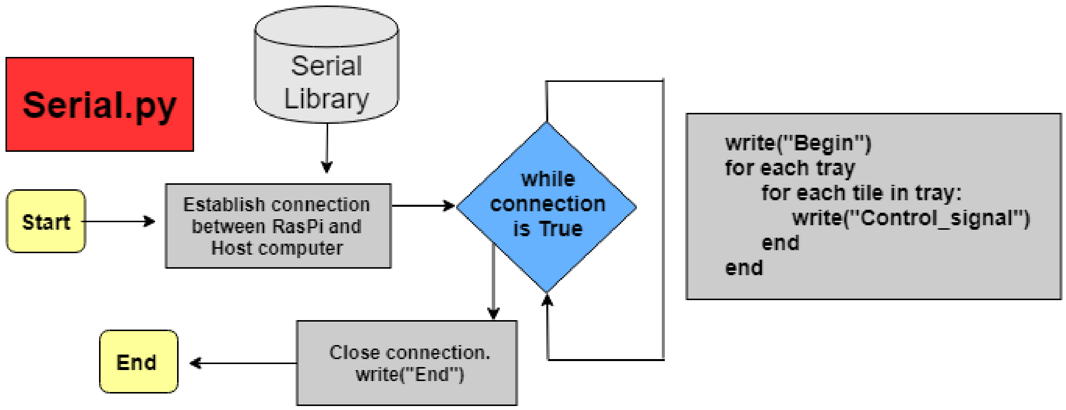


Figure 49: Software flowchart for Serial.py

This script uses the Serial library available in Python for serial data communication. The script starts by establishing a connection between the Raspberry Pi and Host computer. While the connection is still True, control decisions are sent from the Raspberry Pi to the UART-USB serial data connecter hardware and to the Host computer for each tile in each tray. These are the control decisions first determined in control.py. Once the 30 control decisions are sent asynchronously to the Host computer, the connection is terminated and the script exits.

4.3.6. Developing main.sh

The individual scripts developed for image processing are called via a bash shell script called main.sh. This executable completes image processing from start to finish by running each individual software module in the correct order and after error-handling. The local directory of test files is first scanned to see if the current test number has a directory of the same name. If “Test1" for instance already exists, a new directory will be created for “Test2" and so on. On each test, the raw_capture software is run to capture two test images and two temperature text files that will be saved in the current test folder. Since the image processing is automated to run on a continuous loop, multiple test cases will be run for each time the OTheRS system is operational. With the image capture completed, the image stitching script is run and loads the images stored in the most current Test/ directory folder. The stitched image is stored in a local Outputs/DayofTest/TestX folder. Temperature data processing is handled by calling the tile.py script, which pulls in the stored temperature data from the camera. With the tiles located and mean temperature values calculated, the data is sent to the control.py script. After control decisions are made, the control flags are sent over asynchronous communication with the Host computer for monitoring.

5. Verification and Validation

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5.1. Design Requirement Validation

There are five phases used to verify and validate every OTheRS sub-system. Although almost each phase begins independently, they must be completed in order. The sections below detail the tests and procedures used in each phase.

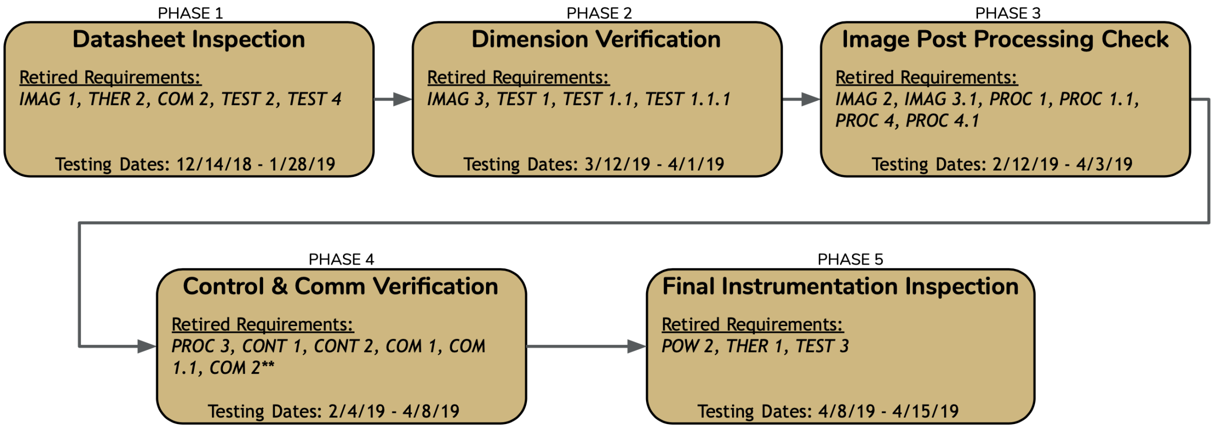


Figure 50: Schedule for Test Plan Phases along with testing flow

5.1.1. Phase 1 - Datasheet Inspection

In this phase of testing, requirements are retired by inspecting datasheets to obtain technical information about the expected nominal operating cases of various subsystems. These operational cases can be compared to requirements to verify that they are met.

5.1.1.1 Thermal Imaging Device

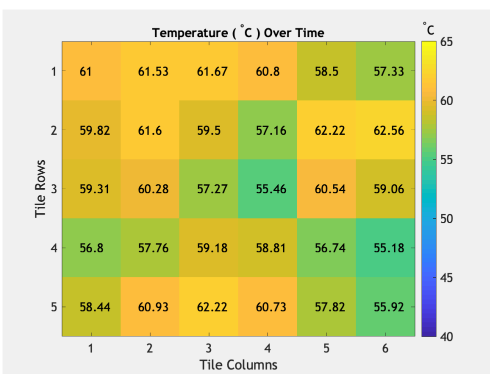
As per requirement, the thermal imaging devices shall be sensitive to IR Radiation, measuring between 8.70 to 11.93 microns or -30°to +60°C. By inspection of its datasheet, the FLIR Lepton 3.5 is capable of measuring wavelengths between 8 and 14 microns, thus retiring this requirement.
Requirement: DR-IMAG 1
Status: Validated
Method: Inspection
Explanation/Results: Inspection of the datasheet for the selected sensor showed that the requirement was satisfied and the sensor can measure the required range.

5.1.1.2 Operational Range

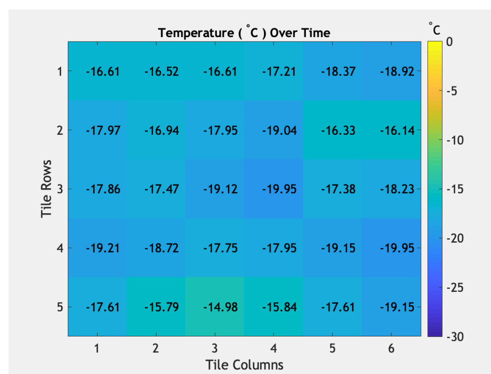
The requirement states that the minimum operating temperature of the OTheRS shall be determined by highest minimum operating temperature of other subsystems or components. It will be satisfied by comparing the operational temperature ranges in the data sheets of the other sub-systems against the tested operational temperature of OTheRS.
Requirement: DR-THER 2
Status: Validated
Method: Inspection
Explanation/Results: Inspection of the datasheet for the selected sensor shows the lowest operating temperature. This sensor is the only major component in the thermal chamber thus defining the minimum operational temperature of the system within the chamber. Inspection of the software shows this value as a input and set variable.

5.1.1.3 Heaters and Simulation Electronics

The requirements state that OTheRS shall communicate with a heater communication protocol, if any is needed and that the electronics stack shall replicate the thermal operating range of electronics contained in the stack as defined in **FR 1**. These requirements will be satisfied by checking the power resistor datasheet to ensure that typical electronic components are within the range of the power resistor. As for the heater communication, the OTheRS will implement a LED system, thus the requirement is satisfied as this kind of system does not have communication protocol.
Requirement: DR-COM 2
Status: Validated
Method: Inspection
Explanation/Results: The chosen hardware for the simulation electronics are passive devices and do not require a communication protocol. The method of control for these simulation electronics is simply supplied voltage. Also, the requirements state that the OTheRS shall return a thermal data map for multiple components between -30°C and 60°C. This requirement is filled by replicating the thermal operating range of electronics contained in the stack as defined in **FR 1**. The requirement is satisfied by ensuring that the resistance of the power resistors used and the voltage supplied by the test bed result in a power dissipation corresponding to typical processor temperature outputs. The voltage supplied is verified through a multimeter connected in parallel to the power resistors, and the temperature is recorded through a dedicated thermistor to ensure our power dissipation estimations are correct. Also, the combination of the simulation electronics and the thermal chamber will allow the simulation electronics to simulate the full testing range.
Requirement: DR-TEST 2
Status: Validated
Method: Testing
Explanation/Results: Correct Voltage and amperage supplied to the heater is confirmed through inspecting a multimeter. The temperature given off by the simulation electronic components is confirmed using thermistors during testing. For the lower bound testing the test bed was cooled using the thermal chamber provided by GA. The following figures provide data given by the thermistors showing both the upper bound and lower bound temperatures reached during thermal chamber testing.



Upper Bound Results



Lower Bound Results

Figure 51: Results given by the Reference Data System

5.1.1.4 Construction Material Properties

DR-TEST 4 states that the test bed structure shall replicate material thermal properties of GA's satellite bay. This requirement is satisfied through using appropriate substitute materials defined from GA.
Requirement: DR-TEST 4
Status: Validated
Method: Inspection
Explanation/Results: Correct material thermal properties were ensured by comparing our Construction materials used against the substitute material list supplied by GA.

Category	Material	Application	Substitute Material	Notes	Ref. DR
Material	AL 6082-T6	Can be substituted in all situations	AL 6061-T6		
Material	AL 2014 Clad	Can be substituted in all situations	AL 2024 Clad		
Material	AL 2014-T3		AL 7075-T3/T7351		
Plating			ANODIZE PER MIL-A-8625, Type III, CLASS 2, .001 THICK, BLACK	Hard Anodize, Black	
Plating			ANODIZE PER MIL-A-8625, Type III, CLASS 1, .001 THICK, BLACK	Hard Anodize, Clear	
Plating	BS EN 12373-1:2001 Grade AA15	Can be substituted in all situations	MIL-A8625, Type II, Class 2	Black anodize (not Hard Anodize)	
Plating	Alcocrom 1200	Can be substituted in all situations	Chemical conversion Coating, Color Gold, Per MIL-DTL-5541, Class 1A	Maximum corrosion protection	
Plating	Alcocrom 1200	Can be substituted in all situations	Chemical conversion Coating, Color Gold, Per MIL-DTL-5541, Class 3	Electrically conductive	
Adhesive	Hysol EA 9321	Spot bonding heater edges and mounting thermostats	Scotchweld 2216 or DP190		DR 126
Adhesive	DP190	Can be substituted in all situations	Scotchweld 2216		
Adhesive	CV-1142	Can be substituted in all situations	DC 6-1104		DR 125

Table 17: Material substitution list supplied by GA

5.1.2. Phase 2 - Dimension Verification

The goal of this testing phase is to retire requirements via the verification of dimensions. These requirements are related to manufacturing process. A limitation of the manufacturing is the accuracy of the measuring devices, machines, and machine setup used. As such, it is required that the test bed dimensions are within 5% of the required values or a negligible difference.

5.1.2.1 Thermal Imaging Device

As the requirement states, The thermal imaging devices shall be 100 to 146.73 mm from the stack.
Requirement: DR-IMAG 3
Status: Validated
Method: Inspection
Explanation/Results: The distance from the thermal imaging devices to the stack in the final test bed was measured to be 136.52 mm.

5.1.2.2 Test Bed Structure

The test bed structure has several manufacturing requirements, which are presented here:

1. The outer dimensions of the stack in the test bed shall 246.3mm x 290mm x 318mm.
2. The interior dimensions of the test bed shall be 261.3mm x 515mm x 547mm.
3. The overall stack surface material shall be 5mm thick.

Requirement: DR-TEST 1
Status: Validated
Method: Inspection
Explanation/Results: The outer dimensions of the electronics stack were measured to be 238.12mm x 287.33mm x 305.59mm.
Requirement: DR-TEST 1.1
Status: Validated
Method: Inspection
Explanation/Results: The interior dimensions of the test bed were measured to be 263.52mm x 517.52mm x 550.86mm.
Requirement: DR-TEST 1.1.1
Status: Failure
Method: Inspection
Explanation/Results: The thickness of the stack surface material was measured to be 6.27mm, outside the 5% error tolerance of 5mm.

5.1.3. Phase 3 - Image Post-Processing Check

The purpose of this test phase is to verify that the algorithms are written to function with the designed, physical test setup. Initially, testing and verification will be completed using test images which are beneficial for core functionality verification, however, this plan will require the actual images to be used.

5.1.3.1 Capture Frequency

DR-IMAG 2 requires that images of the stack shall be taken by the FLIR Leptons at no more than 90 second intervals. This corresponds to a 1°C temperature change on the surface of the stack wall found through preliminary testing and applicable predictive thermal models. **DR-PROC 4.1** also requires that all image processing be completed within this 90 second interval between image captures.
Requirement: DR-IMAG 2 and **DR-PROC 4.1**
Status: Validated
Method: Testing/Analysis
Explanation/Results: A timing analysis was performed for the image processing software. The results of this timing analysis demonstrated an estimated upper bound of 37 seconds to complete image processing. In this time interval: image capture by both cameras, image stitching, temperature data processing, and serial data communication were successfully completed in under 90 seconds.

5.1.3.2 Overlapping Field of View

DR-IMAG 3.1 requires that the FLIR Lepton cameras image an entire side of the stack. In particular, the FOVs of the cameras should overlap such that common geometric indicators can be identified in each image. The infrared markers will serve to determine the outlines of the edges of the stack and to distinguish each electronics tray via the vertical and horizontal extents of the overlap. Successful camera overlap will be verified through visual inspection of the images. Also, all edges of the face being viewed should be contained in the overlapped FOV.
Requirement: DR-IMAG 3.1
Status: Validated
Method: Testing/Inspection
Explanation/Results: Both FLIR Lepton cameras were able to image an entire side of the stack. An image of the stack taken by the cameras is given below. This is the output of the image stitching algorithms where the corners of the face are not fully imaged due to high skew and fewer pixels per tile. The raw output images from both Leptons do have overlap, thus satisfying the requirement that the full face is contained within the FOV of both Leptons.

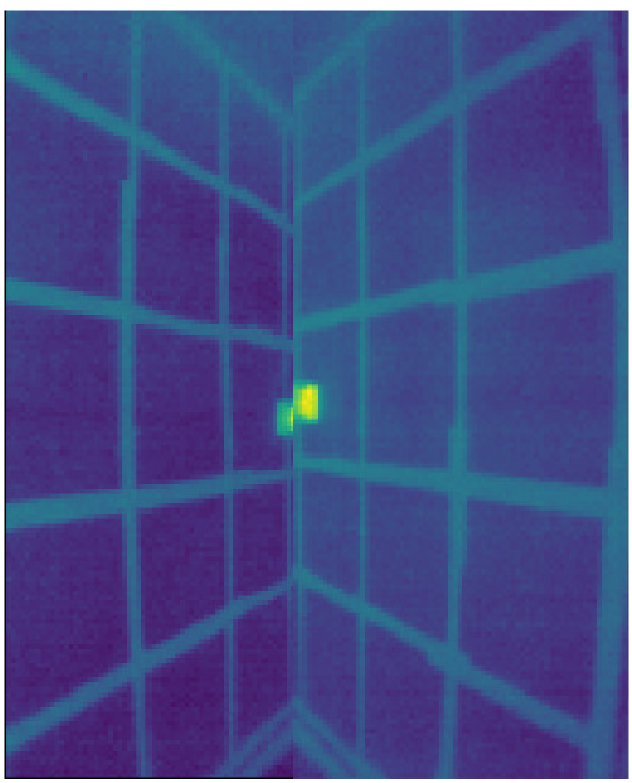


Figure 52: Stitched image taken by FLIR Leptons showing entire side of the electronics stack

5.1.3.3 Object Identification

Object Identification relates to **DR-PROC 1** and **DR-PROC 1.1**, which requires the thermal map created by the image processing system to differentiate and distinguish between up to 6 trays in the stack. This relates to the satellite configuration created by GA which contains 6 module trays inside of the avionics stack.
Requirement: DR-PROC 1 and **DR-PROC 1.1**
Status: Validated
Method: Inspection, Demonstration
Explanation/Results: As can be seen in Figure 52, image data is captured for the 5 functional trays of the stack. This qualifies for visual inspection, completed on each image stitching pass. Data is collected and processed for the 30 tiles. The image processing algorithms are successfully able to demonstratively differentiate between the 5 tray objects.

5.1.3.4 Data Extraction

To satisfy this requirement, images from the Lepton are analyzed using image processing software. The image processing software takes the overall thermal profile of the stack in a temperature matrix and uses the object identification to compute the tile temperature. The tile temperature is computed as an average of the pixel temperature in the identified tile. The temperature data is converted from intensity in the background using built in functions on the Lepton.
Requirement: DR-PROC 4
Status: Validated
Method: Inspection, Demonstration
Explanation/Results: Output from the FLIR Lepton thermal cameras is comprised of an image and text file of temperature data for each camera. This temperature data is input to the image processing algorithms and converted from Kelvin to Celsius. Utilizing the radiometric feature available through the FLIR Lepton SDK results in temperature data being extracted from the thermal images. Early testing validated this requirement by inspecting and locating these text files in the correct location.

5.1.4. Phase 4 - Control & Communication Verification

5.1.4.1 Internal Thermal Regulation

The Lepton's operational range is -10°C to 80°C and its survivability range is between -40°C to 80°C. In order to satisfy **FR 1** the Leptons must be able to remain above -10°C while imaging stack components at the lower bound of **FR 1** with a 10°factor of safety as given by **DR-PROC 3**. This requirement is the basis for thermal control of the sensor by specifying the system shall control the thermal regulation of the sensor and other components within the chamber. This requirement was verified during thermal testing at GA's thermal chamber due to the aforementioned ranges.
Requirement: DR-PROC 3
Status: Validated
Method: Demonstration
Explanation/Results: Testing demonstrated that electrical heaters could control the temperature of a thermistor located in close proximity to the cameras using embedded software on the Raspberry Pi.

5.1.4.2 Stack Control

Full stack control needs to satisfy the requirements of **DR-CONT 1** and **DR-CONT 2** were verified through testing at the customer's thermal chamber. The data monitoring software was used to output a representative indicator showing that heaters were to be turned on when the lower bound of **FR 2** was exceeded as well as outputting a representative indicator to show that components were to be turned off when the upper bound of **FR 2** was exceeded.
Requirement: DR-CONT 1
Status: Validated
Method: Testing
Explanation/Results: When temperatures sensed by the camera system exceeded the lower bound specified by **FR 2** the data monitoring system provided a representative indicator of turning heaters on. The figure below shows the representative heater indicators are lit up for all trays except tray 6. The data that caused the representative indicators to turn on can be found in the IP section with the array of numbers for the measured tile temperatures.

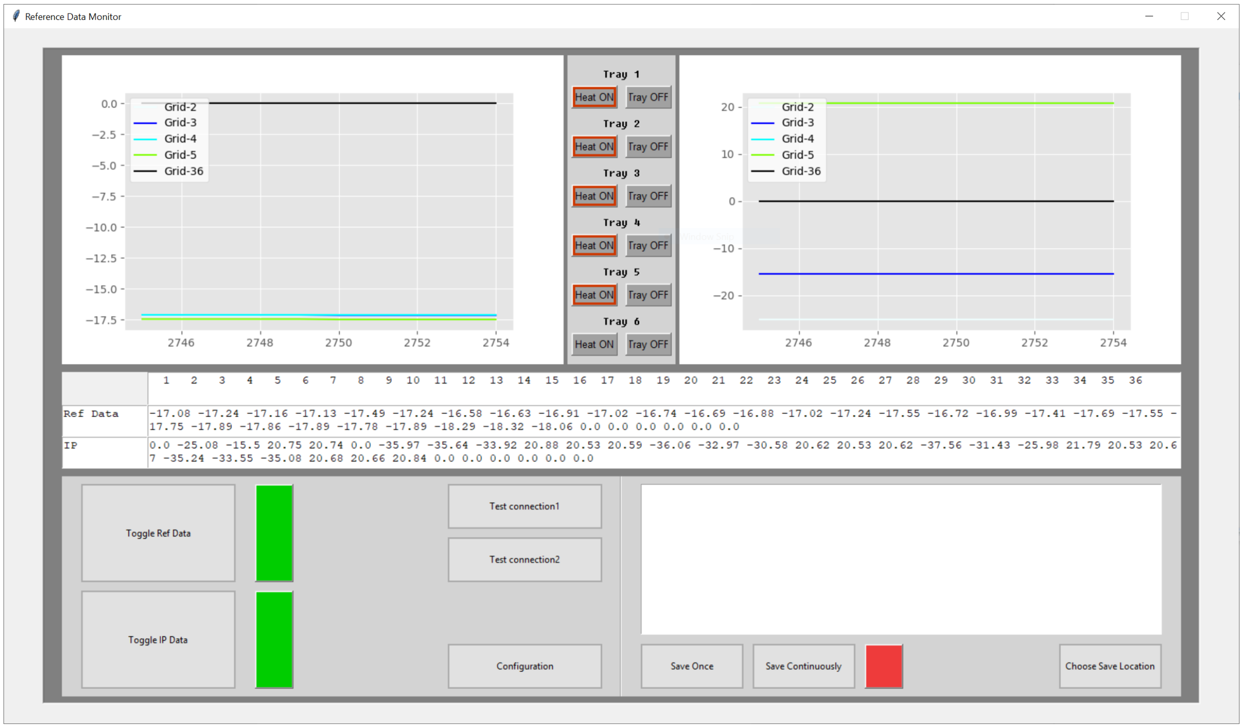


Figure 53: Data monitoring results showing the heaters are on with the red highlighted boxes

Requirement: DR-CONT 2
Status: Validated
Method: Testing
Explanation/Results: When temperatures sensed by the camera system exceeded the upper bound specified by **FR 2** the data monitoring system provided a representative indicator of turning satellite components off. The figure below shows the representative tray indicators are lit up for all trays except tray 6. The data that caused the representative indicators to turn on can be found in the IP section with the array of numbers for the measured tile temperatures.

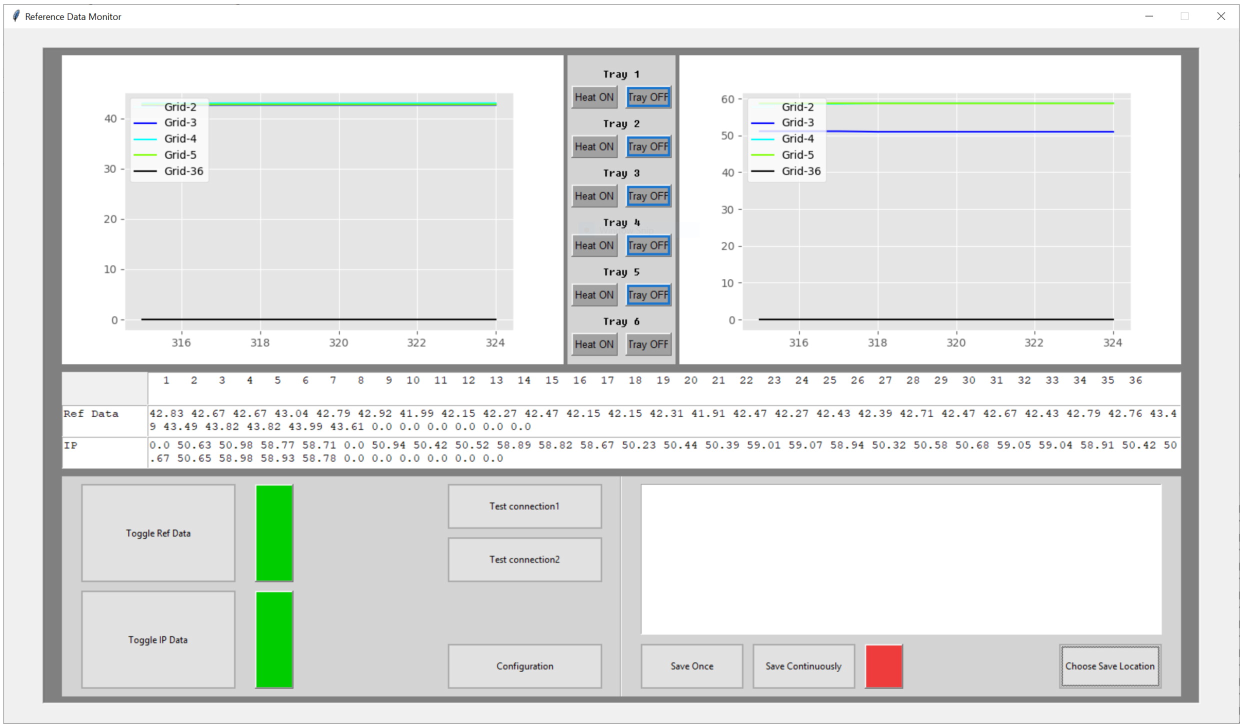


Figure 54: Data monitoring results showing the trays are off with the blue highlighted boxes

5.1.4.3 Output Communication

DR-COM 1 and **DR-COM 1.1** require the OTheRS system to use the RS-232 serial protocol to communicate with the simulated spacecraft bus, in this case a monitoring device. This protocol will be communicating thermal data outputs along with any information needed for test analysis. These requirements will be verified via inspection: the data stream from the Raspberry Pi's UART port will be inspected with an oscilloscope or logic analyzer to make sure the correct protocol is used, and the data output will be visually inspected on the monitoring device to ensure that the transmitted bits and the received bits are the same.
Requirement: DR-COM 1 and **DR-COM 1.1**
Status: Validated
Method: Demonstration/Inspection
Explanation/Results: The data stream from the Raspberry Pi's UART port was inspected with an RS-232 to USB reciever and was confirmed to be using the RS-232 communication protocol. The data output was also inspected and confirmed that the transmissions were correct and intact.

5.1.5. Phase 5 - Final Instrumentation Inspection

5.1.5.1 Power Transmission

DR-POW 2 requires that power shall be transferred and distributed using D-type connectors. This will be verified by visually inspecting the connector type.
Requirement: DR-POW 2
Status: Validated
Method: Inspection
Explanation/Results: Power was transferred and distributed using D-Type connectors from the heater driver to the stack.

5.1.5.2 Internal Temperature Monitoring

DR-THER 1 requires that the internal temperature of OTheRS shall be monitored by at least one thermistor. This was verified by inspection.

Requirement: DR-THER 1
Status: Validated
Method: Inspection
Explanation/Results: Two thermistors, one for each Lepton, were used to monitor the temperature of OTheRS. During ambient testing and thermal testing at GA it was confirmed the thermistors were outputting accurate data.

5.1.5.3 Thermal Imaging Device(s) Mounting

DR-TEST 3 requires that OTheRS shall not be mounted to the outer walls or stack of the test bed. During the assembly of the final test bed, the cameras will not be mounted to the outer walls or stack of the test bed. For this final instrumentation inspection, it was visually verified that the camera nor anything else was mounted to the stack or walls of the test bed.
Requirement: DR-TEST 3
Status: Validated
Method: Inspection
Explanation/Results: The cameras were mounted on camera mounts connected to rods stretching from the ceiling to the floor of the test bed held in place by collars.

5.1.6. Non-Phased Requirements

5.1.6.1 Power Distribution

Since the system must take in 28V unregulated as required in **FR 3**, the voltage must be stepped down and distributed to the various subsystems that require power. This was not within the phased test plan but completed as components were completed and their power needs determined.
Requirement: DR-POW 1
Status: Validated
Method: Demonstration
Explanation/Results: The output of the designed board was observed to supply the correct voltages when measured by a handheld multimeter. The step down converter was measured to provide 5V for the OTheRS system's processor and 28V was provided directly from the input to terminal blocks for powering the heaters, proving the functionality of the distribution and stepping down.

5.1.6.2 Lepton Calibration

The requirement states both thermal and spacial calibration for the Lepton. Spacial calibration was achieved by defining the camera positioning within the test bed such that the images were correctly stitched each time. On the other hand, thermal calibration requires an object at a know temperature and emissivity value, preferably a black body. This was ruled out of scope for this project due to the high cost of black body calibrators and the limited budget available to the team. Calibrating the Lepton for the emissivity was possible via a variable in the SDK but the internal workings of the proprietary manufacturer code were not known.
Requirement: DR-PROC 2
Status: Partial Failure
Method: Testing
Explanation/Results: Spacial calibration was achieved using the software although the thermal calibration was failed. An attempt was made at thermal calibration using the emissivity of the face under test but produced erratic data so this calibration was reverted.

5.2. Functional Requirement Validation

5.2.1. FR 1

This requirement defines the operation bound, -30°C to 60°C, of the system. The thermal data that is required is represented by a grid of tiles that can be compared to a single point measurement, the thermistor on the other side of the wall. The customer's thermal chamber is required for validation of the requirement due to the endpoints of the bound. The system can be initially proven in room temperature but retirement of this requirement will need to show the system is able to operate, measure, and transfer data at the endpoints of the range. The customer did not define a dwell time so the team wrote their own plans for the testing. The testing procedure is similar for both the upper and

lower bound but will broken down by their respective bounds in the following subsections. The results of the testing and the ability to retire the requirement are found below.
Status: Partial Failure
Method: Testing
Explanation/Results: The system was functional at the upper bound and transferred data to the monitoring software without issues. When the chamber temperature was brought down to the lower bound, both Leptons were not operational. The chamber temperature was then raised to -15°C before one of the Leptons came back online for a short period of time. Thus this requirement is partially failed as the sensors were not able to provide a thermal data map at -30°C

5.2.1.1 Upper Bound Test

Setup
The procedure for this test initially starts with the chamber set at 50°C. Before the simulation electronics are powered on, all reference data must read at least 45°C with at least a single point reading 50°C. Once this occurs, the cameras begin taking data with the simulation electronics powered off to establish a baseline. After this, the simulation electronics are powered on in a inner/outer pattern. Testing duration is 30 minutes and at least thermistor must reach 60°C. Testing may end earlier than scheduled if all thermistors reach 60°C. The heater setup shown in Figure 55 was used for all chamber tests to generate a thermal profile on the face under test. This test took place with the calibration grid as the face being viewed by the Leptons.

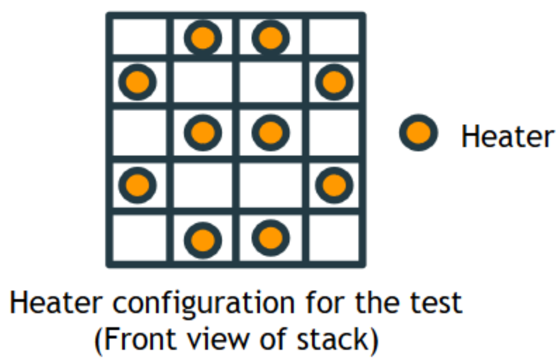
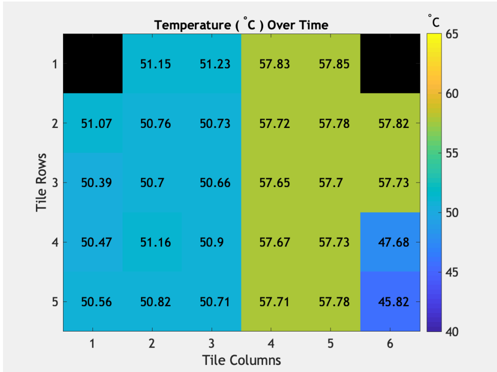
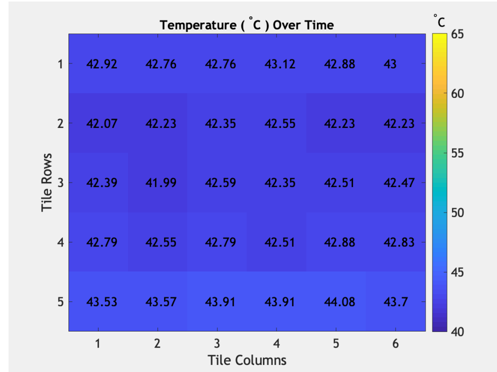


Figure 55: Simulation heater setup used for thermal chamber testing

Results
Three discrete time steps are shown in Figures 56 to 58 for the beginning, middle, and end of the testing period. Testing began slightly earlier than scheduled with an average plate temperature being approximately 42°C. This was decided due to the expected time testing would take along with how much time was left in the workday.

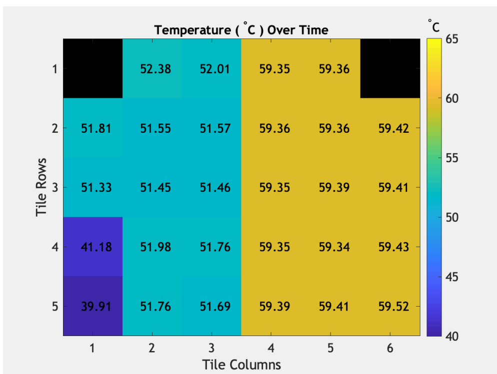


Camera Data

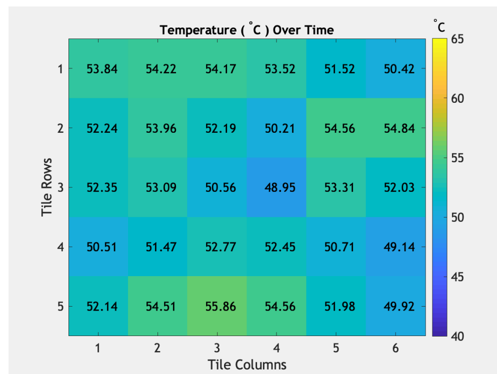


Reference Data

Figure 56: Initial Hot Chamber testing results

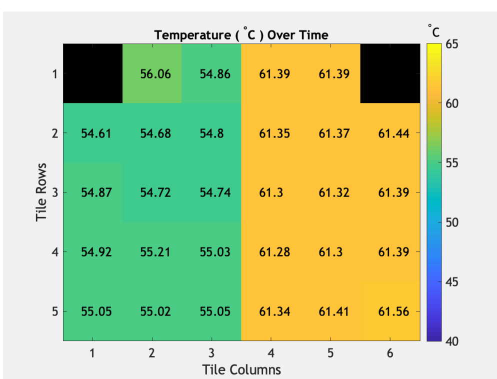


Camera Data

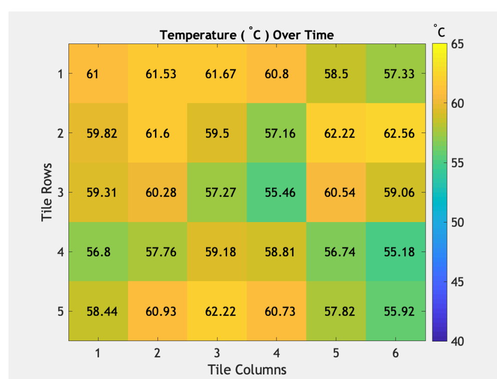


Reference Data

Figure 57: Hot Chamber testing results at 15 minutes



Camera Data



Reference Data

Figure 58: Hot Chamber testing results at 30 minutes

The results of the testing show a defined split between the data seen by each camera. This may indicate some form of sensor failure during the test or an added effect of reflection within the chamber when heated up. Also over the duration of the test, the reference data noted a larger change than the camera although the cameras were initially reading much higher temperatures than the reference data system. Another data anomaly is in the lower corner of the camera data in Figure 57. This shows the tiles reading extremely low, around 38°C. This visually shows some of the unreliabilities in the sensor and the challenges in using it as this could force the system to issue a command with bad data.

Errors

The split in data between the left and right cameras is clearly shown in the error distribution over the entire test in Figure 59. The right camera produces more error than the left both in the overall spread of the data and the center of the distribution. The tiles with more time averaged error can be found in Figure 60. The tiles produced by the right camera along with stitching line have a higher mean error along with a greater standard deviation. This is not ideal due to the high error and variability in the tiles. One of these tiles, tile 10 or (4,2), has the reflection of the other camera on the surface leading to a reflection that can be seen in Figure 52 for the right camera seeing the reflection of the left camera. It is not clear why the adjacent tile, tile 9, does not have the same issue with the reflection of the right camera for the left camera's data. This test shows the right camera having worse performance than the left camera in both the center and spread of the distribution. When looking at the camera data as a single distribution, the mean of the distribution is 9.848°C while the standard deviation is 1.649°C. The range of the error is from a lower value of 0°C in tile 9 and a upper value of 28.5°C in tile 10.

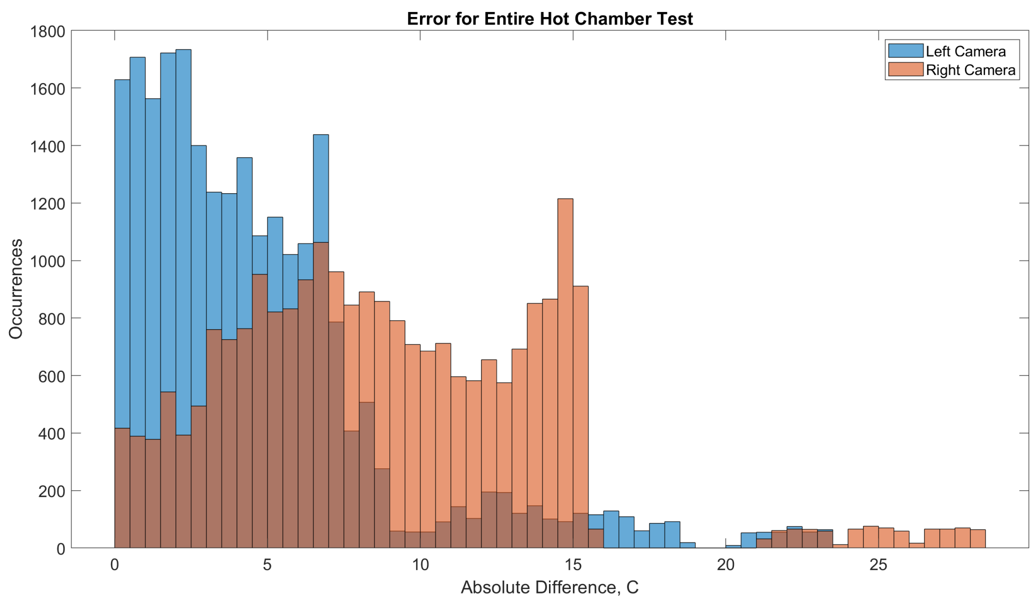
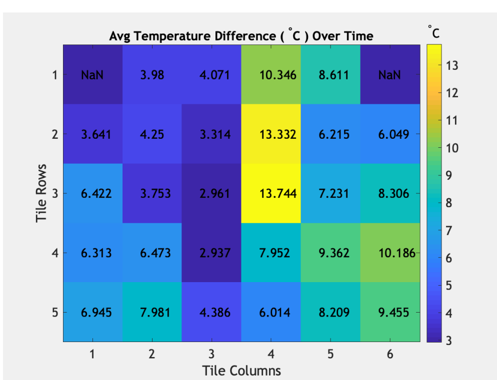
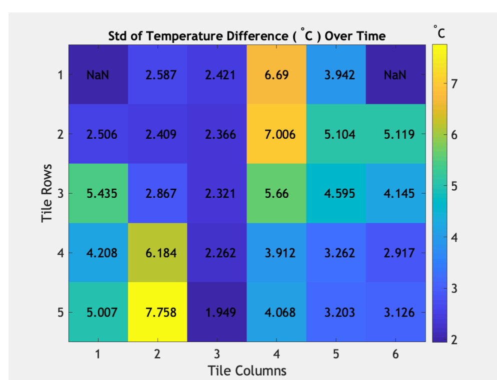


Figure 59: Histogram of the errors over the entire testing period for both Leptons



Time Average Error



Standard Deviation of Error

Figure 60: Average and standard deviation of temperature difference per tile

Conclusions

The results of the test along with the error analysis show that this setup can be used to perform thermal control although in this case, the left camera would be more accurate and reliable. This test could benefit from some improvements to the accuracy of the system that are presented in Section 5.5 as they were completed after the completion of the thermal chamber testing at the customer. The improvements could limit the errors past the 10°C limit that are lower frequency than the bulk of the errors. Also, another test with the accuracy improvements in place could show if the clear split in data was due to the warmer environment than ambient or a error during this test as it is not as apparent in other tests, with the exception of camera failure in the cold testing. Overall, the system was functional at the upper bound specified in **FR 1** and returned a thermal data map leading to a partial success for this requirement. The remained of the requirement is tested in the next section.

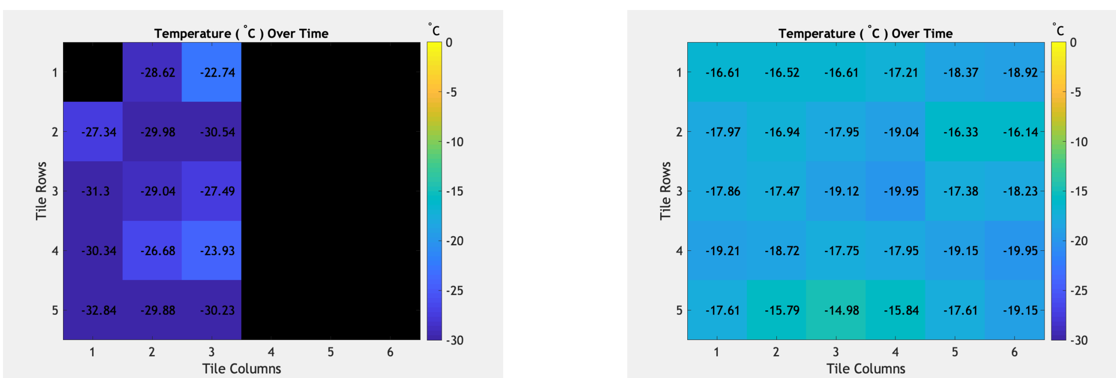
5.2.1.2 Lower Bound Test

Setup

The lower bound testing took place after the upper bound testing inside of GA's thermal chamber. The chamber was set to -30 °C for testing. While the temperature of the thermal chamber was dropping the chamber was dry gas purged in order to limit the effects of condensation. After ensuring that all thermistors read at least -25°C and at least one reached -30°C, the camera system was then powered on to begin taking thermal images of the stack for two minutes. After two minutes the heaters on the inside of the stack were powered on and full testing began.The duration of the test was 30 minutes with a requirement that one thermistor must reach -20°C. If all thermistors reach -20°C before the 30 minutes mark, the test can end early. The same heater setup as the upper bound testing, shown in Figure 55, was used for all chamber tests to generate a thermal profile on the face of the stack under test. This test took place with the calibration grid as the face being viewed by the Leptons.

Results

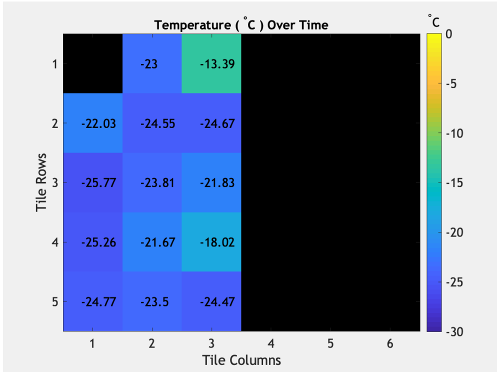
During testing at this temperature, both cameras were not responsive. The chamber temperature was then raised to -15°C and one camera was brought back online. The camera imaging the right side of the stack was not operational which is why the tiles are blacked out in the following results images. Near the end of the testing period, the left camera stopped responding hence the blacked out tiles across the entire image in Figure 63.



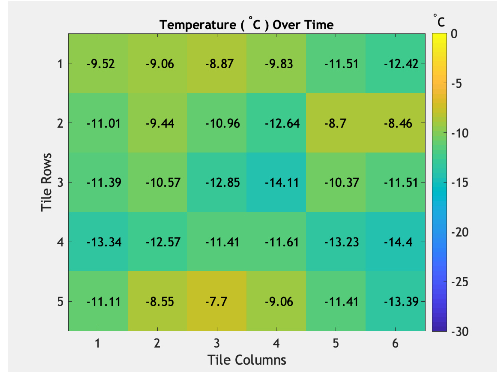
Camera Data

Reference Data

Figure 61: Initial Cold Chamber testing results

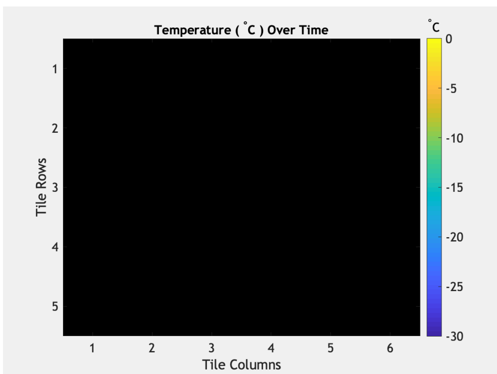


Camera Data

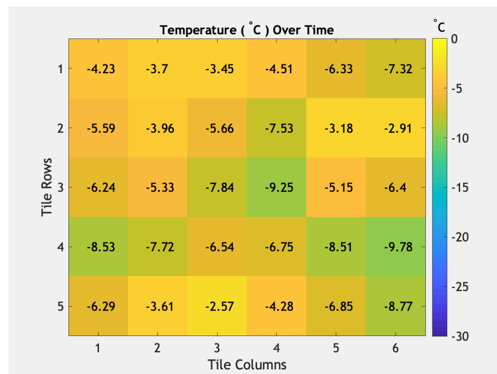


Reference Data

Figure 62: Cold Chamber testing results at 15 minutes



Camera Data



Reference Data

Figure 63: Cold Chamber testing results at 30 minutes

The results of cold testing show the sensor cannot operate at the lower bound defined by **FR 1** even with the addition of a single heater regulation system. Multiple issues could have caused the cameras to drop offline although it is likely a thermal gradient across the sensor could have led to the shutdown. The datasheet for the Lepton states that a 2°C gradient cannot be exceeded across the sensor but due to only a single side being measured by the regulation system, this mode of failure cannot be confirmed.

Errors

The histogram of errors over the duration of the test can be seen in Figure 64 showing the camera fault by the right camera during testing. The left camera has a significant spread to the data along with the center of the distribution being quite high, approximately 20°C. The right camera failures are show as NaN, Not a Number, in the tile errors in Figure 65 while the left camera has a significant time averaged value. When looking at the camera data as a single distribution, the mean of the distribution is 27.778°C while the standard deviation is 7.104°C. The range of the error is from a lower value of 0.210°C in tile 3 and a upper value of 195.060°C in tile 8. This is a much high range for all reported quantities than the testing at the upper bound. To give a better representation of the actual distribution, only errors less than 150°C are shown in the histogram in Figure 64.

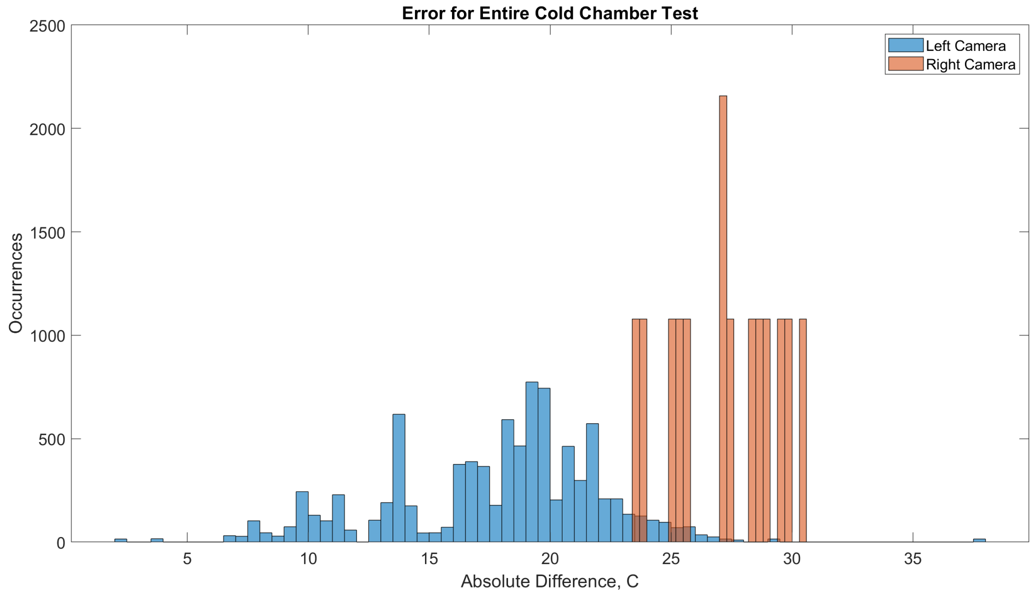
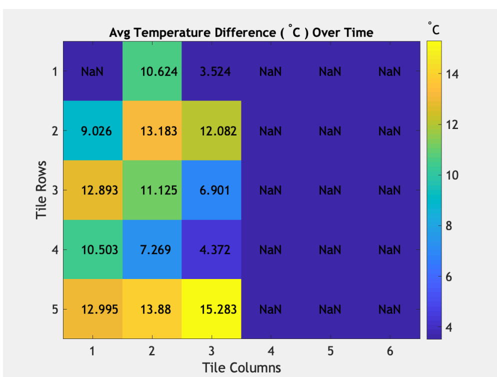
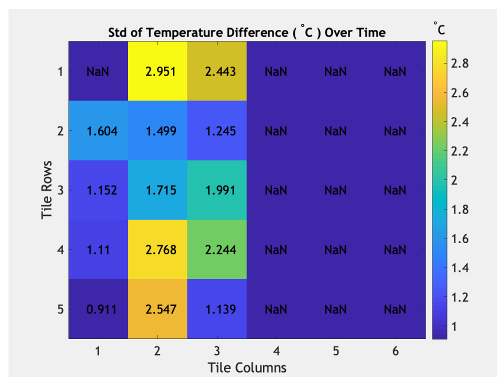


Figure 64: Histogram of the errors over the entire testing period for both Leptons



Time Average Error



Standard Deviation of Error

Figure 65: Average and standard deviation of temperature difference per tile

Conclusions

The combination of camera faults and high error show the current design is not feasible for the critical thermal control of the stack or operation in this environment, especially where thermal margins between optimal performance and shutdown are tight. This shows room for improvement in both the reliability of the Lepton, thermal regulation system of the Lepton, and the accuracy of the Lepton. The reliability of the Lepton could be achieved by shielding the wires as both failed when initially installed in the thermal chamber, while thermal regulation for the Leptons could be improved with more thermistors mounted to the sensor to more accurately monitor the temperature surrounding the sensor. In addition, more heaters could be used to generate more heat in the sensors' vicinity, though accurate thermal modeling would be the first step to determine if this is required. Finally, the accuracy of the Lepton could have been improved with the strategies discussed further in Section 5.5. This data shows why the requirement is not retired and a partial failure.

5.2.2. FR 2

Status: Validated
Method: Demonstration/Testing

Explanation/Results: The design requirements related to the OTheRS system providing regulatory commands, **DR-CONT 1** and **DR-CONT 2**, were both confirmed during thermal chamber testing at GA. Since the correct regulatory commands were provided when the upper and lower bounds of **FR 2** this requirement is retired. Also, test cases were used to confirm the full functionality of the representative indicators due to the limited testing within the thermal chamber and camera errors when testing at the lower bound.

5.2.3. FR 3

Status: Validated
Method: Demonstration
Explanation/Results: The design requirements related to the power distribution, **DR-POW 1** and **DR-POW 2**, allow the system to take in the required 28V, step it down to the required component voltages, and distribute the correct voltages accordingly. Since these design requirements have been successfully retired, this requirement is also retired.

5.2.4. FR 4

Status: Validated
Method: Inspection
Explanation/Results: The Raspberry Pi that OTheRS utilizes is 4.9cm x 8.5cm. This is the only hardware needed to run the image processing and Leptons. The simulation electronics are not considered in this requirement as they are not needed for the system to function but to test configurations and the feasibility of the Leptons for thermal management. The heater driver boards also handle the ability to supply a set amperage in the next requirement. These are 2 other boards of similar size thus all can fit next to one another.

5.2.5. FR 5

Status: Validated
Method: Testing/Demonstration
Explanation/Results: The current output was read on a power supply during testing of the heater driver board. This shows the required Amperage can be supplied by the designed board, satisfying the initial portion of the requirement. The control of a representative indicator was placed within the software and can be observed when a tile from the image processing is outside the limits defined in **FR 2**. This leads the full requirement being satisfied and retired.

5.2.6. FR 6

Status: Validated
Method: Demonstration
Explanation/Results: The thermal imaging devices were able to image a single side of the stack as shown in Figure 52. This demonstrates that a single side of the stack is contained within the combined FOV of the Leptons so this requirement is retired.

5.2.7. FR 7

Status: Validated
Method: Demonstration/Testing
Explanation/Results: OTheRS was able to command heaters to activate when the temperature of the cameras were below 0°C. The figure below shows the heater commands being issued to keep the Leptons within the chamber above their operational bounds. This test was performed with the Leptons both powered off to prevent damage to the sensors. The displayed temperatures show the thermistor monitoring the sensors reading a temperature above the operational bound thus the requirement is retired.

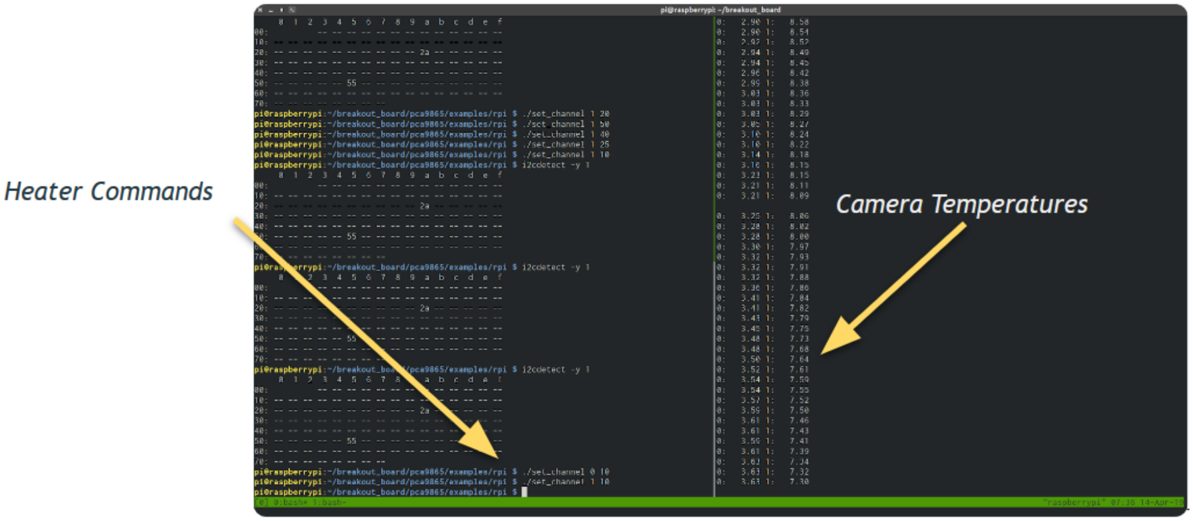


Figure 66: Results of the thermistor with the heater powered on with the thermal chamber set to -30°C

5.2.8. FR 8

Status: Validated
Method: Demonstration/Inspection
Explanation/Results: The child requirements relating to **FR 8** include **DR-TEST 1**, **DR-TEST 1.1**, **DR-TEST 1.1.1**, **DR-TEST 2**, **DR-TEST 4**, and **DR-IMAG 3.1**. All requirements were met within a 5% margin of error, which can be considered negligible, with the exception of **DR-TEST 1.1.1**. Since **DR-TEST 1.1.1** was only failed by a 1.27mm error and all other requirements were met this requirement is retired as the designed test bed does mimic the customer satellite bay, within the margin of error, to a high degree.

5.2.9. FR 9

Status: Validated
Method: Inspection
Explanation/Results: This was required by the university so all components were checked prior to being purchased. Since no components were purchased that were restricted with ITAR, this requirement is met.

5.3. Project Success Criteria Validation

Criteria	Camera	Image Processing	Elec/Comm/Ctrl	Test Bed
Level 1	Camera system will sense temperatures between -30˚C and 60˚C and will fit within the interior of the given satellite	Software can differentiate between module trays in the stack being monitored while recording their temperature. Software can also facilitate spacial and thermal calibration of the OTheRS system	The control system will command representative indicators based on thermal data from the image processing system and will handle 2.5A.The entire system will also be able to operate on 28V of unregulated power	The test bed will have two different heated objects, whose temperature is read by both the thermal camera and thermistors in an ambient air, room temperature environment. This is a minimum to help ensure the camera can differentiate and monitor multiple components
Level 2	Camera system will survive below a temperature of-30˚C			A range of coatings will be tested to determine effect on temperature readings
Level 3		Software can determine temperature of components inside of the Avionics Bay		System operates successfully when tested in thermal chamber between -30˚C and 60˚C

Level of Success fully met

Level of Success partially met

Level of Success not met

Figure 67: Final annotated Levels of Success for the project

5.3.1. *Camera*

5.3.1.1 Level 1

The camera system was able to sense the temperature range given in **FR 1** and validated in **DR-IMAG 1** and fit inside the interior of the given satellite. However, the camera system was only able to briefly operate at the lower bound and the errors between the temperatures sensed by the camera and the thermistors were over 10°C. These errors at the lower bound of **FR 1** made this level of success only partially met.

5.3.1.2 Level 2

The camera system was able to survive briefly during thermal chamber testing at -30°C. During this test, the Lepton was initially powered off with the regulation system functioning properly as shown in **FR 7** and Figure 66. Due to the sensor failure with the sensor powered on shown in **FR 1**, the chamber was brought up to -15°C and testing resumed. Therefore, this level of success is only partially met due to not measuring the range defined in Level 2 success.

5.3.2. *Image Processing*

5.3.2.1 Level 1

Image processing was able to differentiate between module trays in the stack while also recording their temperature. Although **DR-PROC 2** was failed, the software was able to facilitate both thermal and spacial calibration. Thermal calibration was through calibrating the Lepton for the emissivity of the surface while spacial calibration was proven through reliably stitching the images.

5.3.2.2 Level 3

This level of success was determined to be out of scope for our project which is why it was not met.

5.3.3. *Electrical, Communication, and Control*

5.3.3.1 Level 1

This level of success is completely met through the successful retirement of **FR 2**, **FR 3**, and **FR 5**. **FR 2** pertains to the regulatory commands, **FR 3** shows the system is operation using the provided 28V unregulated power, and **FR 5** showed the correct Amperage being outputted by the system along with the ability to switch representative indicators.

5.3.4. Test Bed

5.3.4.1 Level 1

During ambient air testing the test bed stack had multiple objects, or heaters, which were heated with the simulation electronics system. During these tests, the heater configuration was also modified showing that difference heater patterns could be applied. The temperature of the stack was also read by the reference data system and thermal camera system, thus this level of success was met.

5.3.4.2 Level 2

During ambient testing a range of coating were tested which included black construction paper, blue construction paper, and high emissivity stickers. The high emissivity stickers were both applied as a full face coating and a calibration grid that was approximated as bare Aluminum. Therefore this level of success is met.

5.3.4.3 Level 3

All OTheRS system components operated successfully between -30°C and 60°C with the exception of the camera system. The camera system did not function at the lower bound of -30°C so the chamber was heated to -15°C. One Lepton operated briefly at -15°C before failure, therefore this level of success is only partially met.

5.4. Model Verification

5.4.1. Setup

The OTheRS thermal model was developed with the goal of validating the reference data system output and providing a further metric against which the camera performance can be measured. In the early stages of the project, it was identified that convection would be the primary form of heat transport in the system. During the design of the test bed and reference data system, it was overlooked by the team that free air temperature measurements should be taken in both the satellite bay, as well as inside the avionics stack, with the goal being to quantify the amount of heat transferred from the heaters to the air within the system. This quantification would allow for more accurate convection values to be used in the model. Thermistor probe points have been selected on the face of the stack as follows in Figure 68, with a symmetry condition assumed along the centerline y-axis.

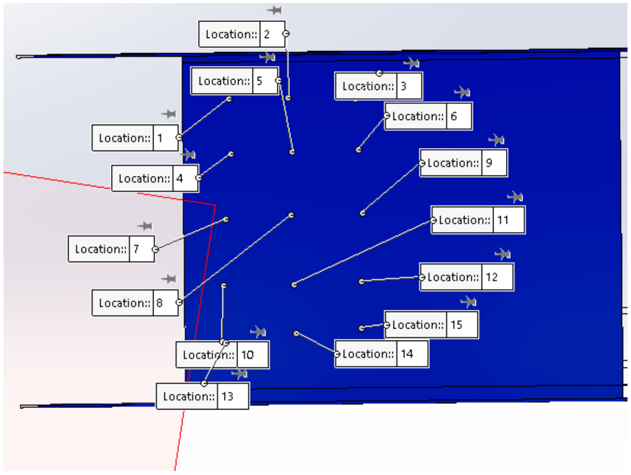


Figure 68: Model Probe Point Configuration

5.4.2. Results

The results from these tests are compiled below in Figure 69, where the model simulates a 30 minute test with heaters located on the bottom tray in the front corners, powered at 30W each.

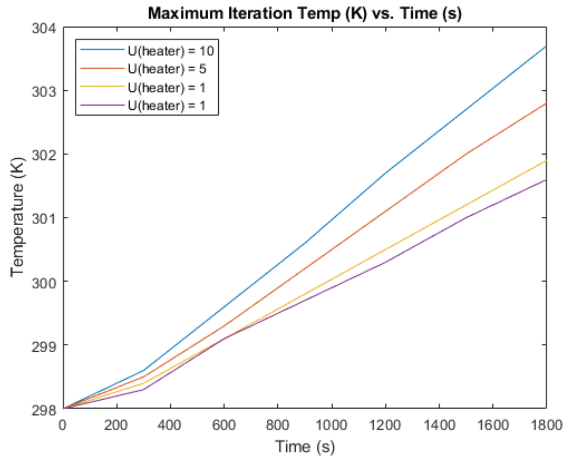
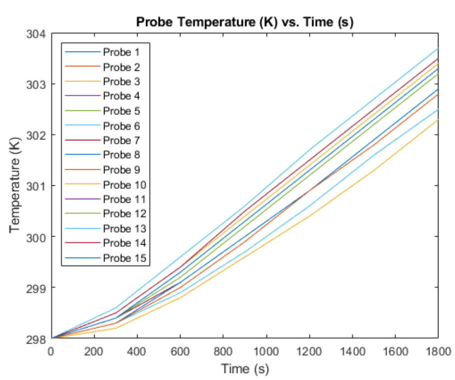
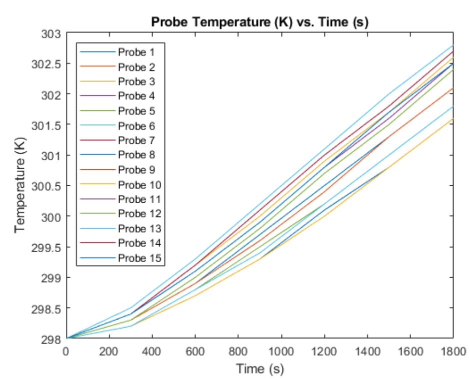


Figure 69: Iteration Max Temperature

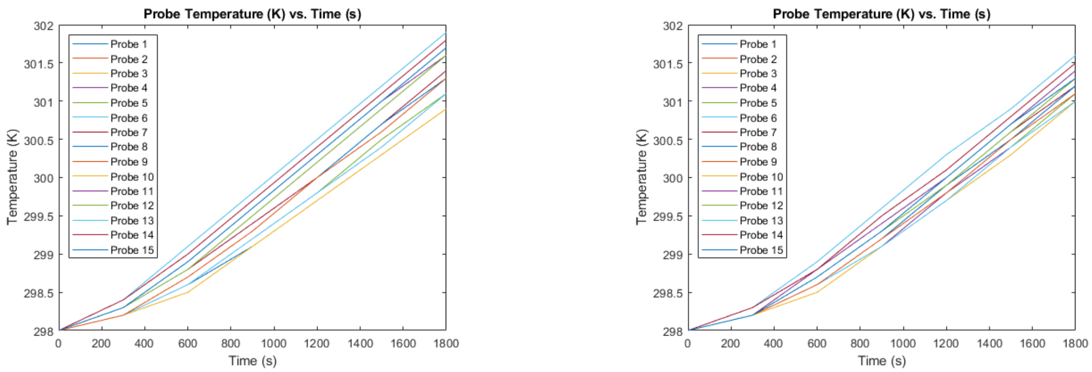
For this model, because ideal heat transfer assumptions are made, it is possible to assume that the temperature on one side of the system will be equal to the heat at a similar point on the other side of the system, divided in half along the face being imaged. Convection across the aluminum surface is set to a constant U = 1 W/m2 K value for testing purposes, while the value of convection on the heater ranges from U = 1 to 10 W/m2 K, as the heater will be the hottest component in the system for the duration of the test. The goal is to see how much heat is transferred to the aluminum wall being imaged in order to provide an analytical baseline to compare the camera data against. In Figure 69, it is noted that as the convection coefficient on the heater is increased, the temperature at the surface of the stack wall decreases. This is counter intuitive to what is expected for an ambient test. The expected result with increased convection is that the fluid air within the system would increase in temperature and transfer this temperature to the stack and bay walls at a rate significantly higher than is occurring in the model. What is being observed here is that as the convection value over the heater is increased, the maximum temperature of the heater in the model decreases from a value of approximately 915 K with convection set to 1 W/m2 K versus approximately 805 K with convection set to 10 W/m2 K. When the temperature of the heater goes down, the heat transfer to the walls via the heater-PCB-wall path decreases both for radiation and conduction. The same occurs for the radiative heat transfer from the heater directly to the wall. Below in Figure 70 is a comparison of the thermistor probe points in each of the 4 trials. In every trial, Probe 13 reaches the highest temperature. This makes sense, as it is the closest point to the heater.



U = 10 W/m2 K



U = 5 W/m2 K



U = 2 W/m2 K

U = 1 W/m2 K

Figure 70: Trial Data

The total temperature difference at each of the model probe points during the duration of the tests were calculated to determine the maximum difference in final temperature between the different test cases. This value was computed to be 2.1 K at probe point 13, between the tests where heater convection was set to 10 versus 1. For reference, start to finish delta and maximum temperature values for each trial have been compiled below in Table 18.

Convection Value	*Max. Temp* K	Δ *T*
U = 1	301.6	3.6
U = 2	301.9	3.9
U = 5	302.8	4.8
U = 10	303.7	5.7

Table 18: Heater Convection Sensitivity

5.4.3. Error

To quantify the error between the thermal model and the thermistor system, data from a test running the configuration used in the model setup was collected. However, during the testing, an error occurred in which one of the two powered heaters malfunctioned, resulting in the team seeing temperatures rise on only one side of the avionics stack. At the end of a 30 minute testing interval, the thermistor that equates to probe point 13 read a temperature value of 61.3°C, or 334.3 K. Using even the closest results from the model, the error in the model is over 30 K or a 1000% error compared to the total temperature increase seen in the model.

5.4.4. Conclusion

Analysis of the model results reveals a glaring issue as the convection value across the heaters is increased by a factor of 10, the probed temperature on the wall surface should increase significantly. Hand calculations put this value around approximately 30 to 40 K. Instead, it is observed that an increase of only 6 K occurs. This is an immediate indication that convection is not occurring the way it should be in our system. The air within the stack should heat up significantly, and transfer this heat directly to the walls and PCB components. However, it is clear that heat transport via conduction and radiation is still occurring at largely linear rates, as is to be expected considering that both are strictly dependent on the temperature of the radiating body. The most likely source of this error is discussed later in the thermal model "Lessons Learned" section.

5.5. Testing Results

5.5.1. Ambient Baseline

5.5.1.1 Setup

The purpose of Ambient testing was to establish a baseline for data comparison using an unmodified test setup. During testing baseline data was taken for two minutes by the camera and reference data system with the heaters off. After these two minutes were up the heaters were powered on with the configuration shown in Figure 71. Data was then taken for 30 minutes. The face used for this test was the calibration grid.

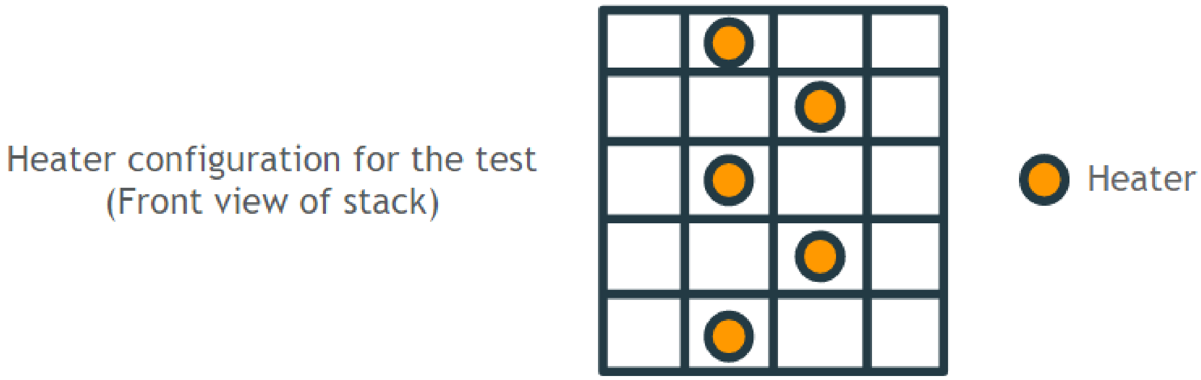
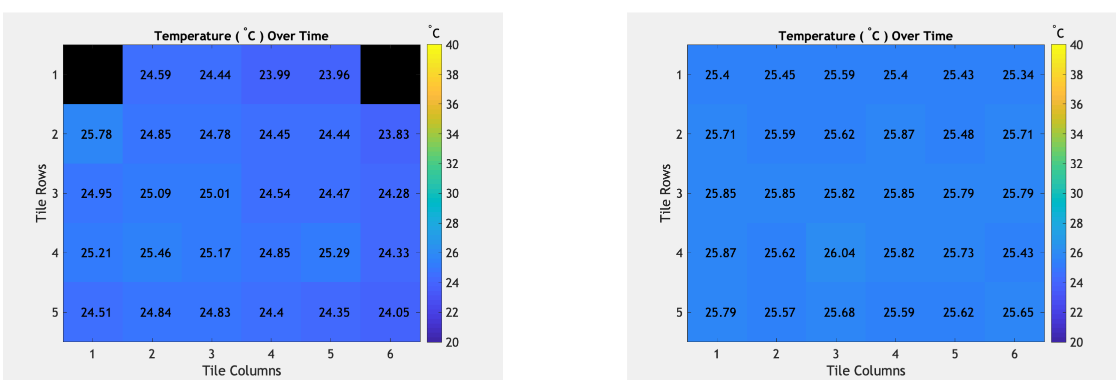


Figure 71: Heater Configuration for Ambient Testing

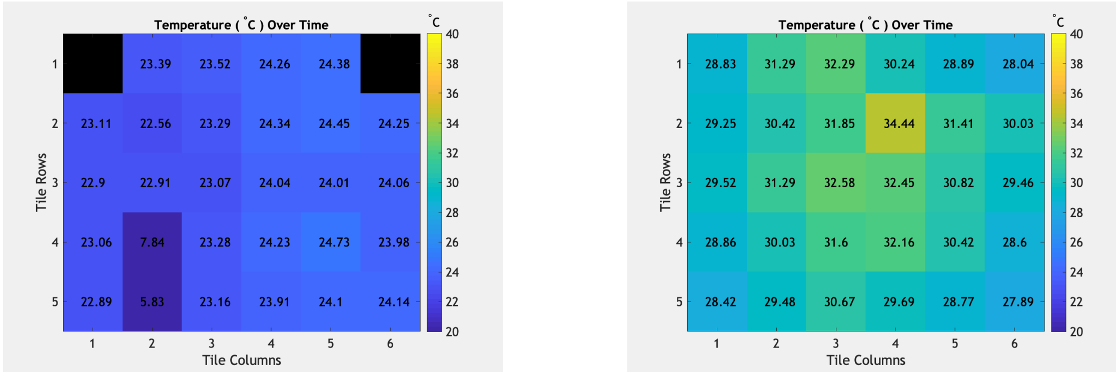
5.5.1.2 Results

At the beginning of the test the data from the cameras and the reference data system was very similar as shown in Figure 72. However as the test progressed and the stack began to heat up the differences in temperature between the reference data system and the camera system began to increase as shown in Figure 73. This difference kept increasing until the end of the test as shown in Figure 74.



Camera Data Reference Data

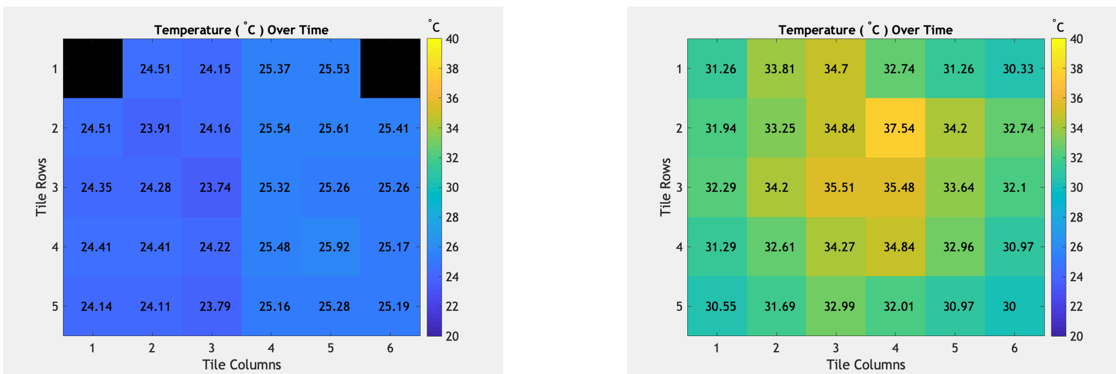
Figure 72: IP and Thermistor Temperature Data at Beginning of Testing



Camera Data

Reference Data

Figure 73: IP and Thermistor Temperature Data at Middle of Testing



Camera Data

Reference Data

Figure 74: IP and Thermistor Temperature Data at End of Testing

Visual inspection of these figures shows that the camera data does not see the same trends as the reference data system. In the middle of testing, the cameras show a decrease in the temperature in two tiles, lower corner of Figure 73, which is not realistic as the plate started at 25°C and the tiles read below 10°C. Once again, this is an issue with the reliability of the sensors measurement and could cause erroneous commands to be sent by the system. There is a slight split along the center line of the stitch as seen in the upper bound tests in the thermal chamber but not as pronounced, approximately a degree or two difference. This indicates the split may be temperature dependent as it is more defined at high temperature than lower temperature although conclusions cannot be drawn about the lower bound of temperatures due to the sensor failures.

5.5.1.3 Errors

As expected, there was a large amount of error between the cameras and the reference data system. The mean difference between IP and reference data was 7.632°C for the duration of testing and the standard deviation was 2.115°C. The maximum temperature difference took place in tile 10, the tile where the camera's heat signature is reflected. This delta was equal to 41.760 °C. The mean error over time in this tile was 9.446 °C. Errors during this test can be attributed to many different factors. Firstly, the reflection of the aluminum is a major factor due to heat signatures being reflected onto the stack. This affected tile 10, shown in Figure 76, the most due to the heat signatures of the cameras reflecting off of it. Secondly, bad pixel data would affect tile readings. During testing bad pixel data would read as -273°C which would cause large errors on the average tile readings. Lastly, the camera used is only rated for accuracy of up to ± 5°C which can drastically affect the temperature readings. This error is seen in 75 since absolute differences of over 5°C have the most occurrences during the ambient test for both cameras. The error between the cameras is similar with the right camera having a slightly smaller center but also having more variability to the spread of the distribution.

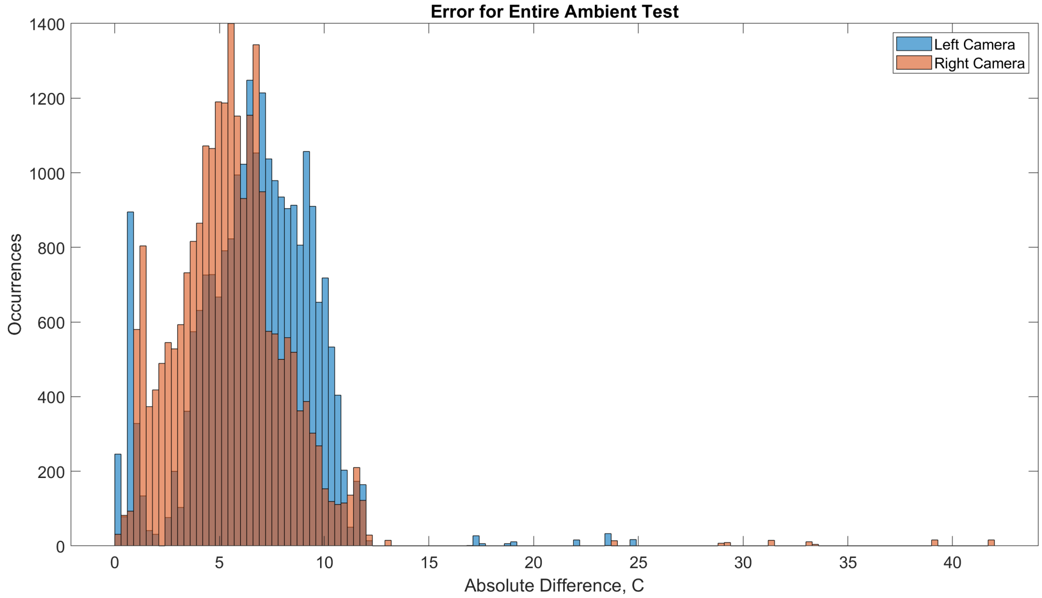
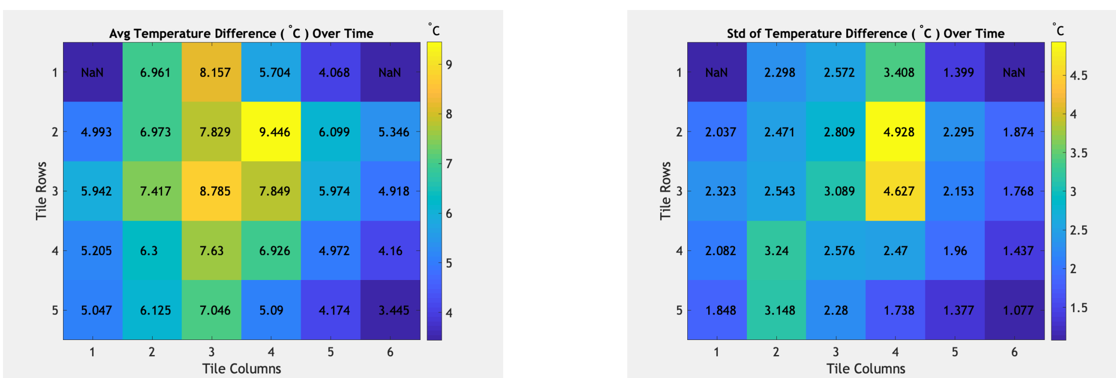


Figure 75: Histogram of the errors over the entire testing period for both Leptons



Time Average Error

Standard Deviation of Error

Figure 76: Average and standard deviation of temperature difference per tile

5.5.1.4 Conclusions

Overall, the error distribution exceeds the desired limit of 10°C as seen in Figure 75. There are also many outliers to this distribution. These outliers are sources of error for the commands as the testing bounds are approached. Some of the errors in this case could cause bad commands to be sent when the electronics are well within their operational bounds. A large quantity of the distribution does occur within the desired 10°C error bound but the distribution is desired to fall completely within this bound to qualify the method as feasible for thermal control of the stack. This is defined due to the difference between what is required to measure, defined in **FR 1**, and the operational bounds, defined in **FR 2**. This distribution is close to the required tolerance which shows room for improvement to the system which will be further testing in the remaining testing sections.

5.5.2. Reflection Calibration

5.5.2.1 Setup

The purpose of the Reflection Calibration test was to attempt to improve the accuracy of the camera by removing extra reflections within the bay. To do this the entire bay was blacked out using black construction paper as shown in Figure 77. The ambient baseline data test plan was then followed. Data was taken by the camera and reference data systems with the heaters off for two minutes and then the heaters were powered on for 30 minutes. A new heater configuration was also used as shown in Figure 78 to attempt to create a quicker thermal change at the surface. This test was performed using the calibration grid for the face being viewed.

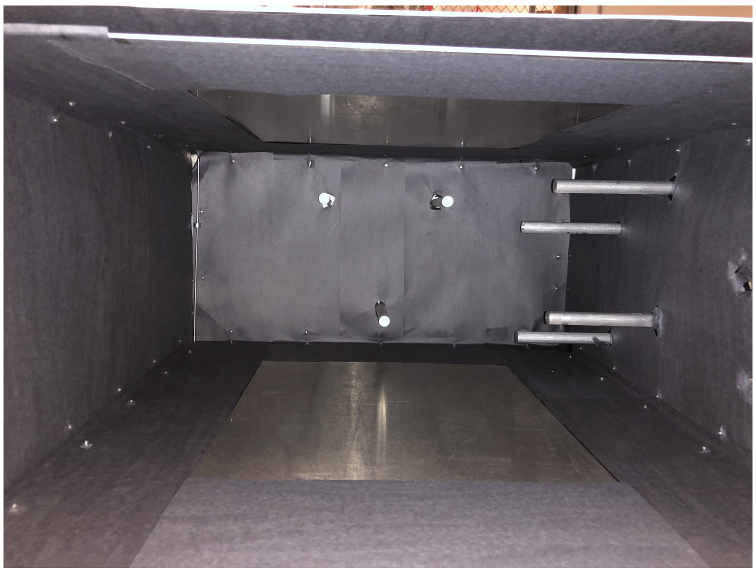


Figure 77: Test Bed setup used in Reflection Calibration Testing

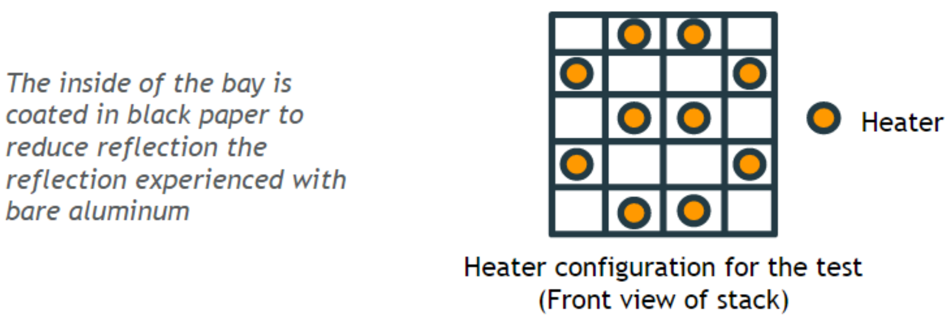
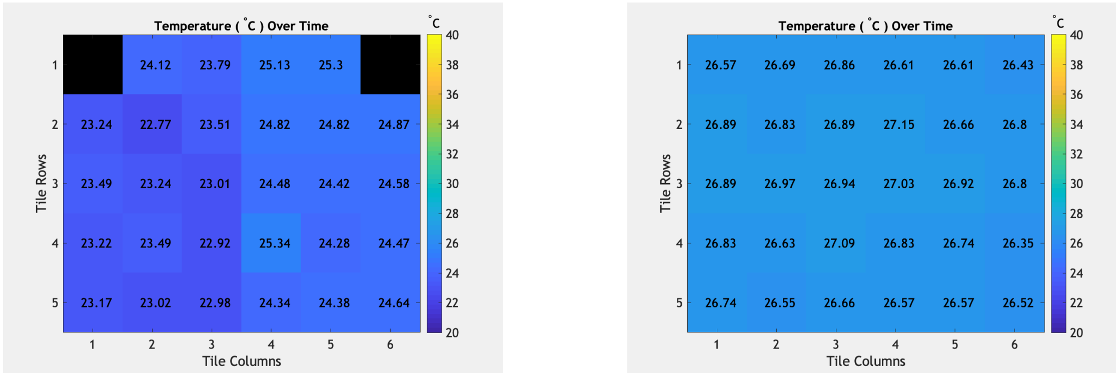


Figure 78: Heater Configuration in Reflection Calibration Testing

5.5.2.2 Results

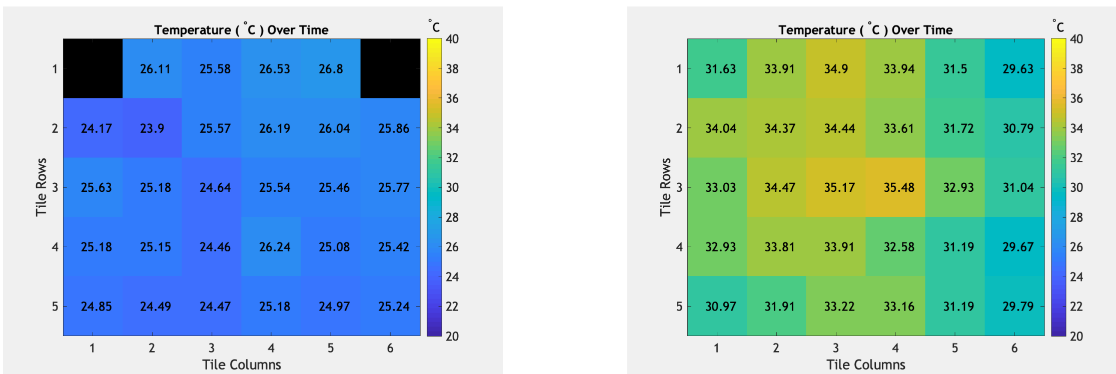
The reflection calibration testing data followed the general trend of the ambient testing data with the difference between IP data and reference system data increasing linearly with time. At the end of testing both cameras began to display bad pixel data which is indicated by the black tiles in Figure 81. This shows that the cameras can be unreliable in not other their pixel data, but their operation.



Camera Data

Reference Data

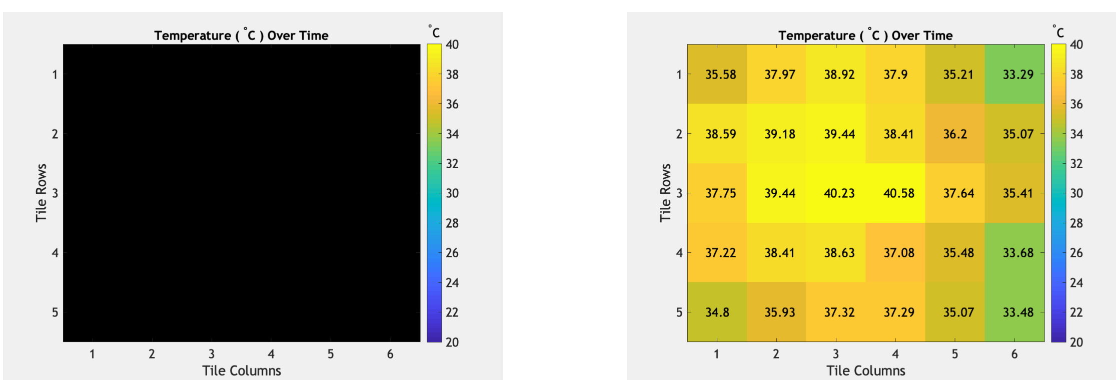
Figure 79: IP and Reference Data at the Beginning of Testing



Camera Data

Reference Data

Figure 80: IP and Reference Data at the Middle of Testing



Camera Data

Reference Data

Figure 81: IP and Reference Data at the End of Testing

Once again, the clear split between the left and right camera data is seen but closer to single degree of error between the sides. Also, the cameras do not see the same thermal profile as the reference data as the test progresses. This may indicate there is a delay for the thermal profile moving from the inner surface to the outer surface. Initial thermal modeling predicted the thermal difference through the wall to be small, less than 1°C, due to the thin wall but did not account for two plates combined to construct the wall. This assumption does not account for both thermal contact resistance and the possibility of a convection heat transfer boundary between the plates.

5.5.2.3 Errors

After reflection calibration testing was completed the mean temperature difference between IP and the data reference system was found to be 7.6°C with a standard deviation of 2.933°C. This was a very small improvement compared to the ambient testing mean error. A big difference in this test however that instead of tile 10 having the worst error during testing it was found that tile 15 had the worst error averaged with time as shown in Figure 83. This test was also drastically affected at the end due to the cameras dying causing them to output bad data. This can be seen in tile 22, (4,4), in Figure 83.

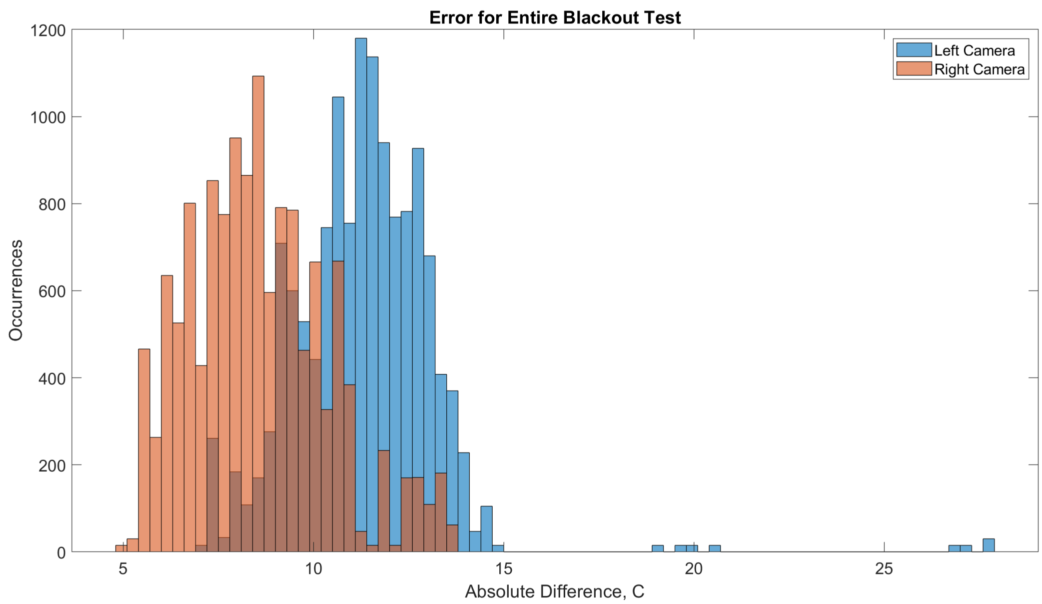
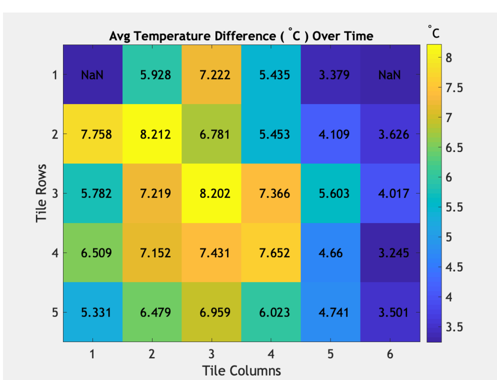
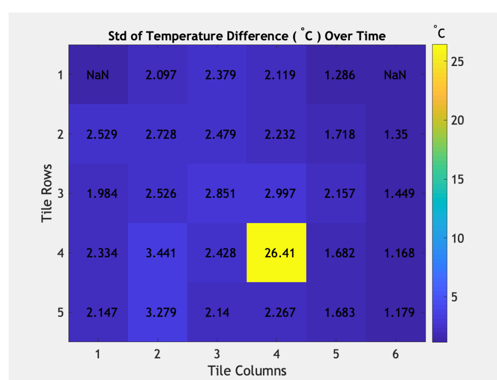


Figure 82: Histogram of the errors over the entire testing period for both Leptons



Time Average Error



Standard Deviation of Error

Figure 83: Average and standard deviation of temperature difference per tile

5.5.2.4 Conclusions

This test shows some improvement to the accuracy of the system but only for one of the cameras. Figure 82 also shows that for this test, the left camera produces more error which is also confirmed with an inspection of Figure 83. The results from this test cannot be directly compared with the most other tests due to the change in the heater pattern and thus a loss of a control variable for the test. However, this heater setup was used in the thermal chamber tests so direct comparisons could be made. This can be made although it should be noted that there are 2 control variables for this comparison, the blacking out of the box and the temperature. Comparison to the lower bound testing is less useful due to the sensor failures during the testing. Upper bound testing does show that the spread of the distribution is decreased but the left and right camera may have been swapped between the testing days.

5.5.3. Coatings

5.5.3.1 Setup

For coatings testing, a range of different coatings were applied to the face of the stack being imaged. This included black construction paper and blue construction paper. The results from these coatings were compared to the results from the ambient testing results which used the calibration grid. Everything else about the test setup was the same as the ambient baseline test setup including the heater setup given in Figure 71.

5.5.3.2 Results

Both coatings tests produced the same general trend as seen in all the other test. The temperature difference between IP and the reference data increased linearly with time. The results for the black paper face, Figure 84, and the blue paper face, Figure 85, produce similar results from the two discrete time steps shown below.

Black Construction Paper Face

Similar to previous ambient tests, the image processing data seems to have a lag in the temperatures on the surface or less of a thermal profile on the outer face. Both time steps of the test and both the reference data and IP are shown below in Figure 84 along with the heater profile from Figure 71 superimposed. The initial temperature of the plate is at approximately 25°C when the test begins but IP predicts the surface to be closer to 23°C. This is a slight difference compared to what is noted at the final frame or time stamp 1000. The reference data shows a clear thermal profile similar to the heater pattern applied with a maximum of approximately 36°C and nearly all tiles above 30°C. The cameras read the surface temperature 1 or 2°C above the initial, starting temperature.

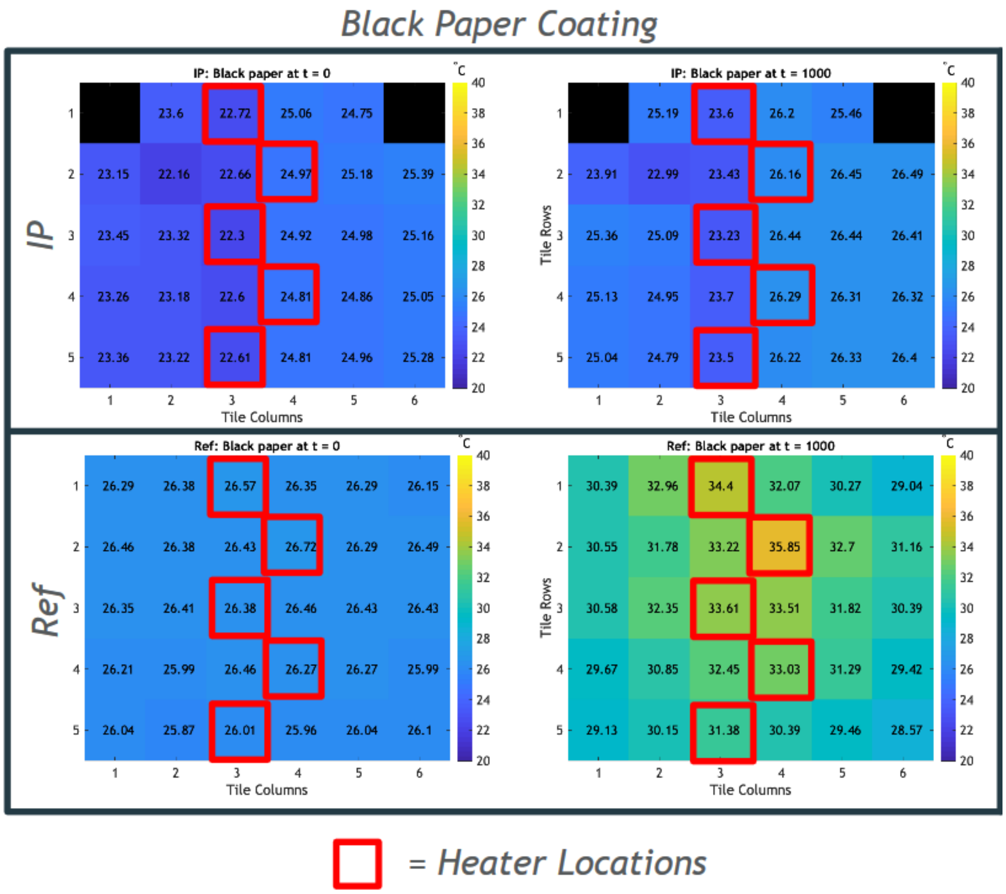


Figure 84: Black paper coating results for time steps 0 and 1000 seconds

The definition between the two sides of the stitched images is more difficult to see in the figure above due to the superimposed heater locations. This split still exists and is more pronounced as the temperature increases with the simulation electronics powered on. This shows that it is less of a product of the surface and more likely to be a sensor issue.

Blue Construction Paper Face

The results of the blue face are presented, shown in Figure 85, in the same fashion as the previous coating test. There is a small difference between the two tests. The blue test starts at a slightly lower temperature by approximately 1°C. This also shows in the final frame being approximately 1°C difference from the previous test.

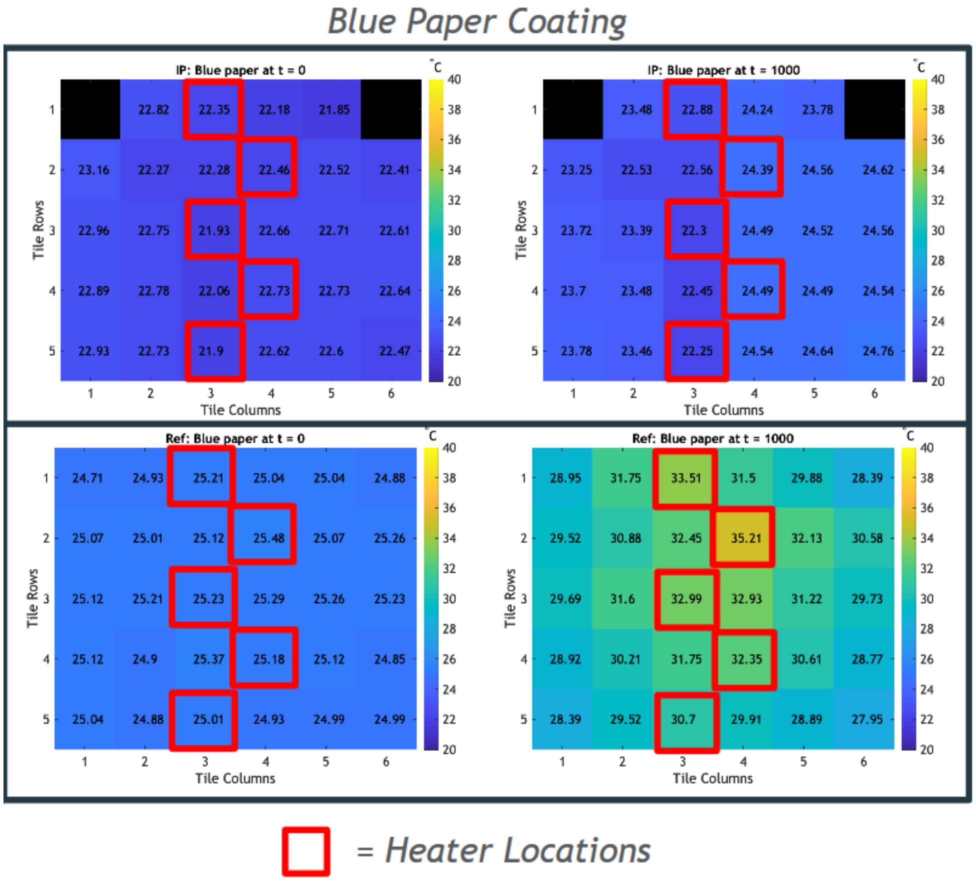


Figure 85: Blue paper coating results for time steps 0 and 1000 seconds

The definition between the two sides of the stitched images is more difficult to see in the figure above due to the superimposed heater locations. This split still exists and is more pronounced as the temperature increases with the simulation electronics powered on. This shows that it is less of a product of the surface and more likely to be a sensor issue. This effect is similar for both coatings tested, providing more evidence that the issue is not a thermal profile on the surface.

5.5.3.3 Errors

Due to only 2 points in time being displayed for the results of the coatings test, the graph in Figure 86 was generated to show the average errors over the entire face of the stack between IP data and reference data. This shows the overall behavior through out the testing period with a direct comparison to the baseline ambient test with the calibration grid, shown in red in Figure 86.

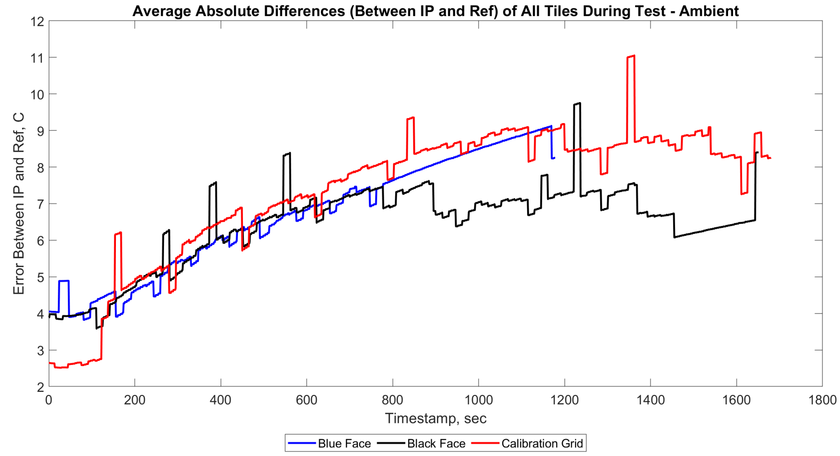


Figure 86: General trends in the error for the coatings tests

Black Construction Paper Face

With the black construction face coating on the removable side of the stack, the mean error was observed to be 6.982°C which is an improvement from the ambient testing. The standard distribution of this test is slightly less at a value of 1.514°C. This shows a drop in both the center and spread of the error distribution. Tile 10 still contained the maximum instantaneous error of 39.050°C. This shows reflection can still be a large propagator of error during construction paper testing. Also, the coatings are not effective for modifying the range of the error. The minimum error between tiles is found in tile 30, the lower right corner of Figure 88, with a value of 0.440°C. Bad pixel data also caused errors throughout the the testing as seen by the sharp increases in errors for short periods, shown in Figure 86. During this test, a bulk of the errors from the left and right camera are fairly similar. The right camera has more overall spread to the data with some outliers while the left camera has more substantial grouping of higher errors around 10°C.

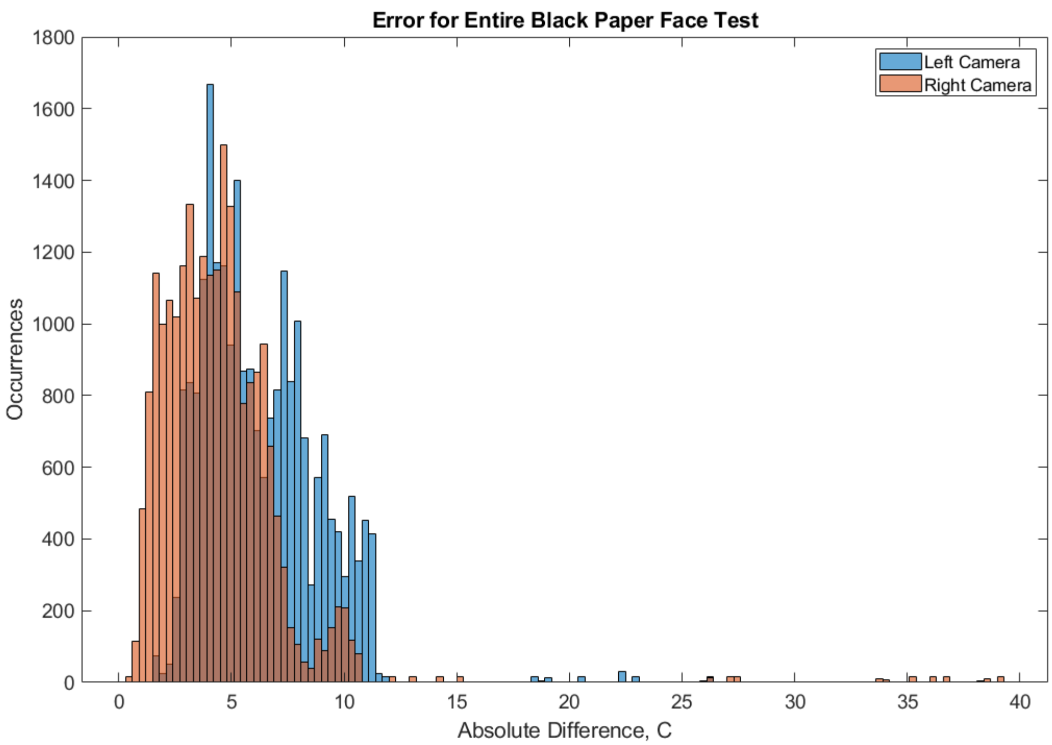
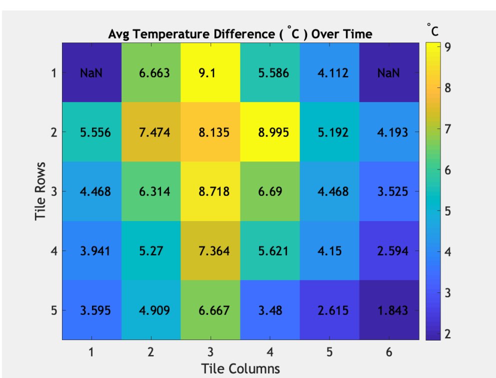
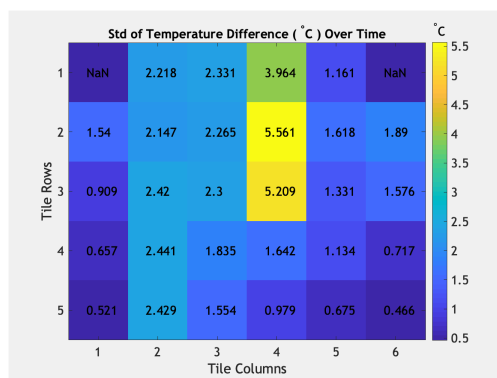


Figure 87: Histogram of the errors over the entire testing period for both Leptons



Time Average Error



Standard Deviation of Error

Figure 88: Average and standard deviation of temperature difference per tile

Blue Construction Paper Face

The blue construction paper coating provided less error between the IP and reference data system then the black construction paper coating. The mean difference between the IP data and the reference data was found to be 6.627°C with a standard deviation of 1.573°C. The minimum error occurred in tile 30 with a 0.440°C error, and the maximum error was found in tile 26 with 19.360°C which was most likely due to bad pixel data. As seen in Figure 86, bad pixel data did not affect the blue construction paper coating as much as the black construction paper coating but there were still some effects in data caused by it.

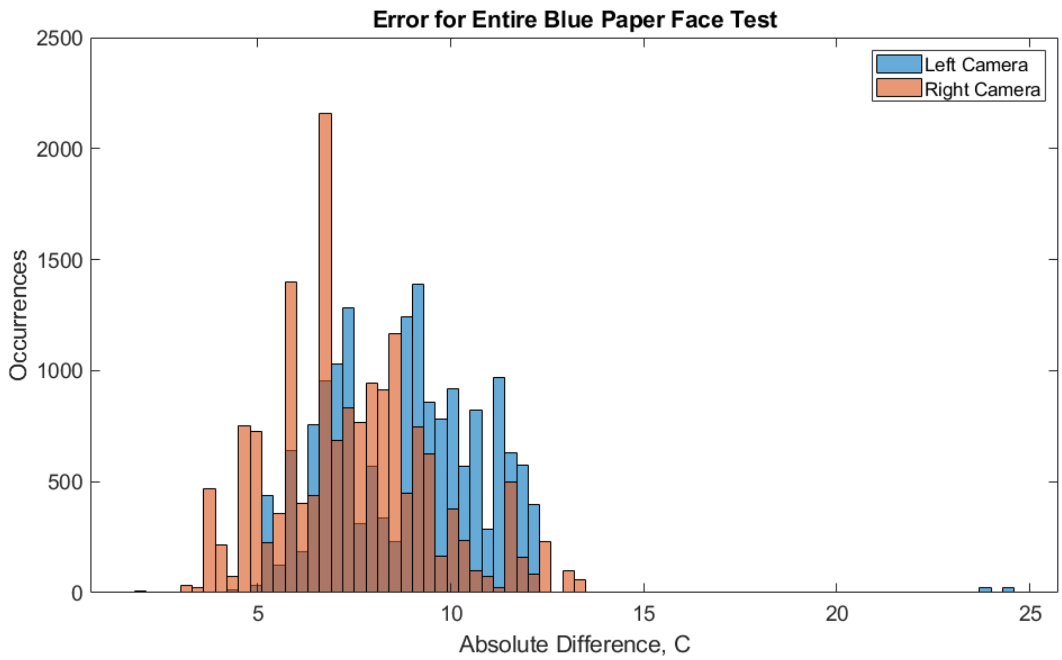
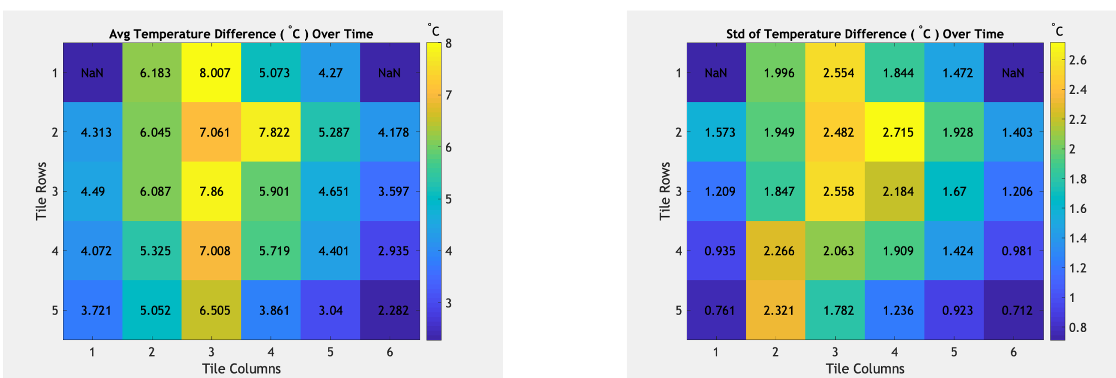


Figure 89: Histogram of the errors over the entire testing period for both Leptons



Time Average Error

Standard Deviation of Error

Figure 90: Average and standard deviation of temperature difference per tile

5.5.3.4 *Conclusions*

Overall, both coatings show improvement to the errors although neither fit the required tolerance for accurate commands. A decent portion of the data from both Leptons still occur over the 10°C cutoff. The drop in the mean and standard deviation of the error distribution is a promising step toward the accurate thermal control of the electronics stack but the range of the error is not modified as much by this test. This allows for further room for improvement in the accuracy of the data by improvement of another subsystem such as the structure or software. The applied coatings were done in a simple method, using a glue stick. This shows that a more permanent method, with known and closer to ideal thermal contact resistance properties could improve the accuracy improvements shown by this test. This was not pursued by the team to avoid destructive testing. Another form of destructive testing that could benefit the system would be experimentation with surface roughness to modify how specular, or mirror like, the reflections are.

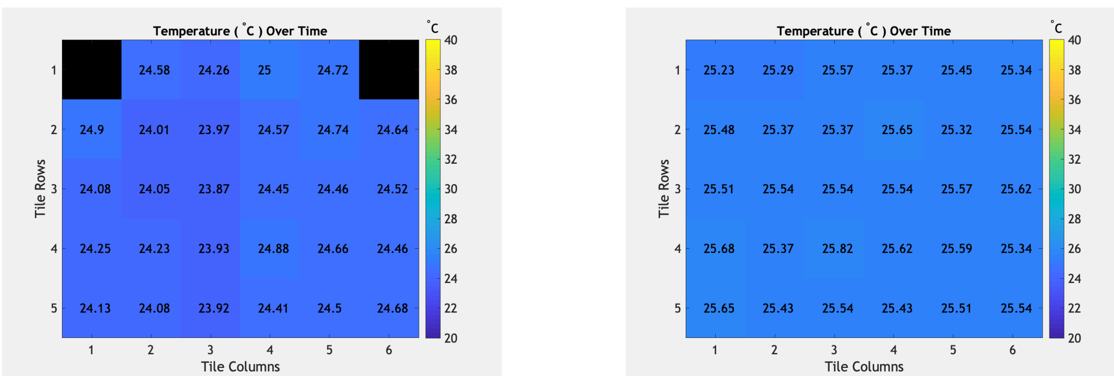
5.5.4. Error Filtering

5.5.4.1 Setup

The purpose of this test was to filter out bad pixel data provided by the FLIR Lepton before computing the temperatures of the tiles. Bad pixel data displayed as -273°C which caused large errors between IP data and data provided by the reference data system. For reference, in a pixel grid of 100 pixels at 25°C, the average of the tile would be reduced to approximately 22°C. If the pixel count per tile is lower, the effect of this bad pixel is greatly increased. This is due to how the software computes the average temperature of a tile that is given to the GUI for comparison to a reference data point. The same test setup and heater setup was used from the ambient baseline data testing after the software change was implemented. This test is used to show if simple modification to the software subsystem and how errors are handled can improve the results. Similar to previous testing, the heater setup in Figure 71 was used for the test along with the same baseline testing procedure.

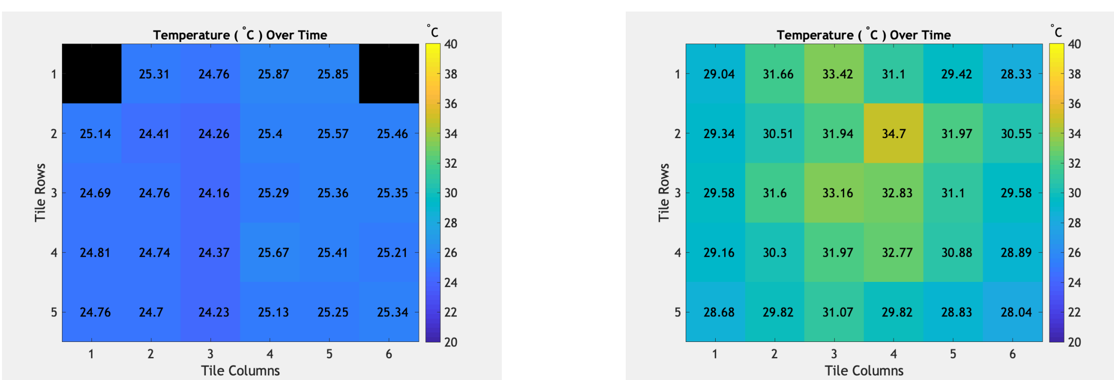
5.5.4.2 Results

After implementing the software change, the error filtering testing data followed the same trend as the ambient testing data. Errors between temperature data provided by IP and the reference data system were increasing linearly with time. However, the error between these values was greatly decreased.



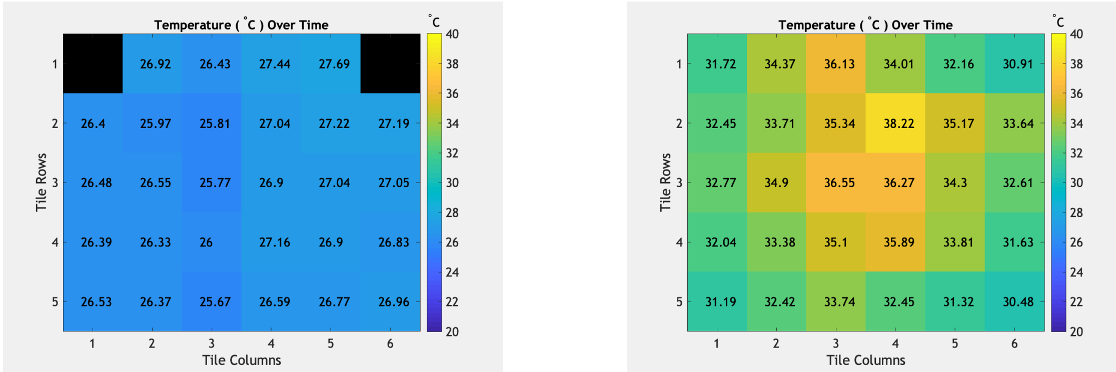
Camera Data | Reference Data

Figure 91: IP and Reference Data at the Beginning of Testing



Camera Data | Reference Data

Figure 92: IP and Reference Data at the Middle of Testing



Camera Data

Reference Data

Figure 93: IP and Reference Data at the End of Testing

Similar to the previous tests, there is a slight definition line between the data produced by the right and left camera. Also, there is a delay in how the thermal profile appears on the outer surface that is being measured by the Leptons. The behavior over time for all ambient tests appears to be similar when using the same heater setup when visually inspected with slight variations to the temperatures of the surface. Many tests experienced camera failure forcing the team to perform a hard reset during testing and introducing error to the system.

5.5.4.3 Errors

Removing the bad temperature pixel data given by the camera improved the overall error the most. The mean difference in temperature for the duration of this test was 6.455°C with a standard deviation of 2.052°C. The minimum error throughout testing occurred in tile 30 with a 0.060°C error and the maximum error occurred in tile 10, as expected, with an error of 11.180°C. The maximum error was also was much smaller compared to the previous tests due to the implemented software change. The histogram shown in 94 also matches what is to be expected since most errors between IP and reference data were about 5°C which is the uncertainty associated with the camera.

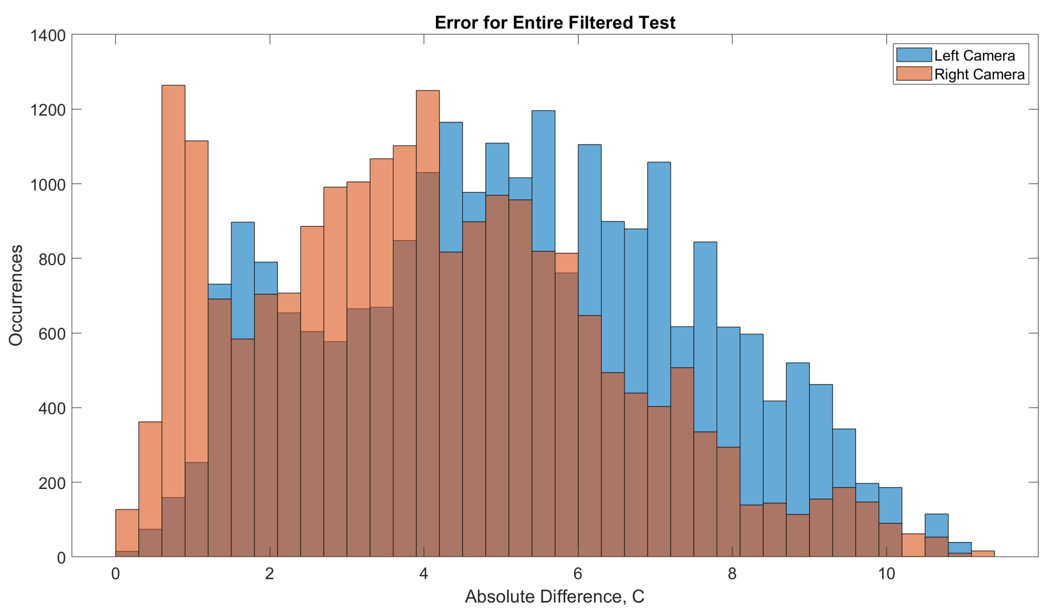
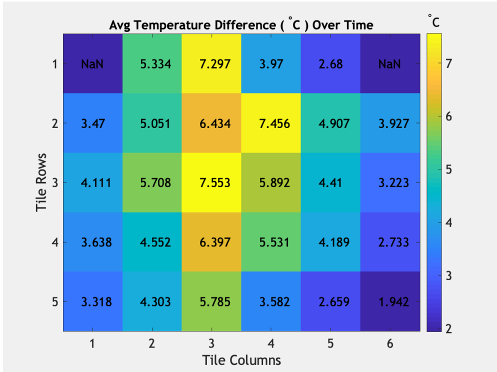
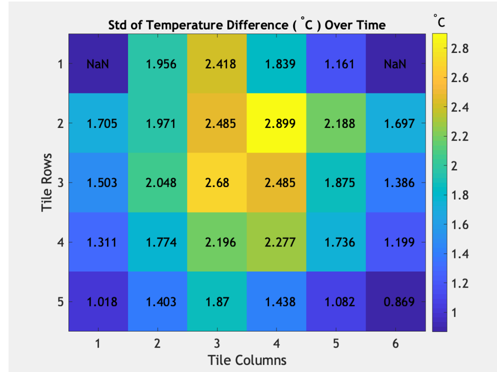


Figure 94: Histogram of the errors over the entire testing period for both Leptons



Time Average Error



Standard Deviation of Error

Figure 95: Average and standard deviation of temperature difference per tile

5.5.4.4 Conclusions

This software change was a simple error rejection method when outside a set tolerance but provided drastic improvements to the range of the error and improvements to the center and spread of the error distribution. The distribution of error from the results in Figure 94 show that this is nearly in the desired range for control decisions. The results of this test begin to approach the limit of the uncertainty of the sensor in the radiometry mode. Other, more complex error rejection strategies could be used to improve these results due to the simplicity of the used method. A suggestion made by Professor Rhode in SFR is a viable option to increase the accuracy of the error rejection. This method may increase the computational time but as shown earlier, the worst case for computational time is within the required range. The suggested method is to reject pixel temperatures if the pixels in the vicinity of the selected pixels are not within a certain range. This range could be automatically defined using a normal distribution and the mean and standard deviation of the neighboring pixels. Further work on this project or topic should explore this rejection method as the simple method provided a benefit to the error distribution in testing.

6. Risk Assessment and Mitigation

Author: Nash Jekot, Jacob Killelea, Ryan Bennett, Kendall Worden

6.1. Risk Determination & Mitigation

To best protect project success, OTheRS took steps to compile a comprehensive assessment of potential risks to the project, organized by relevant aspect of the project. Special importance was given to risks identified as critical early in the semester: reflectivity and as a result, surface coatings/preparation, accuracy of the proposed system, and providing accurate truth data to quantify the complete data set.

6.1.1. MAT-1 : IR Reflectivity

Risk: Modern satellites are made almost exclusively of heat-reflective metals. When the OTheRS team had the opportunity to tour the GA facility, combined with the color-mapped data obtained with the one camera initial test bed, it was quickly evident that any heat sources within the satellite avionics bay will reflect around the bay and into the lens of the thermal imaging devices. Components like heat sinks and reaction wheels are just a few examples of heat sources that may exist in a satellite's avionics bay. Based on initial research, aluminum plates reflect more than 80% of the IR radiation they receive. This means that the true surface temperature cannot be accurately measured and instead shows reflected heat from other sources within the system. Initial testing confirmed that this was the case. For these reasons, IR reflectivity has been assigned the highest likelihood and severity for the project. Without a solution to reduce or remove it, the efficacy of IR cameras as thermal sensors, in this case, will be fully compromised.

Mitigation: The goals of the project will focus on creating a variable parameter test bed. This test bed will allow for the plate being imaged to have the ability to vary material, surface roughness, and surface coatings to find the best method of mitigating reflectivity seen by the camera. After the OTheRS project is complete, the customer can use the test bed to further explore the use of a thermal imaging solution. The proposed solution begins with testing easily available materials and progressing to more expensive and complex anti-reflective solutions as needed.

Result: Only the easily available materials were tested. Initial tests were completed on bare aluminum, aluminum covered in construction paper, and high emissivity stickers. A reduction in temperature error was observed. However, more advanced surface treatments were not explored along with destructive testing methods such as sanding and non-removable thermal epoxies..

6.1.2. MAT-2 : Manufacturing Accuracy

Risk: Machine shop training, material procurement, and initial test bed manufacturing taught many lessons to the team. Through completion of the machine shop training course, the team learned which aspect of component manufacturing require extra care and planning. High precision manufacturing is extremely difficult, requires extreme care, and takes exponentially longer than rapid prototyping.

Mitigation: In lieu of this hands-on challenge, manufacturing time has been allotted accordingly. Should any components fail the validation process set forth in section 5.1.2.2, the team has also given time for re-manufacturing.

Result: Manufacturing only met two hiccups. During manufacturing, the electronics stack was unintentionally made too large and could not fit within the avionics bay for the final test bed. This was due to tolerance stacking and the result was losing functionality of a tray. Also, the thickness of the material of the surface of the stack was too large and that requirement was failed. The other 3 manufacturing requirements were met.

6.1.3. IP-1 : Individual Tray Identification

Risk: Derived from **DR-PROC 1.1**, the ability to identify the individual trays and heat coming from them may allow for the temperatures of known components to be interpolated although this is left as a goal for the team. Being able to do so is important because further development may allow for the interpolation of temperature of a component located some distance behind the wall. The feasibility of this is in question and will require further testing and study. The Lepton will return raw data with pixel sizes between 8 and 12mm square, both are still less than the size of each tray, with an expected accuracy of $\pm$ 5 °. The height of each tray is 41.05 mm.

Mitigation: Distinguishing between individual stack trays is an important aspect of the OTheRS system. The main method that has been chosen uses high emissivity markers with various shapes located at strategic points on the surface of the electronics stack. This will prove useful for quantitatively measuring the size of each pixel in the image and discovering relative error factors that result from the image skew processing algorithms. Reflective markers may also be useful in testing and performance comparison between several design solutions. An alternative design solution is to use the reflective markers as tray locators, allowing for precise spatial calibration to be performed, while still relying on other design solutions to allow the temperature data of the system to be measured.

Result: The system was able to distinguish between the trays. The geometric stitching algorithm combined with the calibration grid allowed for easy separation of the trays.

6.1.4. IP-2 : Image Stitching

Risk: Like IP-1, the process of image stitching helps to achieve the goal of satisfying **DR-PROC 1 & 1.1**. The final design solution utilizes two cameras mounted in opposite corners along the subtending line. In order to obtain a single, comprehensive image of the stack, these images will need to be stitched in a matter that takes advantage of the overlap between the two images. To satisfy **DR-PROC 2**, this requires the data or the images themselves to be spatially and thermally calibrated. Image stitching works to partially satisfy this requirement, by working to help spatially calibrate the image. This method introduces significant risk. Primarily, this risk is associated with how well the image stitching algorithm can identify pixel clusters in the overlapped region that appear in both images. Being able to build a single image of the stack is critical to this project, as inaccurate results can lead to a misdiagnosis in the health of the electronics in the avionics bay. This could lead to an inaccurate assessment of the system, and lead to ineffective control decisions.

Mitigation: To fully mitigate the risk of inaccurate results from image stitching, the team looked into stitching the images from the two cameras after each is first skew-corrected. This is because the image stitching algorithm requires two flat images to process and find similarities in the two images. An effective skew transform algorithm will introduce less error and lead to a more effective output image from the image stitching algorithm. In the software for the image stitching algorithm, RANSAC is an error-mitigation strategy introduced to determine the quality of the data point matches for the overlapped region. This algorithm uses a more robust least-squares method after finding the mean score metric to determine which points are within a specific tolerance of the mean. If a majority of matched data points fall outside of this mean, then the image is discarded and the image capture command is sent to the camera. In the case where only a few data point matches fall outside of this tolerance, these data points are labeled outliers and discarded. On top of this, only the top 15% of matches are kept from this pool. The remaining matches in the pool are used in the image stitch to guarantee accurate identification of the overlapped region. This will ensure the image stitching algorithm produces a single image of the stack and an accurate thermal data extraction.

Result: This aspect of the system was discarded in favor of manually defining the offsets and the areas being sampled.

6.1.5. CTRL-1 : Control Loop

Risk: It will be difficult to obtain accurate temperature data from the thermal imaging device given the highly reflective environment, meaning feeding back this temperature data to a controller may not produce the desired results. This risk is mostly dependent on the success of the reflectivity solution mentioned above. Temperature will be measured in several places in the OTheRS test bed, and each of these measurements is critical to closing the command loop. Measurement errors or failures in either the camera to stack data, stack to thermistor data, or camera to thermistor data compromise the successful closing of the control loop, as each depends on input from the others to make comparisons and provide useful data.

Mitigation: Successful control requires that the temperature measured by the thermal imaging device is accurate enough to fall within the specified factor of safety of 10°C. However, if the camera fails, the OTheRS test bed can rely on the truth data from thermistor measurements to test that the controller operates successfully. This means that the controller can be validated independently of the success of the reflectivity mitigation strategies.

Result: As the project was descoped, control decisions were indicated on the GUI instead of a fully closed loop.

The sensing ability of the cameras is less than initial expectations and the times for the test bed to change temperature were longer than initially anticipated due to design decisions.

6.1.6. CTRL-2 : System Control Failure

Risk: In addition to monitoring the temperatures of the test bed stack and camera components, the designed system must also be capable of processing and sending control decisions should temperatures exceed defined ranges. This failure could come from degraded quality data, control loop failure, or poor design. As **FR 1** and **FR 2** define, OTheRS cannot allow the temperature of any system component to fall below -20°C or rise above 50°C in a -30°C to 60°C environment. This is critical to address, as the modeling completed to date has included underlying assumptions that will not translate to the operational system. It is also important to note that the minimum temperature for the Lepton camera is -10°C. The maximum temperature of the Lepton is 70°C, so OTheRS will not need to worry about exceeding this bound as a 10°C safety margin is included in the design of the system.

Mitigation: The first strategy for mitigation is to begin with a simple on/off controller that will provide binary commands to each stack tray through representative indicators. This, in combination with the mitigation strategy in the previous risk, will allow confidence in the robustness of thermal control of the stack.

Result: Overheating issues were not encountered over the course of the project. During testing, a channel on the heater driver PCB was damaged resulting in an uncontrollable channel. However, the team quickly noticed the excess current draw and moved the heater from that channel to a functioning one. Also, the thermal control of the scope was descoped as discussed in the previous error, CTRL-1.

6.1.7. ELEC-1 : Static Discharge

Risk: In the designed system, early handling and machining of the initial test bed confirmed a risk identified by the team. All of the electronic hardware proposed comes packaged in ESD bags, as even a small static discharge could destroy the component. Shocking a component could cause issues during testing, where diagnosis of an error might not be as simple as unplugging and removing the component.

Mitigation: To fully mitigate the risk of static discharge ruining electronics components, the system will be fully grounded as follows: camera to test bed, test bed to testing environment, environment to ground, human to ground.

Result: No negative effects were observed from electrostatic discharge due the effective mitigation strategy.

6.1.8. TEST-1 : Coating/Material

Risk: Upon investigation into the LWIR properties of the system with bare Aluminum 6061, it was deemed necessary to prepare the surface to be imaged. Some of the proposed solutions present unique quantification challenges in that the thermal properties of the imaged surface are changed, namely reflectivity and emissivity.

Mitigation: The team has no prior experience working with IR systems. To determine the best, most cost effective solution that allows the stack to be imaged and temperature data to be extracted, several proposed design solutions are to be explored. Initially, OTheRS will provide simple testing using simple reversible coatings such as sticky notes to obtain a baseline solution that follows in the design path the customer took. Beyond this, the next solutions to be tested will be surface roughness modifications and then sprays or paints. COTS solutions like sprays and paints may be a potential solution to reducing or removing reflectivity, but often don't have relevant material properties listed as this is not their intended use. In conjunction with this, surface roughness and finish could potentially be a cost effective solution as proper application might produce a surface diffuse enough to be imaged directly. Finally, if the previously mentioned design solutions fail, the team plans to use more expensive, purpose built coatings like Acktar Black Velvet to achieve the best performance possible, with the added benefit of quantified emissivity and reflectivity variables.
Result: Simple testing was carried out using black and blue construction paper, as well as with high emissivity stickers. As a result, the OTheRS system produced test data that compares these various surfaces quantitatively.

6.1.9. TEST-2 : Fogging at low temperatures

Risk: During initial testing, it was noted that at low enough temperatures, it might be possible for moisture in the air to collect on the surface of the camera lens. While testing will occur at Denver ambient, where the relative humidity is usually low, the dew point remains far above the lowest temperature bound testing occurs at.

Mitigation: Dry gas nitrogen purging and environmental control will be sufficient to prevent condensation, but careful monitoring along with pre and post visual checks will be performed. This feature is available on the thermal chamber at the customer's facility, which has been secured for testing.
Result: Moisture did not form on the camera throughout the duration of any test. This result was achieved by dry gas purging the thermal chamber while the bring brought down to the lower bound, -30°C, for testing.

6.1.10. THERM-1 : Surface-to-PCB Mapping

Risk: To determine the temperature of specific PCB components, there are several things that must first happen successfully. First, the thermal imaging device must be able to read the temperature of the plate. Then, the thermal imaging device must be able to track the transient temperature changes over time. Third, the processor must take this data, apply a predictive model, and interpolate to determine the exact component temperature. The issue arises in this final step, as it is likely that the accuracy, rate of image capture, and processing requirements will put a huge strain on any predictive modeling that needs to be done. Also, the time constants of the heat transfer could have an effect on the time to notice the internal changes. This is difficult enough with the heaters placed directly on the surface of the aluminum, but becomes exponentially more complex when the heater is placed some dist ante behind the wall. This is related to the fact that the thermal imaging device taking images of the stack only sees one 2D face.

Mitigation: Because 3-D thermal modeling of the stack is out of the scope of this project, the feasibility of Surface-to-PCB mapping can only be explored via experimentation. This is not a critical element of the deliverables to the customer as they only require surface temperature data and overall temperature profiles. Rather, it will be explored to provide a comprehensive look at the capabilities of the designed system. Upon suggestion of Trudy Schwartz, the team has spent time to learn and familiarize with a common thermal modeling tool, CosmosWorks. Temperature fluctuations in the designed system could prove to be very difficult to predict with home-built simulations, which drives the need to be able to complete simple 3D modeling. Cosmos provides the ability to include all three forms of heat transfer than will be present in ambient testing, and allows the team to factor in more complex thermal behavior in an attempt to build a model more accurate than what can be achieved on paper.

Result: Cosmos was able to provide models of several conditions within the test bed but this risk was largely ruled out of scope for the project.

6.1.11. THERM-2 : Thermistor Truth

Risk: The designed system intends to use thermistors to provide monitoring of the thermal imaging device's temperature as well as to provide reference truth data of the stack wall temperature. Initial research has show that thermistors are far more user-friendly than thermocouples, with added accuracy and ease of implementation. However, without a reference compensation, usually 0°C water, bias error is introduced into the system at the lower bounds of the required operational temperature range. Here, initial work has shown that up to a 7°C error exists at this lower bound, which is worse than the uncertainty of the FLIR Lepton at 5°C although the Lepton requires heating to operate when the system is at -30°C.

Mitigation: In testing, the uncertainty in the thermistor measurements at low temperature means that the OTheRS team will likely need to run several tests. As the thermistors are being used as truth data, the team will need a data set of sufficient size in order to establish truth with statistical significance.

Result: 6 Thermistors were placed in each tray and successfully provided truth data.

6.1.12. THERM-3 : Thermal Imaging Device Temperature Gradient

Risk: In early product acquisition, it was made clear to the OTheRS team that the FLIR Lepton camera system is extremely sensitive to temperature gradients on the order of 3°C across the camera.

Mitigation: Due to the nature of the OTheRS mounting system and component design by FLIR, getting heat to flow out of the camera and into the satellite structure shouldn't be as much of an issue as cold and standard operating conditions. To ensure that the gradient across the camera PCB is kept to a minimum, OTheRS intend to use a system of heaters and thermistor temperature monitoring, along with a carefully designed and implemented control system, to ensure that the gradient remains below the 3°C threshold. Testing will also be performed with a known gradient, so that image correction solutions can be established.

Result: A power resistor was attached to the camera that was able to provide heat when the camera became too cold.

6.2. Risk Summary

Collected below in Table 19 are the 12 most important risks identified by the OTheRS team. Note that most of the risks directly flow from MAT-1 and the issues associated with proposed solutions described above.

RISK	*Description*	*Flowdown*	*Likelihood*	*Severity*
MAT-1	IR reflectivity	FR 1, 6	5	5
MAT-2	Manufacturing accuracy	FR 4, 8	2	2
IP-1	Tray identification	FR 1,6	4	4
IP-2	Image stitching	FR 1, 6	2	4
CTRL-1	Control loop open	FR 5	2	2
CTRL-2	Control failure	FR 2, 7	1	5
ELEC-1	Static discharge	FR 3	3	5
TEST-1	Coating/Material	FR 1, 6	5	2
TEST-2	Fogging at low T	FR 6	2	3
THERM-1	Surface-to-PCB mapping	FR 6	4	5
THERM-2	Thermistor truth	FR 7	2	4
THERM-3	TID Gradient	FR 7	3	4

Table 19: Risk Summary Table

6.3. Risk Matrix

Figures 96 and 97 below are useful for comparison of before and after mitigation of expected project risks. The goal of OTheRS was to reduce the likelihood of these risks as much as possible - in most cases, the severity of the issue could not be reduced due to their nature critical in determining project success.

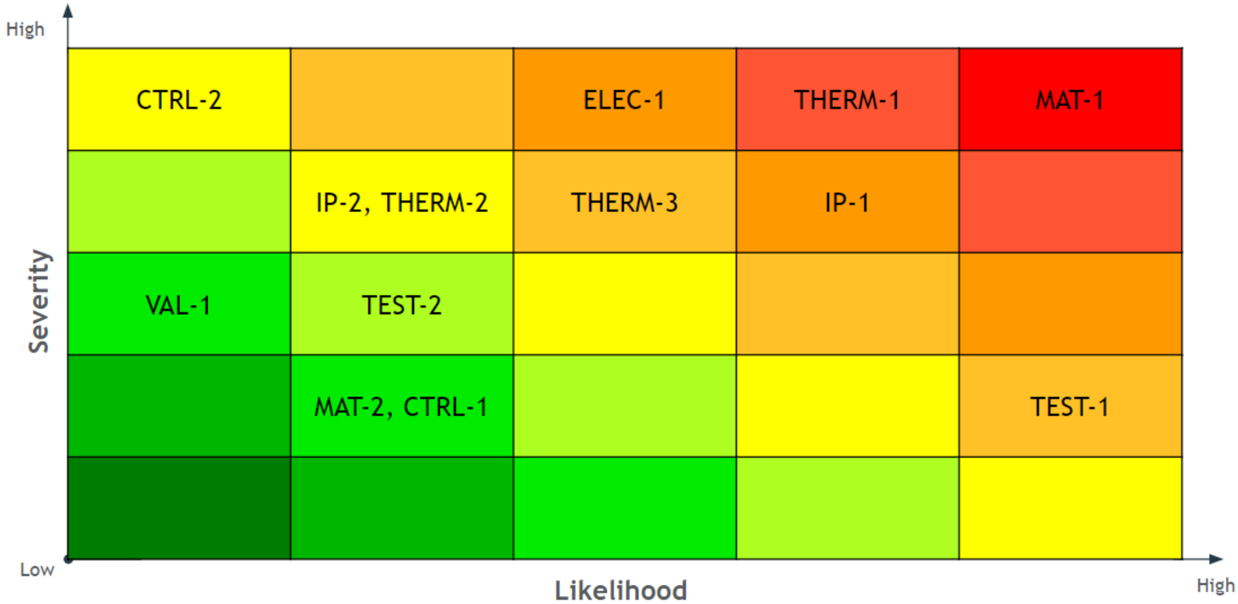


Figure 96: Risk Matrix Before Mitigation

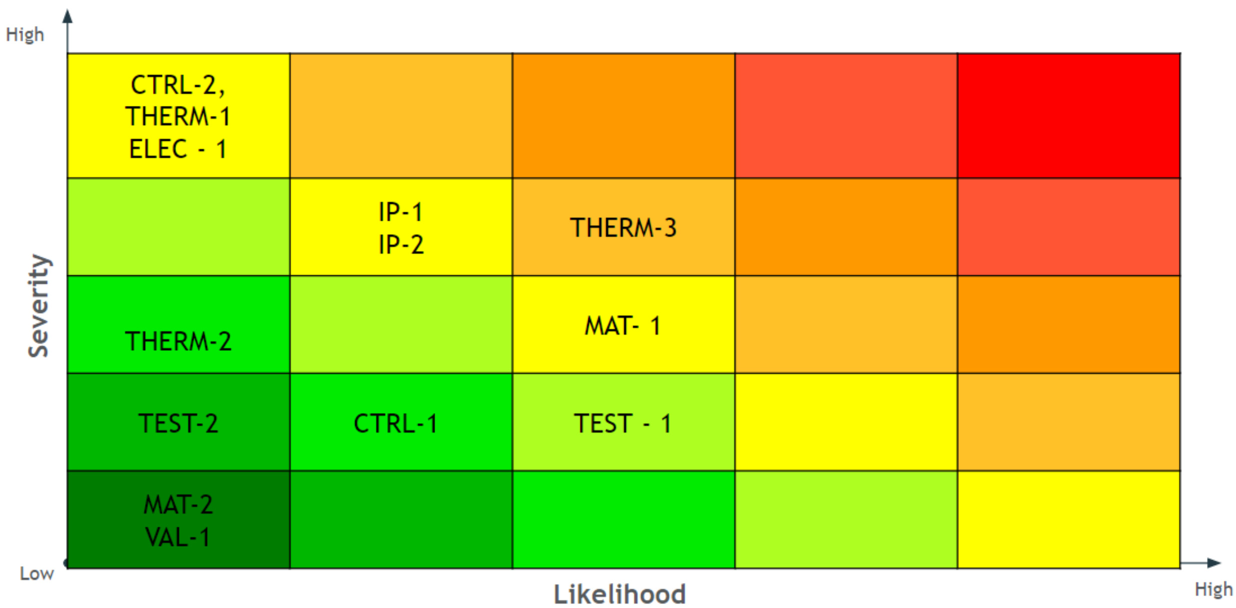


Figure 97: Risk Matrix After Mitigation

7. Project Planning

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7.1. Team Organization

The team organization structure above shows a basic leadership breakdown with the Project Manager and Systems Engineer overseeing various system leads. Although these lead roles require unique skills sets, the nature of the OTheRS sub-systems requires that the leads work closely together. The Manufacturing lead is responsible for structural design in CAD as well as tool path generation and machining. There are also several members that aid in the completion of these tasks. The Thermal lead is in charge of designing and running thermal models that will be used to validate the test bed design as well as guide development based on thermal concerns. The Controls lead guides the design of the control systems in the OTheRS project. In this case there are three distinct sub-systems that require control and are all overseen by the controls lead although there will also be contributions by other members. The safety lead is responsible for reviewing test plans for compliance with safety protocols and handling of sensitive components as well as other safety considerations. The software lead guides the development of the Image Processing modules while taking into consideration processing power requirements and challenges associated with camera placement. The Finance lead works with all members to assimilate a comprehensive cost plan for all sub-systems and tracks and reports projected cost concerns. The Electronics lead provides support for all sub-systems and will facilitate the design of all supporting electronics for each sub-system. Finally, the systems engineer and project manager work closely together to plan and manage all project elements. The systems lead works with all leads to develop project requirements and ensure sub-system integration considerations have been taken into account. The project manager works with all members to create a project structure to work within as well as breaking down and scheduling work packages and testing plans. Additionally, the project manager works with leads to ensure sub-system designs fall within the scope of the project in terms of cost, complexity, and scheduling.

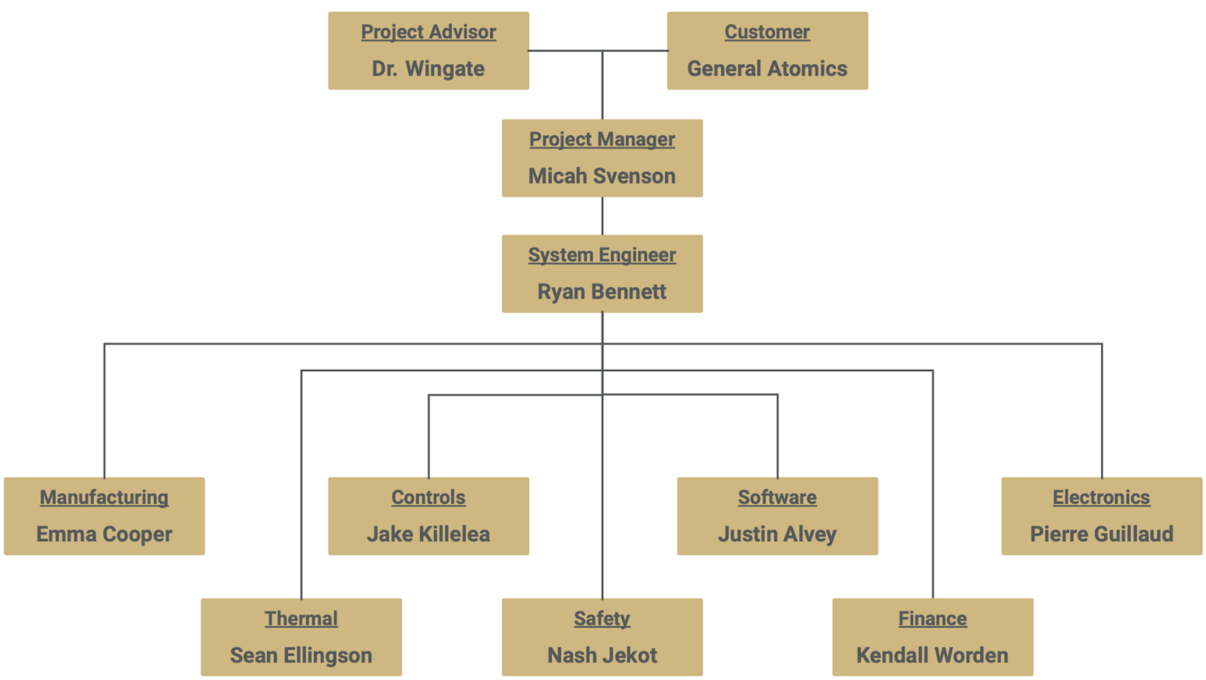

Figure 98: Team Organization Chart

7.2. Work Break Down Structure

The Work is broken down into 4 sub sections: Structure, Camera & Image Processing, Reference Data, and Control. The first three sub-system sections were developed independently and thus were broken into separate work packets. The control section of the breakdown encompassed more than one sub-system, but were closely related and were broken out into their own work packets. It is important to note however, that the over the course of the project, full stack regulation was down scoped to be simple on/off control, which was then easily added to the final steps of image processing and thus fell under the Camera & Image Processing section in it's final implementation. Before final Verification and Validation of the test bed as a whole, all sub-systems were combined in the assembly step of the structure section.

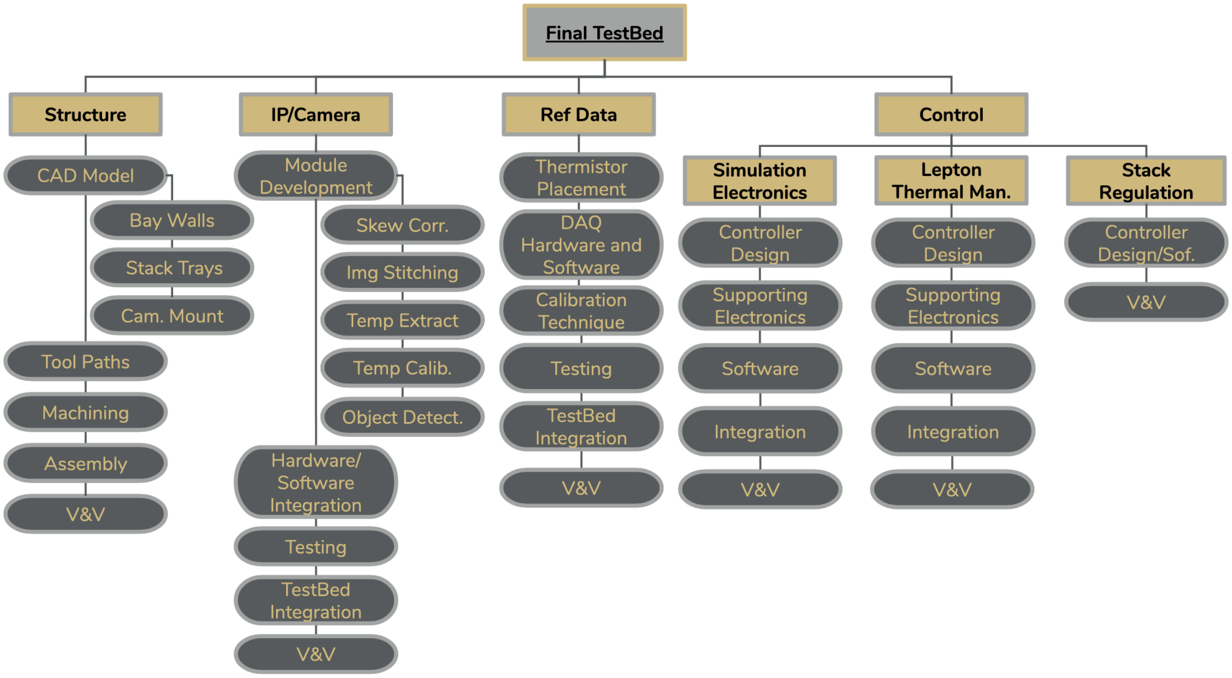

Figure 99: Project Work Breakdown Structure

7.3. Work Plan

The work plan is separated into two phases with phase one occurring during the fall semester for project design and phase two during spring semester with manufacturing and testing. The schedule for phase one was more structured and had little margin, because of rigid assignment deadlines. Because of this there was only a single version of this schedule. This differs from the phase two schedule, which was planned to be more flexible with large margins to accommodate complications in the manufacturing process. There were also some substantial design changes that required a second revision of the phase 2 schedule. All phases and revisions are summarized in the sections below.

7.3.1. Phase 1 Schedule Rev 1 (Fall Semester)

The major milestones of phase 1 included PDD, CDD, PDR, and CDR. Between these milestones, there was a large focus on research and preliminary testing that informed our final design. Specifically, an initial test bed structure was constructed in order to run several tests. The test bed and associated tests drove the critical path for all sub-systems in the first phase as is seen in Figures 100 and 101.

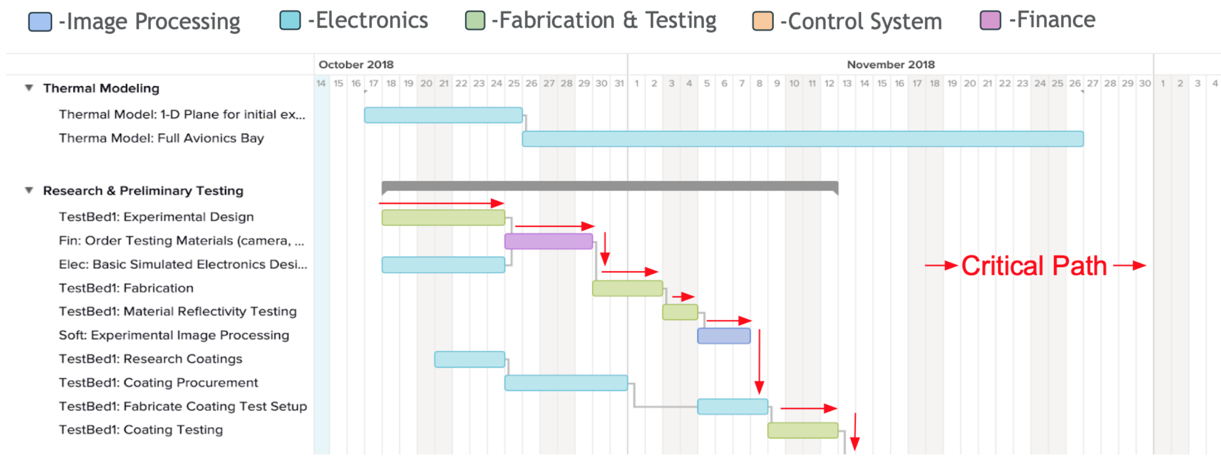

Figure 100: Phase 1 Plan Rev 1: Time Critical Project Elements

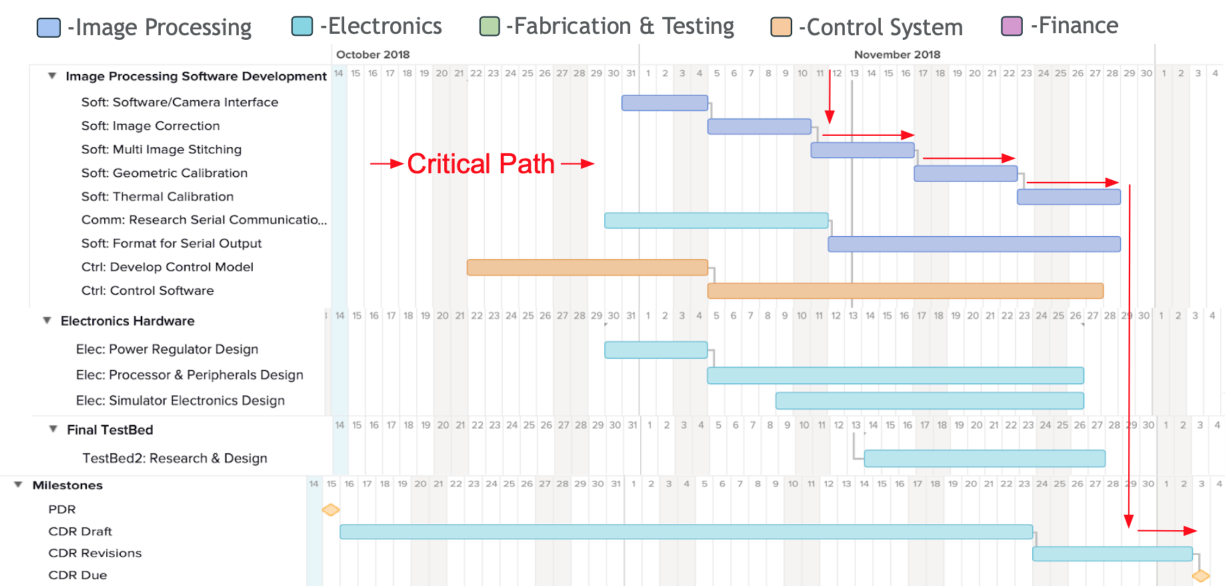

Figure 101: Phase 1 Plan Rev 1: Other Project Elements

7.3.2. Phase 2 Schedule Rev 1 (Spring Semester)

Revision 1 of the phase 2 plan was completed at the end of the Fall Semester and represents the ideal schedule, which flowed from manufacturing each sub-system to integration and testing. However, due to manufacturing complications and optimistic planning, the scheduled was revised halfway through the manufacturing phase. For example, the design of the electronics stack trays was changed in early February, which delayed the already ambitious machining schedule. Additionally, the image processing design was too complex and was significantly down-scoped as development ran into dead ends, which delayed overall progress. Overall, the initial schedule underestimated manufacturing time for every sub-system, which in turn tightened the testing time frame. This was changed in the second revision of the schedule.

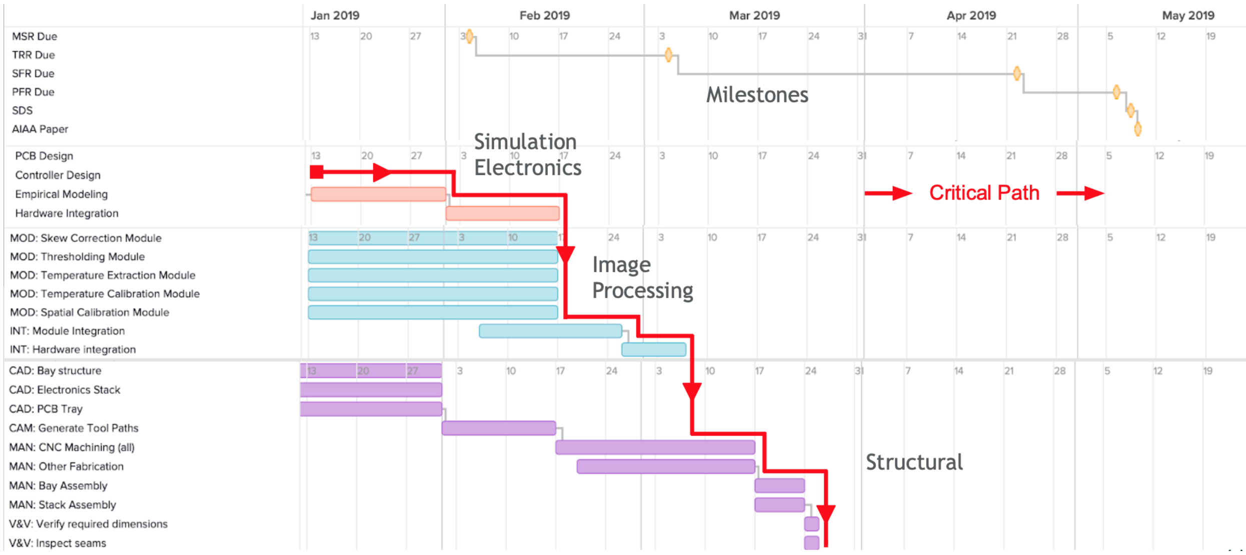

Figure 102: Phase 2 Plan Rev 1: Time Critical Project Elements

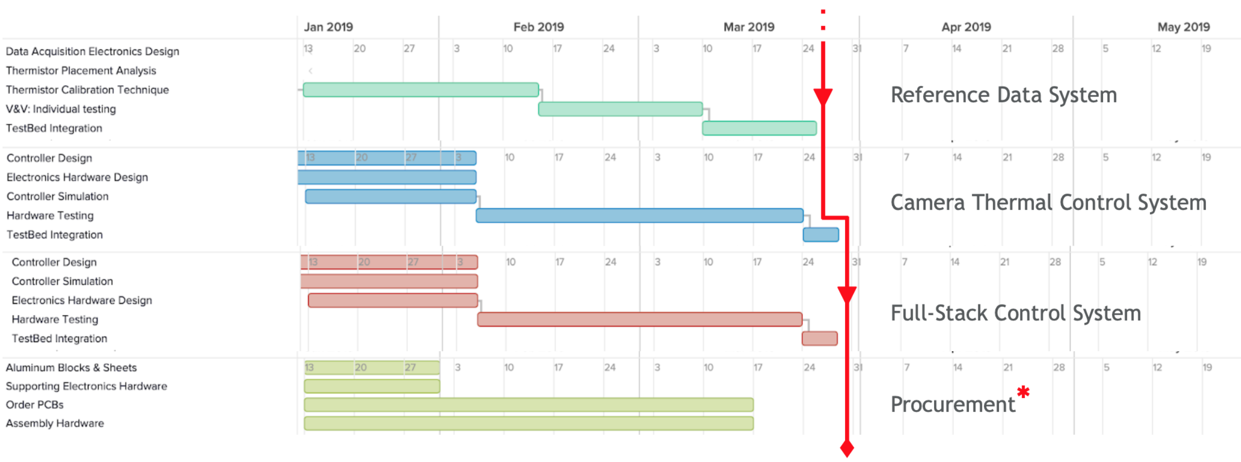

Figure 103: Phase 2 Plan Rev 1: Other Project Elements

7.3.3. *Phase 2 Schedule Rev 2 (Spring Semester)*

As stated in the previous section this revised schedule gives a more realistic time frame for the completion of manufacturing and gives a larger margin for the completion of assembly and testing. Additionally, final thermal chamber testing was pushed to the latest possible date in order to accommodate unexpected developments.

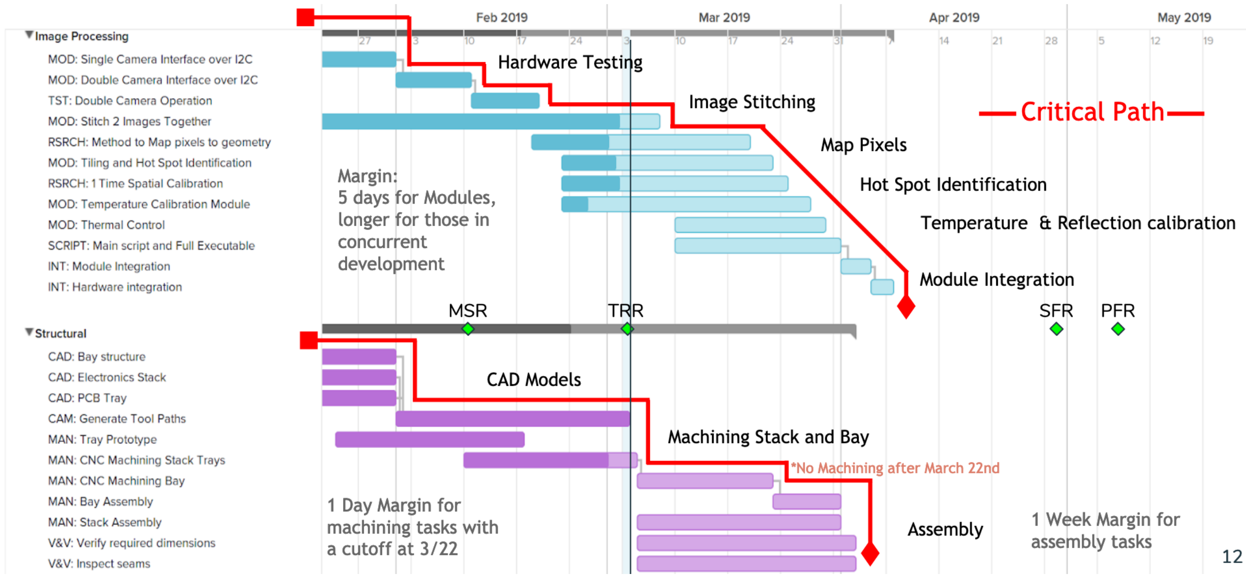

Figure 104: Phase 2 Plan Rev 2: Time Critical Project Elements

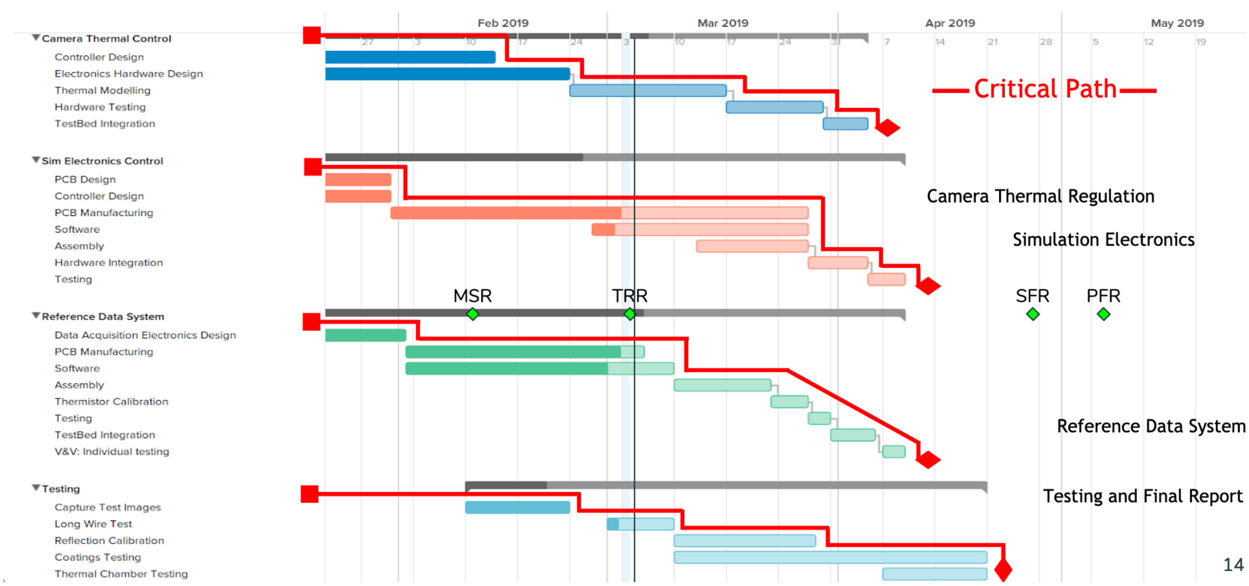

Figure 105: Phase 2 Plan Rev 2: Other Project Elements

7.3.4. Final Schedule Outcomes

Once the second revision of the final schedule was set in place, the actual progress being made was tracking much closer to planned work. However, the biggest difference was allowing a larger margin for tasks that were unfamiliar to the team. In other words, many parts of the manufacturing and especially the assembly were more difficult to execute than anticipated and required reworking in some cases, which took extra time. The lesson learned from this is to allow a larger margin for tasks that have never been done before because it is difficult to anticipate all complications that will arise and the time needed to fix them.

In the end the manufacturing and assembly phase was finished in time for the final thermal chamber testing at General Atomics, but it was very tight. Final testing required a large number of hours as a team, but was also finished in time for the SFR presentation. However, this extremely tight schedule left very little time for comprehensive analysis of the data, which was only partially completed by SFR, but was complete for this PFR report.

Overall, more testing, analysis, and tweaking of the system based on error analysis would have produced more confident results, but given the time frame the results obtained were a provided a solid baseline for future research and development of an Optical Thermal Regulation System.

7.4. Cost Plan

The figure below shows estimated project costs vs. actual project costs. With the estimate being only $1.87 off our actual costs. However, this occurred only because we came in under budget on our structural costs due to a design change that used less material. The Reference data system and simulation electronics system categories were over spent $40-$100 dollars due to unexpected costs. In particular, all the cables connecting the arduino's and raspberry pi to the computer as well as the usb hub were forgotten when testing at General Atomics in Denver. This required purchasing a new set of cables for around $90. Fortunately, however, the budget overall was balanced to be very close to our initial projected costs.

Finally, the table on the next page shows an itemized list of our project costs.

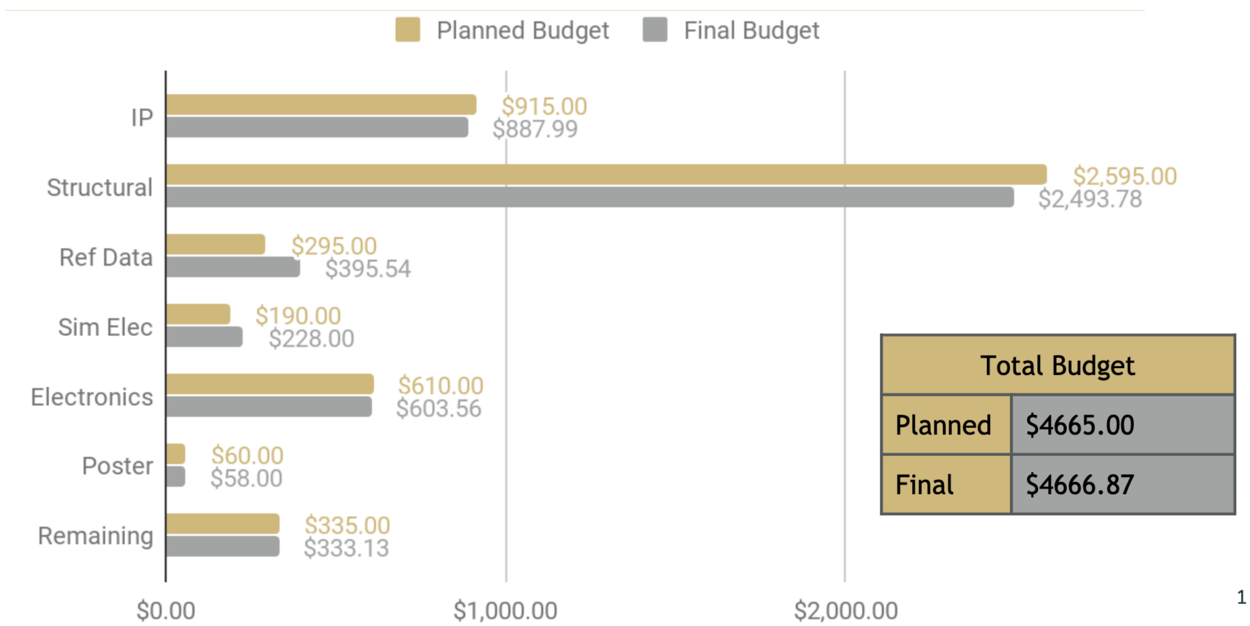

Figure 106: Planned Project Cost vs. Actual Project Cost

Final Cost Plan					
Sub-System	Part	Unit Price	Shipping	Qty	Total
IP/Camera	FLIR Lepton 3.5	$259.00	$8.00	3	$785.00
	Lepton 3.5 Breakout	$0.00	$0.00	2	$0.00
	High Emmisivity Stickers	$53.00	$9.99	1	$62.99
	Raspberry Pi 3b	$40.00	$0.00	1	$40.00
Structural	Offset Plate	$100.01	$0.00	1	$100.01
	Lid	$20.72	$0.00	1	$20.72
	4 Removable Plates	$25.26	$6.43	4	$107.47
	.08" thick Aluminum	$13.03	$18.83	1	$31.86
	McGuckins Emma 3/11	$24.60	$0.00	1	$24.60
	6061 .08" thick Aluminum with ASAP Shipping	$13.03	$33.11	1	$46.14
	McGuckins Emma 3/11	$20.43	$0.00	1	$20.43
	Aluminum 6061-T6 Plates .04"x2'x4' in (Bay)	$59.90	$40.00	10	$639.00
	Toggle Clamps	$19.99	$8.00	4	$87.96
	Aluminum 6061-T6 Plates (1/16") Thick - Cut To Size 25.5"x24" (Part Number S3063-6061)	$69.50	$40.00	3	$248.50
	Aluminum 6061-T6 Plates (1/16") Thick - Cut To Size 13.5"x25" (Part Number S3063-6061)	$69.50	$0.00	3	$208.50
	Aluminum 6061-T6 Plates (1/16") Thick - Cut To Size 24"x13.5" (Part Number S3063-6061)	$49.50	$0.00	3	$148.50
	Foam Insulation	$32.60	$0.00	1	$32.60
	AL 6061 Plate	$59.90	$0.00	2	$119.80
	AL 6061 Sheet Metal	$101.75	$0.00	3	$305.25
	M2 Tap Starting	$16.53	$0.00	2	$33.06
	M2 Tap Closed	$16.53	$0.00	2	$33.06
	18-8 Stainless Steel Slotted Flat Head Screws, M2 x 0.4 mm Thread, 10 mm Long	$7.79	$0.00	1	$7.79
	Paper Tape	$9.89	$0.00	1	$9.89
	Threaded Rod 40x6 H44815E	$1.08	$0.00	10	$10.80
	Nut Hex H140009E	$0.08	$0.00	20	$1.62
	MS Metric Phil Pan M2X12 H4307E	$0.30	$0.00	32	$9.50
	MS Metric Phil Pan M2X8 H4306E	$0.24	$0.00	19	$4.62
	6061 aluminum 1/2" diameter	$2.66	$0.00	2	$5.32
	6061 aluminum sheet .08" thick, 2"x48"	$13.03	$0.00	2	$26.06
	Corner Mount Latch	$22.45	$0.00	4	$89.80
	6061 90 Degree Angle	$2.12	$0.00	1	$2.12
	5/16" Aluminum ASAP Shipping	$65.09	$22.27	1	$87.36
	Thermal Grease	$14.98	$0.00	1	
	Epoxy	$26.07	$0.00	1	
	April 2 6061 McMaster Carr	$2.28	$29.16	1	$31.44
Ref Data	Thermistors - Vishay NTCLE413	$1.39	$8.00	45	$70.55
	Screw Terminals	$0.80	$2.00	10	$10.00
	ADC - ADC128D818	$4.68	$5.00	3	$19.04
	Sparkfun RedBoard	$19.95	$5.00	1	$24.95
	Resistors - CRGCQ0402F18K	$0.10	$0.00	80	$8.00
	Custom PCB	$10.00	$5.00	3	$35.00
Sim Elec	Custom PCB	$8.00	$5.00	10	$85.00
	Power Resistor - 71-RS01025R00FE73	$1.19	$0.00	100	$119.00
	Power Driver Board	$8.00	$0.00	3	$24.00
	D-Type Connectors	$0.00	$0.00	0	$0.00
	Buck Converter	$6.99	$0.00	2	$13.98
	Wiring - 12 Gauge	$15.95	$5.00	2	$36.90
	D-type Connector	$1.57	$0.00	0	$0.00
	AC Adapter	$19.99	$0.00	1	$19.99
	USB for Arduino	$34.99	$0.00	1	$34.99
	MOSFET 60V	$0.71	$8.00	10	$15.05
	IC LED DRIVER	$2.33	$0.00	3	$6.99
	MOSFET 55V	$1.08	$0.00	3	$3.24
	CAP ALUM 47UF 20% 63V RADIAL	$0.33	$0.00	4	$1.32
	TE Connectivity Amp Connectors	$1.04	$0.00	3	$3.12
	CONN HEADER R/A	$3.70	$0.00	6	$22.20
	25W Chassis Resistors	$3.08	$0.00	2	$6.16
	Thermocouple BreakOuts	$12.76	$0.00	2	$25.52
	Power Resistor Kit	$4.76	$0.00	1	$4.76
	MOSFET Transistors	$2.03	$0.00	10	$20.30
	Arduino Uno	$23.38	$7.99	2	$54.75
	A-B USB cable	$2.05	$0.00	1	$2.05
	Female Sockets Connector	$1.81	$0.00	6	$10.86
	Male Sockets Connector	$1.22	$8.99	6	$16.31
	Seeed Studio Power Management IC Development Tools	$4.50	$8.89	1	$13.39
	Monolithic Power Systems (MPS) Switching Voltage Regulators	$2.94	$0.00	1	$2.94
	JLC PCB Heaters	$8.35	$49.59	10	$133.09
	Digikey 3/10	$23.58	$0.00	1	$23.58
	Staples A to A USB	$20.99	0	1	$20.99
	USB Cables for GA testing	$90.99	0	1	$90.99
	Digikey 4/02	$20.09	0	1	$20.09

7.5. Test Plan

The flow chart below shows all the tests planned and performed from data sheet inspection to final acceptance testing. Datasheet inspection was conducted as materials and components arrived, all other testing was scheduled to occur in the first two weeks of April and had large margins that depended on the exact time that each sub-system or unit was completed. Each of the tests were geared towards requirement retirement, which is denoted by the grep diamonds in the flow chart.

Starting with Hardware/Software Testing, this section encompassed a large portion of each subsystem. First, the reference data system thermistors with the additional wiring and connectors, thermistor ADC connection to the software, and software control needed to be tested and verified before the reference data system could move forward in the test flow chart. Second, the simulation electronics system heaters and heater driver boards needed to be tested for operation, then the software to heater driver connection. Finally, the camera and image processing system was split into two different streams, which is seen in the flowchart. First, was long wire testing. This was necessary as the SPI protocol, which was used for data transfer, will fail if the wires from the camera to the PCB are too long. Second was image processing. Unit testing was completed for every module of image processing before integrating all the modules and checking the final output as well as testing software timing.

The next section of the flow chart is manufacturing of parts. The testing process included checking dimensions of the parts after they were machined, assembling components, then checking the final dimensions of the test bed against the requirements.

The final major sections of the flow chart are Lepton thermal control and communications tests. In these sections the communications between the integrated GUI and each sub-system was tested. The GUI is the main user interface that controls all aspects of final testing including control and data acquisition. Additionally, the thermal regulation system for the Lepton cameras was tested for operation individually.

Finally, the previous testing flows end with reflection calibration, test bed integration, and final acceptance testing. Some aspects of final acceptance testing were conducted offsite at General Atomics in Englewood. A thermal chamber was used to test the system at its operational bounds, while room temperature tests were conducted on campus.

It is important to note, that in the final implementation of the test bed, reflection calibration occurred after test bed integration. As such, the reflection calibration box should be switched with the test bed integration box and the control and communications verification should flow into test bed integration.

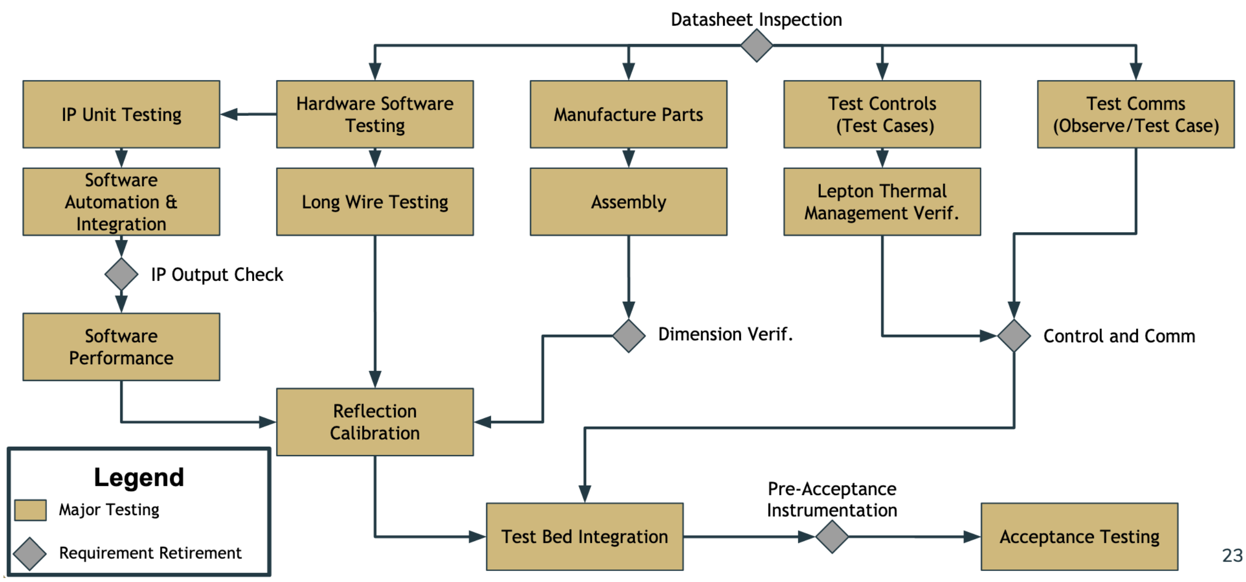

Figure 107: Project Test Plan Flow Chart

8. Lessons Learned

Author: Nash Jekot, Ryan Bennett, Kendall Worden, Micah Svenson, Emma Cooper

8.1. Teamwork & Team Dynamics

The way the team operated constantly evolved over the course of the project. The first few weeks of the project were slower and more disorganized before team roles were selected. After this, the team worked more efficiently and spent meeting times brainstorming and developing the design as a group. Outside of meetings, the work was mostly individual and there was little communication. In the second semester, as the project entered the manufacturing phase, meetings with the entire team were not as productive. Thus the meeting style switched to status updates before splitting into smaller subsystem groups. This allowed manufacturing and design work to be more efficient, but communication between sub teams became more difficult and resulted in complications with system integration. Status updates at full team meetings were not sufficient to convey detailed progress of a subsystem to other subsystem leads. It would have been beneficial to have a series of meetings focusing on each subsystem where other team leads could raise questions about the direction of the system development.

The OTheRS team dynamics were unique because of the way the team was formed, having been voted off of other teams to create this team, there was an immediate sense of camaraderie that helped boost the team in the beginning. However, there were strains at times, and lack of communication made many aspects of the project difficult. In the future, focusing on clear and frequent communication would have improved many situations. For example, clearer communication about how each team member contributes to presentations and documents would have made the team more efficient overall and less strained as deadlines approached. What instead happened, was on the fly communication and division of work especially near the deadline.

8.2. Software Development

Never underestimate software. For the half of this project, only one person handled the software. This is fine when the software development is running smoothly, however, can become detrimental if software falls behind. A solution to this situation is having a couple people on the team that are able to be moved to software as needed in order to make deadline.

8.3. Electrical Design

We learned pretty quickly that the electronics can be somewhat finicky. The cameras were inconsistent, crashed a lot, and were low quality to begin with. The lesson learned was to order hardware as soon as possible, in our case, we were able to send back a defective camera because we ordered it early enough. It was also surprising just how overarching and critical the electronic section is. In a sense, everything is tied to electronics. The other sections require it in order to test. This is another reason to work hard and early on electronics because one cannot test software without the corresponding hardware. The reference data system required the functionality of the ADC's and the software required the Raspberry pi. We also learned that a logic analyzer can be particularly helpful for hardware issues. In our case, the RS232 communication was slowed down because of a defective cable on the hardware end. This was caught earlier enough that we were able to buy another cable without slowing down the project.

8.4. Mechanical Design & Manufacturing

Try to keep manufacturing ahead of schedule when possible. In the case of this project, there was an error in machining that made the electronics stack too large for the outer avionics bay. Fortunately, there was just enough time to implement a fix, if this even had occurred one or two weeks later, the project would not have been able to be finished and tested in all likelihood. Also, talk frequently with the head of the machine shop as they will provide useful advice and suggestions. When manufacturing, things break. This is okay, don't beat yourself up about it.

8.5. Integration & Testing

Time is everything. In order to present results at SFR, much of the testing for the OTheRS system occurred over the span of a couple days shortly before the SFR deadline. These tests took a couple hours each since the test bed had to be near room temperature to start a new test. Thankfully, the system integration was rather seamless besides the difficulty in getting the two cameras to be operational at the same time. If there were more integration issues, the testing would likely not have been complete before SFR because of the tight testing window. A major lesson learned would be to allow more time for testing.

8.6. Thermal Modeling

Thermal modeling represented a unique challenge to the OTheRS team. Thermal analysis was an area that no member on the team felt comfortable performing the required duties, at the start of the project. Through advice from the PAB and supporting student staff, it was determined that SolidWorks Simulation Professional was to be used. Early on in full model development, it was identified that interference issues resulting from poor dimensioning were the primary source of meshing errors. The more robust meshing features of ANSYS were used in an attempt to overcome this issue, to no avail. Eventually, a simplified model with exact dimensioning was used with SolidWorks to create a fully meshing model. From this point, it was identified by students that even with a variety of convection, conduction, and radiation values, wall temperatures did not seem to be rising very much. It is important to note however that at this time in April, the team had still yet to collect *any* data, making it impossible to determine analytically if the model was wrong. Following testing in April, it was determined that there was some sort of issue occurring with convection in the model. While initial research and suggestions from the PAB showed that Simulation Pro was the ideal tool for our team to use, research into the seemingly incorrect convection issues revealed a disturbing problem. Simulation Professional considers only the fluid transport of heat away from a surface, and not the resulting flow due to convection. Some deeper research into Dassault Systems (SolidWorks) documentation shows that for systems where a user expects significant airflow to be occurring, SolidWorks Flow simulation is the correct option. While Simulation Pro can provide estimates of approximate heat transport away from a body, it is wholly insufficient to provide heat transfer to the surrounding air, and thus to the surrounding bodies, via convection. Unfortunately, it was difficult to identify the source of error in the model until the last minute due to a lack of even the most basic test data to compare to. Unfamiliarity with the modeling software by faculty and student advising groups also meant that the fundamental difference in modeling capabilities between Simulations Pro and Flow Simulation went unnoticed. This issue was further exacerbated by the fact that the SolidWorks tech forum post that explained the differences between the two tool kits was not posted until December 28th, well after research into how to model the system had been performed and development plans created. In short, thermal modeling is difficult and is most accurate when each form of heat transport is modeled fully.

8.7. Advice to Seniors

Make the best of the project you get. This project was not any of our first choices, but we were able to make a project that actually ended up working. It's better to work on the project at hand rather than be angry or petty that you did not get on a project that interested you or the one with all your friends.

It's okay to make mistakes. No one is perfect and no one did a perfect job or was the perfect teammate. We are all human and the team dynamic can be pretty healthy with this perspective. Talk often to your advisors, they have real world experience and are much more knowledgeable about engineering.

Work hard, every day. Check your work. Check it again. Ask team members if the work you have done is consistent with the work they are doing, and that your work will allow them to complete their work, correctly, the first time. Itemized, systems oriented thought processes by all members of the team can allow for oversights and design errors to be identified before they become an issue. For every team, a significant portion of time is wasted because of some kind of communication error. For manufacturing, always provide your team with engineering drawings to covey information in discussions about parts and tasks.

9. Conclusion and Recommendations

Author: Micah Svenson, Ryan Bennett, Kendall Worden

The goal of this project was not only to quantify the differences between a thermal camera and contact thermal sensors in a satellite thermal regulation system, but also to provide a recommendation on the feasibility of such a system with future development. The test results show that with error filtering, the measurement error between the internal electronics stack temperature measured by the thermistors and the external surface temperature measured by the Lepton cameras is at a maximum, 11.18°C with an average error of 6.455°C. Since the cameras have a temperature accuracy of ± 5°C, this error could be decreased even further with the use of more accurate, export controlled cameras. The method used for this error filtering was a simple fix using a threshold while more complex and accurate methods could be used. These methods could take into account previous time steps of data or the neighboring pixels prior to the tile temperature being computed through a simple average, or more advanced techniques such as pixel weighting could be used to take a weighted average in locations where temperature values are known to be indicative of internal component temperatures. Another method used to mitigate the error of the Leptons was to add coatings to the surface under test. This method did not affect the range of the errors but did lower both the mean and standard deviation of the error distribution. With a combination of anti-reflective coatings, error filtering, and more reliable cameras, these errors would likely be greatly reduced. The caveat to the data collected with this methodology is that the thermal contact resistance between the aluminum plate and construction paper is unknown. The team was unable to test both methods in a single test, but future work on the topic and project can explore the effect of both methods in place. It is hypothesized that the combination will bring the overall error distribution extremely close to the desired error tolerance, 10°C, for commanding the thermal control of the stack with a lower mean, standard deviation, and range. These are all desirable characteristics and make the distribution more compact and potentially normal and more predictable.

If it is assumed that electronics operating in a satellite adhere to either the Industrial or Military standard operating temperature ranges of -40°C to 85°C and -55°C to 125°C, respectively, then the use of an OTheRS system would have the ability to sense temperatures within the range of -30°C to 60°C and provide enough control to keep internal avionics electronics operational. Even with the inaccuracies associated with the FLIR Lepton the current OTheRS system could keep a satellite within the previously mentioned operational range if a more successful heating system for the camera is used than the one used in testing and the parts are protected in a vacuum environment.

In a satellite mission, if it is sufficient to keep the stack electronics within a wide operational range and thermal regulation commands are not sent at the bounds of this operational range, then an Optical Thermal Regulation System would be a feasible option. It also may be able to provide actionable data for needs on the spacecraft with further development. However, current OTheRS system components are not graded for space flight. Further development and improvement on the system is needed in order for it do be a feasible space ready system.

9.1. Future Work

Overall, this project was successful in studying the feasibility of thermal imaging devices for thermal control at a basic level, namely providing a 2D temperature profile of a surface with known geometry. With this, the project has determined some functionality for the thermal control in a mock spacecraft, although the errors between the imaging device and the actual temperature were too significant to claim accurate thermal measurement. Thus, the goal of a proof feasibility is partially successful. The partial success has laid the groundwork for other projects and research. For example, a more reliable, high fidelity thermal camera, would be beneficial to the system accuracy both in terms of pixel count *and* resolution accuracy. Along with an improved camera, some improvements to the software subsystem could be made to take advantage of the overlap of the FOV of the cameras along with the enhanced error filtering discussed in previous sections. The current image processing design does not allow for the overlap to be utilized but is instead thrown out. Improvements to the data could use this overlap to smooth the split between the left and right images seen in testing and increase the number of pixels per tile when computing the average tile temperature. This may have been an oversight by the team but is left as an area to explore with future work on the topic. Considering further development of this image stitching, it is likely possible that by imaging multiple sides of the stack, advanced predictive models can be developed and applied to determine interior 3D heat profiles of avionics components, as opposed to the rudimentary 2-D profile the OTheRS team was able to present here.

During these tests, it was also shown that the camera regulation system functioned but not sufficiently enough to keep the cameras operable, leading to a partial failure of requirements and levels of success in the project. This results mostly from a lack of testing, as the team was unable to model the physical setup to ensure that sufficient heat transfer would occur from the heater to the camera in low-temperature conditions, and adjust the physical placement of the heater if such transfer was not occurring. Increasing the number of monitoring points on the sensor along with the heaters for the component would allow for a more accurate thermal profile around the camera to be determined, which could then be compared to a thermal model for relative accuracy in the ambient environment. Along the same thought process, increasing the number of reference data points in the structure could improve some aspects of the data and models. These points would not necessarily be mounted to the surface but for measuring the temperature of the heating component or the ambient environment. Measuring the component temperature could allow for quantifying the effect of distance from the wall and how thermal profiles propagate to the wall under test. This was ruled out of scope for this project but could become a possibility if this step was implemented. Monitoring the ambient environment within the bay would allow for improved coefficients in modeling and could provide a more accurate model of the system, namely in the sense that convection coefficient differ greatly from the surface of the heater to the surface of the aluminum, causing non-linear heat transfer to occur. These increased truth points do come with a tradeoff of increasing wiring and harnessing complexity, which presented significant technical challenge to the team and are the driving force behind this project in the first place.

Reflection of heat throughout the test bed was also a problem that was mitigated through the use of simple coatings. These coatings decreased the error between the camera system and the IP system, however if complex coatings were used throughout testing these errors could be decreased even more. These were ruled out of budget for the project due to the limited available budget. The application of these coatings by the team was also ruled out of scope due to the desired precision and team's inexperience with their application. Future work on the topic could take advantage of these available methods as a method for driving down the system error but requires a significant budget. Error was likely also introduced into the reference data system by using Kapton tape to secure the thermistors to the interior surface of the stack. While Kapton tape is actually the industry standard for doing so, it has a significantly different emissivity value than bare aluminum, which was not modeled.

Error between the camera system and reference data system can also be attributed due to how the test bed was fabricated, showing area for improvement in the structural aspects of the project. Gaps in the bay, along with the design decision to use a removable face to test different coatings, left space between hardware components introducing sources of error for the heat transfer within the system. An air gap between the removable face and the actual electronics stack could both account for differences in thermal data read from the camera and reference data system. In a real satellite, a removable face would not be used and gaps in the avionics bay and stack would not be prevalent, potentially decreasing the overall error between the camera and reference data systems. The camera mounts in the test bed were also not fully secured, allowing the cameras to rotate slightly. This caused errors due to the cameras not being perfectly calibrated for each test and introducing slight variations to the skew angles and positioning of the sensors. In a satellite application this could also be mitigated since the cameras would not have to be removed and remounted multiple times which they had to be during testing. With secure mounting in place, the system accuracy may be improved. Many of the structural improvements were due to design decisions as an effort to ensure a variable parameter test setup but future work may not desire the capability to change as many variables.

Electrical improvements could also be made to the system. When the team was completing the instrumentation in the thermal chamber, both cameras were unresponsive when the sealing plug for the wiring access port was placed. This could have been due to interference from the chamber. While testing at the customer, wiring shielding was also recommended by engineers assisting the team to protect from interference while the chamber was operational. Another wiring issue with the project was with the wiring lengths used for the thermal imaging devices. The length of the wire limited the team to an upper bound before signal integrity became an issue. It is unlikely this caused the unreliability with the cameras, but improvement could be made to this with future work on the project.

10. Individual Report Contributions

10.1. Justin Alvey

Final Design

- 3.2.2 - Thermal Camera & Image Processing
- Corresponding flowchart.

- Wrote this section.

Manufacturing - 4.3 Software

- 4.3.2 - Developing stitch.py
- 4.3.3 - Developing tile.py
- 4.3.4 - Developing control.py
- 4.3.5 - Developing serial.py
- 4.3.6 - Developing main.sh
- All associated flowcharts.

- Wrote these sections.

Verification & Validation

- 5.1.3.1 - Capture Frequency
- 5.1.3.2 - Overlapping Field of View
- 5.1.3.3 - Object Identification
- 5.1.3.4 - Data Extraction

- Wrote and rewrote these sections.

10.2. Emma Cooper

Design

- Final Design

Manufacturing

- Mechanical

Lessons Learned

- Mechanical Design & Manufacturing

Appendix

- Final Test Bed CAD Drawings

I made small revisions to other sections while going through the document.

10.3. Pierre Guillaud

Objectives

- Functional Block Diagram

Design

- Various trade studies
- Reference Data System
- System Integration

Conclusions and Recommendations

- Editing

10.4. Ryan Bennett

Verification & Validation

- Design and Functional Requirement Validation.
- Levels of Success Validation
- Testing Results Write up
- Testing Results Error Histograms
- Editing and Formatting

Risk Assessment & Mitigation

- Editing and Formatting

Conclusions and Recommendations

- Future Work
- Editing and Formatting

Along with the above list, I have made minor edits in other sections when reading through the document.

10.5. Sean Ellingson

Verfication & Validation

- Model Validation
- General proofing for flow and grammar

Conclusions and Recommendations

- Future Work
- Editing for content and conciseness

Lessons Learned

- Thermal Modeling
- Advice to Seniors

With the above, I reviewed the entire document for consistency of terminology, spelling/grammatical errors, and ensured that figures and tables were discussed in the body of the document.

10.6. Jacob Killelea

Design

- 3.2.3 - Capturing Still Images from the Leptons
- 3.2.4 - Electrical Design Software
- 3.2.6 - Simulation Electronics
- 3.2.7 - Raspberry Pi Breakout Board

Manufacturing

- 4.2.1 - Printed Circuit Boards
- 4.2.2 - PCB Assembly
- 4.3.1 - Developing raw_capture

10.7. Micah Svenson

Project Planning

- Team Organization Structure and Writing
- Work Breakdown Structure Writing
- Work Plan and Writing
- Cost Plan Writing
- Test Plan Writing

Project Purpose

- All Content

Objectives

- Project Objectives
- CONOPS

Risk Assessment & Mitigation

- Additions and rewrites in various sections.

Verification & Validation

- All tiled results plots
- All error per tile plots
- Minor edits

Conclusion and Recommendations

- Conclusion and Recommendations

10.8. Nash Jekot

Objectives

- Porting from FFR
- updated and edited since FFR

Design

- Porting from FFR
- updated and edited since FFR
- Various addition to the final design section
- Miscellaneous Designs

Risk Assessment

- Porting from FFR
- updated and edited since FFR
- Added result subsections to give context to how risks played out throughout the project.

Lesson Learned

- All except for thermal model lesson learned

10.9. Kendall Worden

Verification & Validation

- DR's, FR's. Errors, results, and setup for testing results, Test setup for Lower Bound, Upper Bound. Levels of Success write up
- Minor edits

Risk Assessment & Mitigation

- minor edits in various sections.

Conclusions and Recommendations

- Future Work
- Editing and Formatting

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11. Appendix

Author: Emma Cooper, Ryan Bennett

11.1. Final Test Bed CAD Drawings

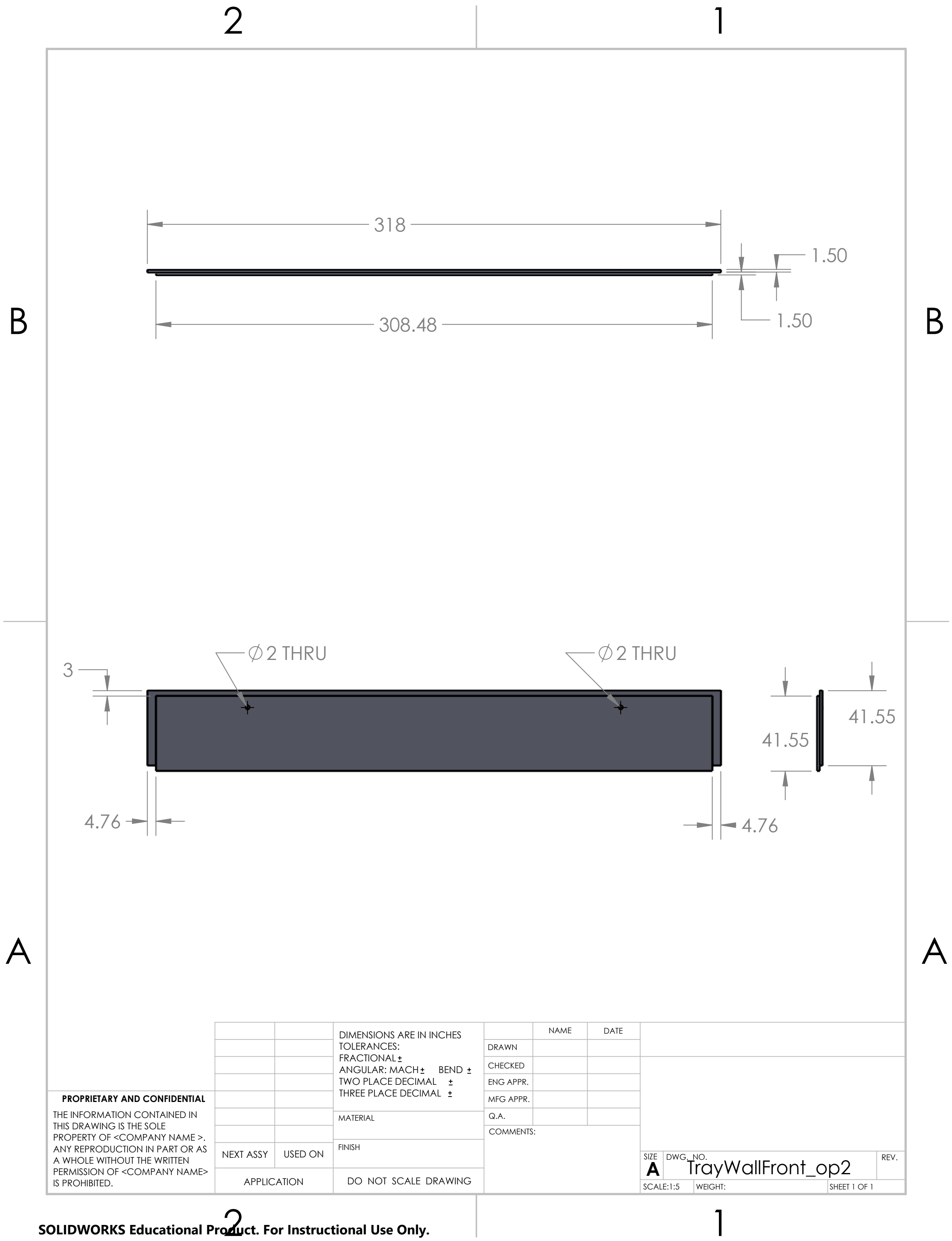

Figure 108: SolidWorks drawing of front tray wall

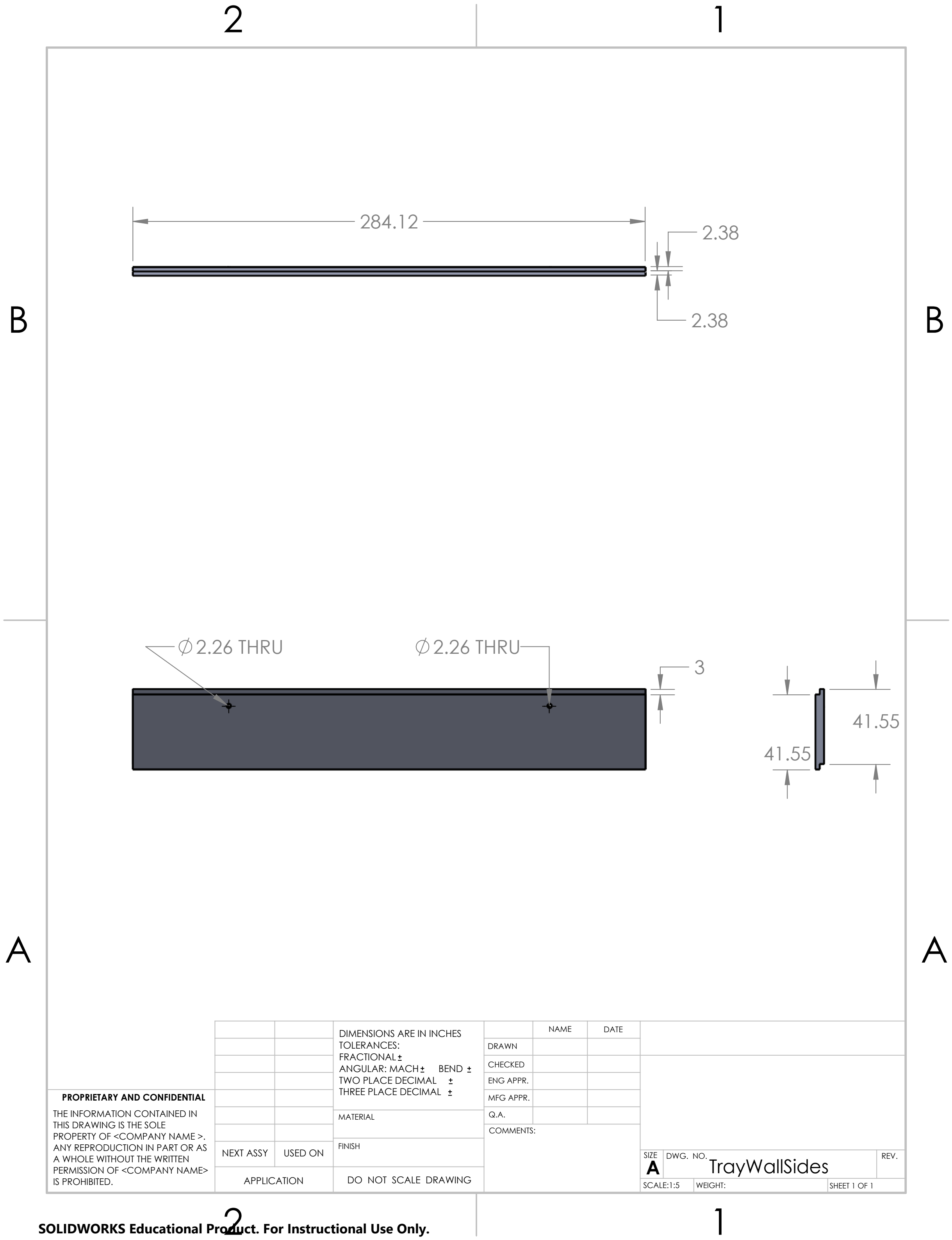

Figure 109: SolidWorks drawing of side tray wall

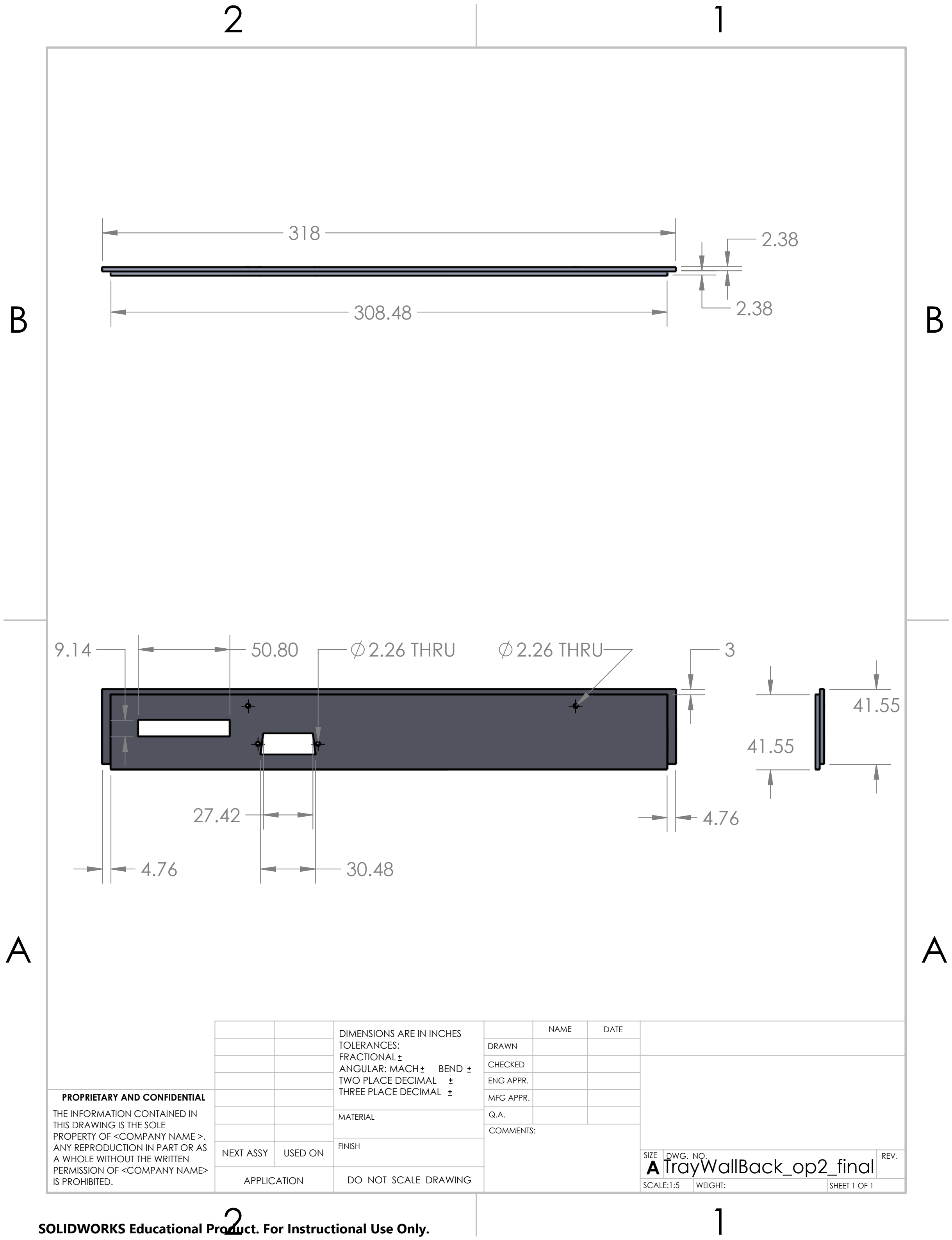

Figure 110: SolidWorks drawing of back tray wall

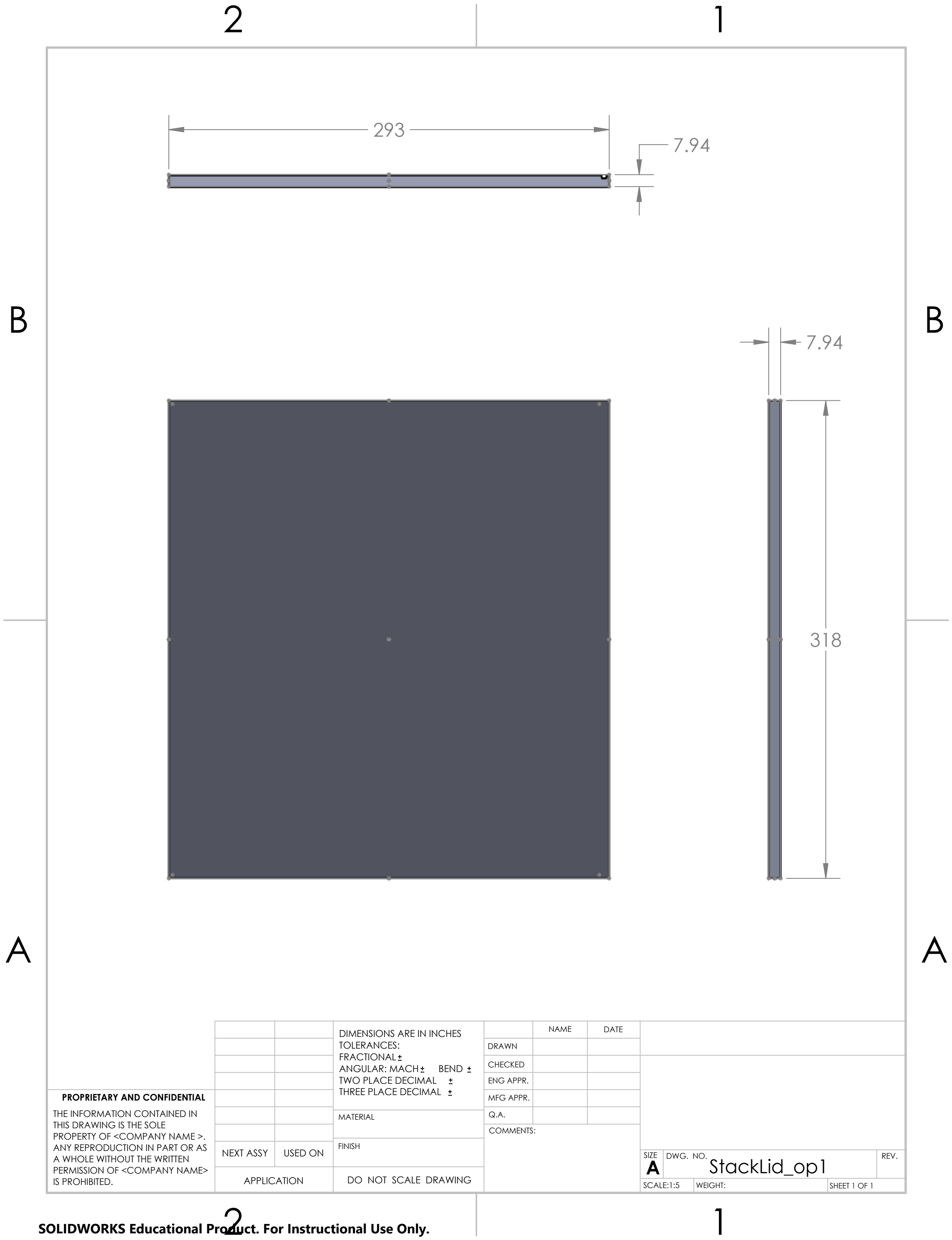

Figure 111: SolidWorks drawing of lid to electronics stack

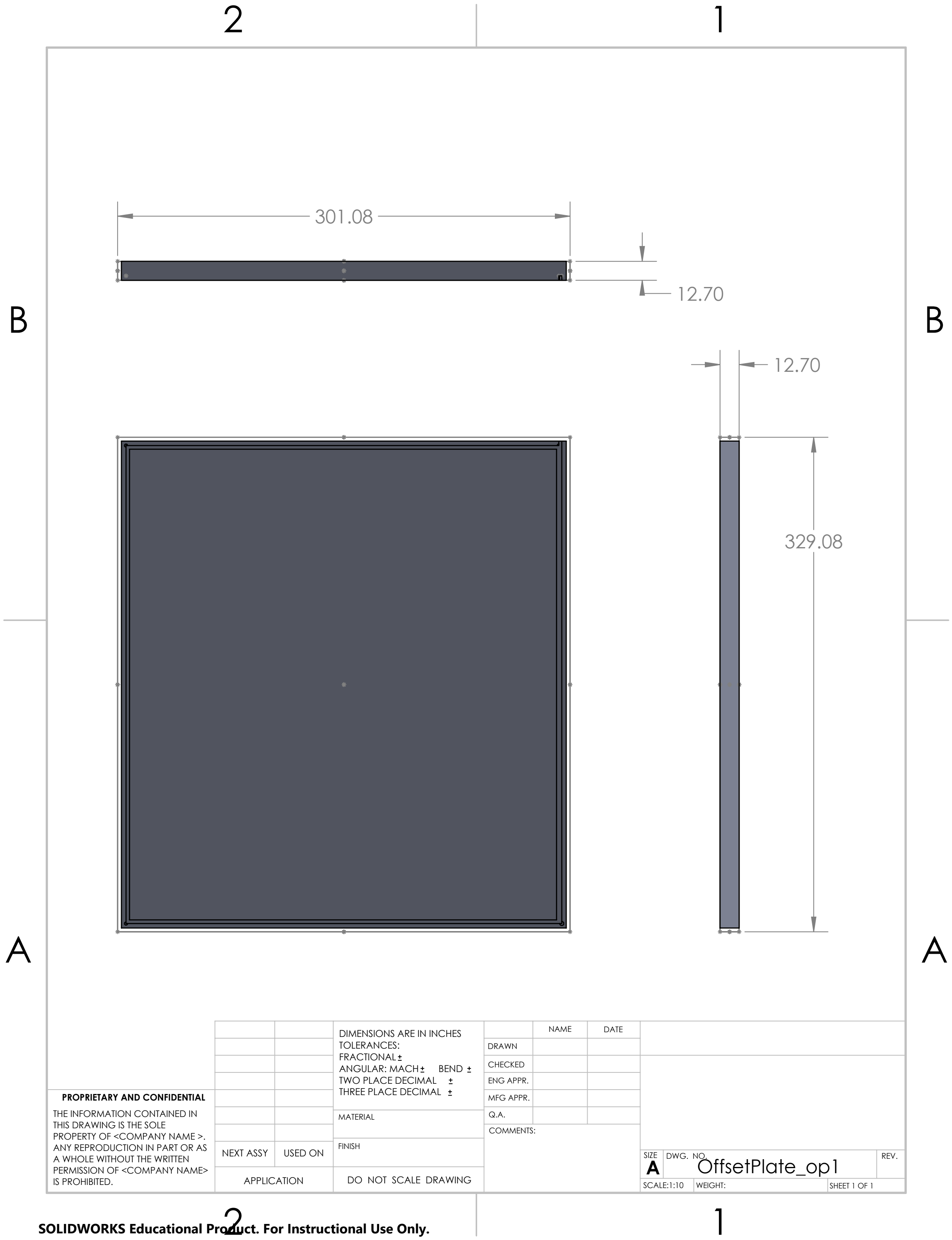

Figure 112: SolidWorks drawing of offset plate for electronics stack

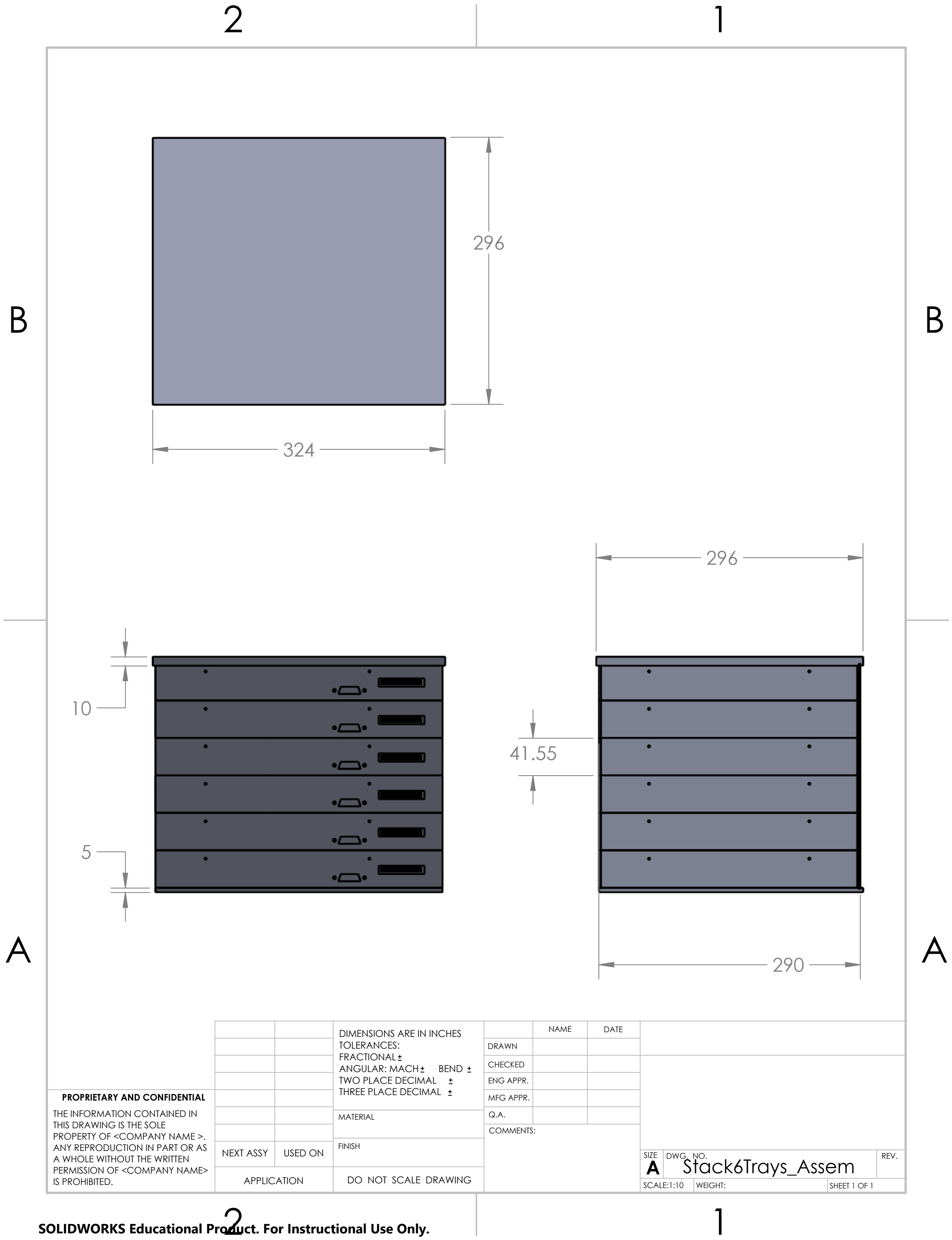

Figure 113: SolidWorks drawing of electronics stack

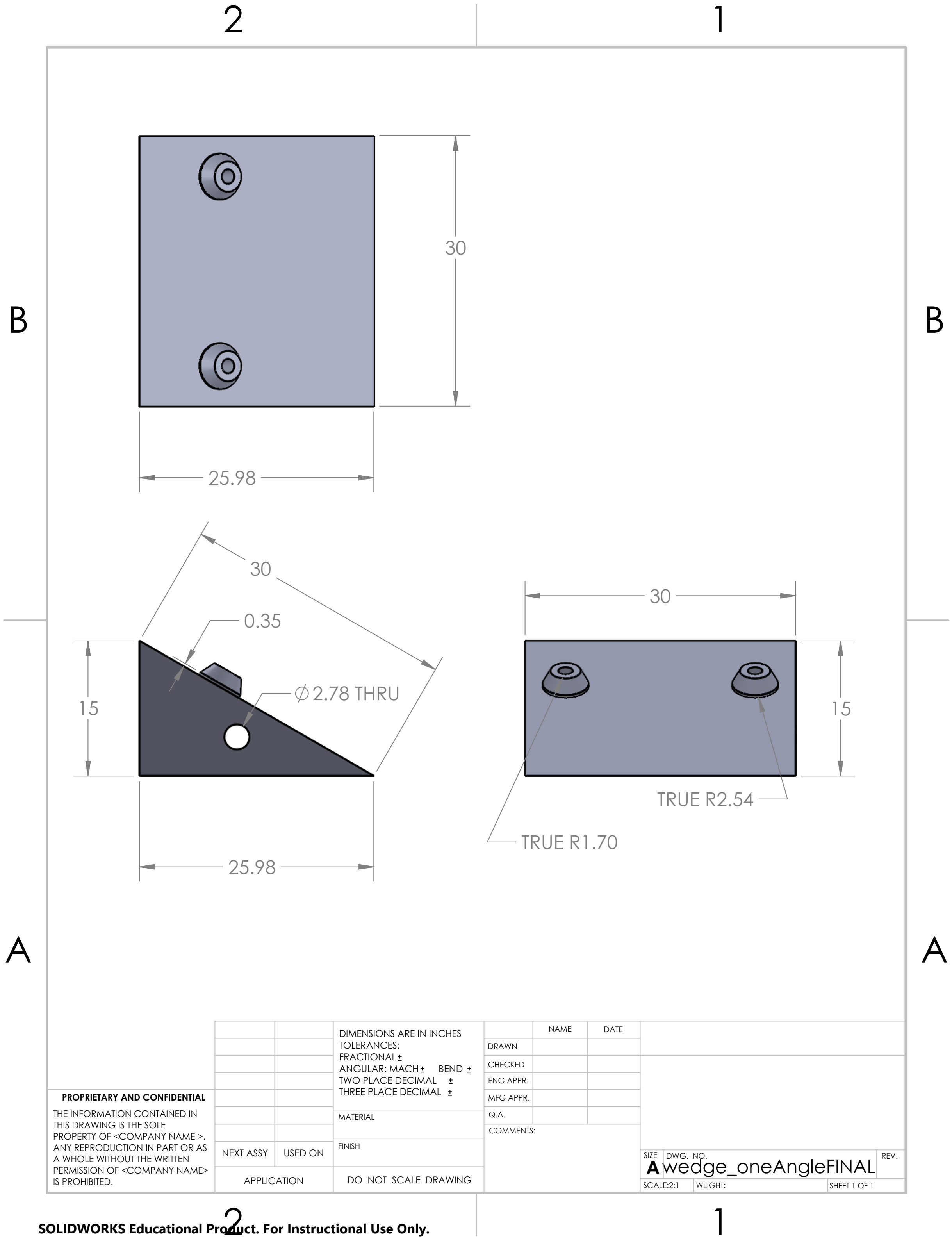

Figure 114: SolidWorks drawing of camera mount wedge

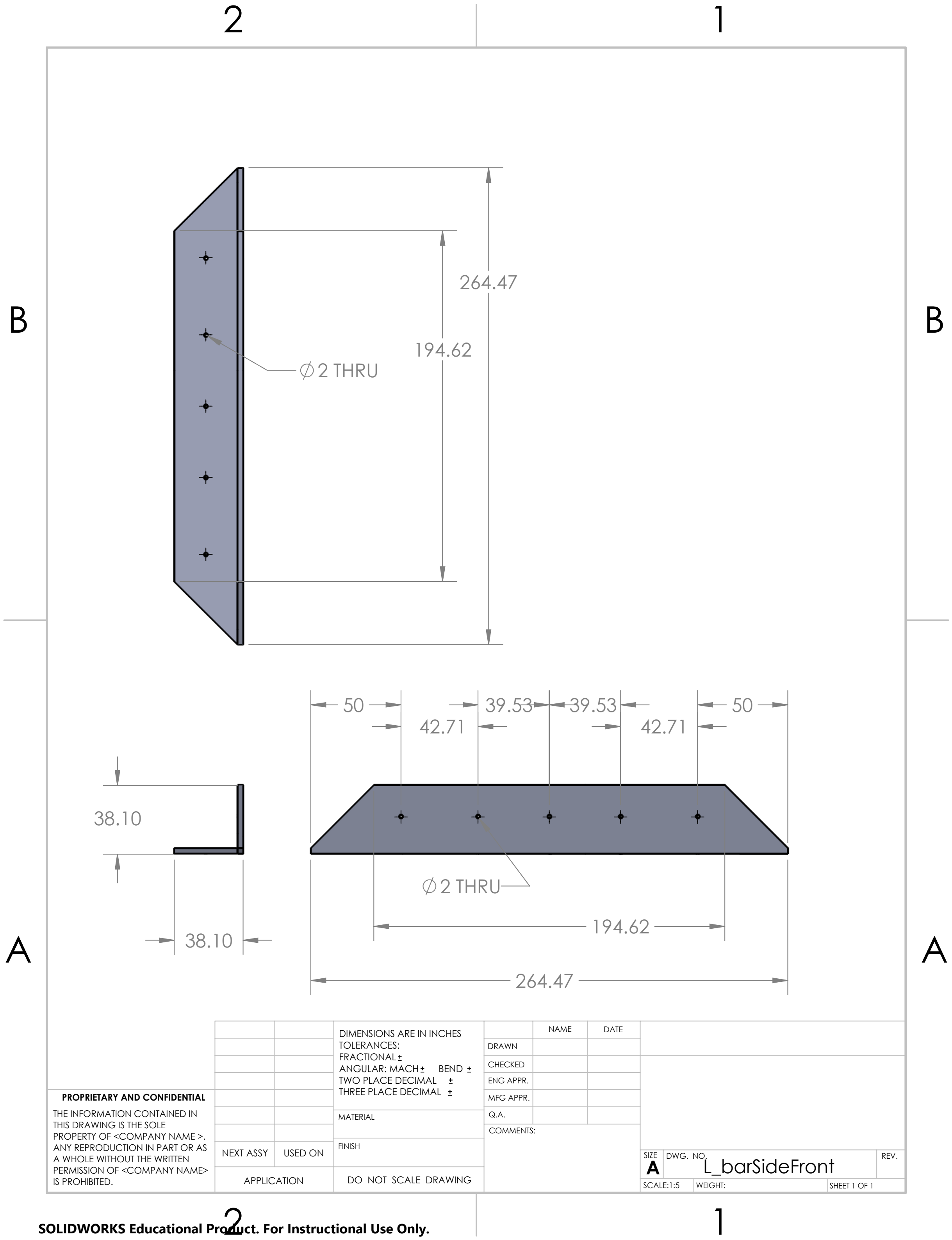

Figure 115: SolidWorks drawing of aluminum angle

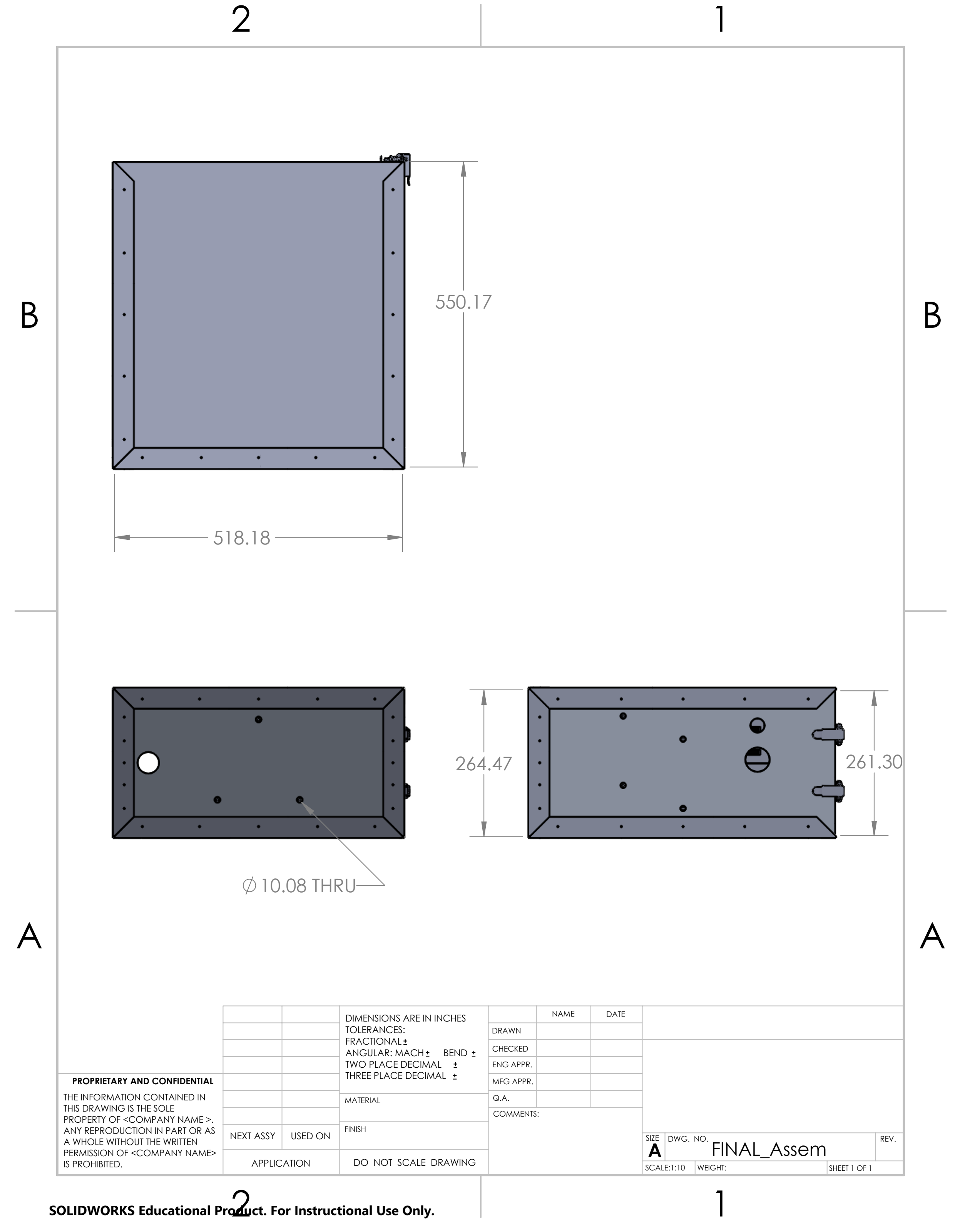

Figure 116: SolidWorks drawing of outside of final test bed assembly

11.2. Material Substitution List Provided by GA

Standard Substitutions List

Material	Application	Substitue Material	Notes	Ref DR
AL 6082-T6	Can be subtituted in all situations	AL 6061-T6		
AL 2014 Clad	Can be subtituted in all situations	AL 2024 Clad		
AL 2014-T3		AL 7075-T3/T7351		
		ANODIZE PER MIL-A-8625, TYPE III, CLASS 2, .001 THICK, BLACK	Hard Anodize, Black	
		ANODIZE PER MIL-A-8625, TYPE III, CLASS 1, .001 THICK, BLACK	Hard Anodize, Clear	
BS EN 12373-1:2001 Grade AA15	Can be subtituted in all situations	MIL-A8625, Type II, Class 2	Black anodize (not Hard Anodize)	
Alcocrom 1200	Can be subtituted in all situations	Chemical Conversion Coating, Color Gold, Per MIL-DTL-5541, Class 1A	maximum corrosion protection	
Alcocrom 1200	Can be subtituted in all situations	Chemical Conversion Coating, Color Gold, Per MIL-DTL-5541, Class 3	electricaly conductive	
Hysol EA 9321	Spot bonding heater edges and mounting thermostats	Scotchweld 2216 or DP190		DR 126
DP190	Can be subtituted in all situations	Scotchweld 2216		
CV-1142	Can be subtituted in all situations	DC 6-1104		DR 125

Figure 117: Material substitutions

11.3. Master Test Plans

CDR Master Test Plan

Team: OTheRS
University of Colorado Boulder

Name	Date	Revisions
Ryan Bennett	12/16/2018	Requirement checking, A-R Test Plans Addition
Ryan Bennett	11/30/2018	Document creation and CDR test plans written

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I. CDR Test Plans

A. Datasheet Inspection Plan

1. Testing Prerequisites

To complete this test plan, specific components must be picked that comprise the OTheRS. This is the only prerequisite for this plan.

2. Design Requirement(s) to be Retired

- **DR-IMAG 1**: The thermal imaging device(s) shall be sensitive to IR Radiation, measuring between 8.70 to 11.93 microns or -30 to +60 °C.
- **DR-THER 2**: The minimum operating temperature of the OTheRS shall be determined by the highest minimum operating temperature of other subsystems or components.
- **DR-COM 2**: OTheRS shall communicate with a heater communication protocol, if any is needed.
- **DR-TEST 2**: The stack shall replicate the thermal operating range of electronics contained in the stack, as defined in FR 1.
- **DR-TEST 4**: Test bed structure shall replicate material thermal properties of GA's satellite bay.

3. Introduction

The purpose of this test plan is for the inspection of specific components' datasheets such that the above requirements may be satisfied. This is a simple test if the components are picked so the validation step is a simple answer or a matter of looking a single sheet per component. The constraint of this plan is the public availability of information although if a component is being checked by a team member, the datasheet should have been checked prior to procurement of the part. There is also a large limitation of this test plan. The team will not be verifying the information given by the data sheet which means the team is assuming the manufacturer is reporting the accurate values that this component can achieve. This could lead the team into a place where adjustments must be made and this is acknowledged at this point in the design as a possibility in spring.

4. Test Articles

No physical objects are needed. The data sheets of the items are the only articles needed to verify this plan with the exception of a possible required serial number if the datasheets contain more than one article.

5. Approach

The approach for this plan is simple as it requires the ability to find and view the datasheet for the component. The source of these sheets is preferred to be the manufacturer but in cases where campus resources are used, the data sheet provided will suffice. This will allow for the team to be inspecting accurate and up to date information. This makes the requirements have a pass/fail criteria for acceptance and a simple test case of inspection.

The approach for a few requirements may not be intuitive thus these requirements are listed with specifics in this paragraph. For THER 2, the minimum operating temperature will be the given value on the datasheet. This value will have safety values added in for the controls of the system, but this step is to verify the survivability of the components that will be inside the test chamber during chamber testing. Next, COM 2 pertains to the selected heating components for the stack. This may be a simple step if the heat is not an active component that talks with the controller meaning the controller supplied a set voltage or current to drive the heating element. If this component does require a communication protocol, although it is likely not be needed, then a separate test plan will be added similar to the Controls and Communication Verification test plan so this protocol is verified. For TEST 2, the thermal chamber will define the ability to replicate the temperature range as after some amount of time in the ambient temperature, the stack will also be at this temperature. This requires the thermal chamber to be able to achieve and hold the temperature ranges as called out in the first functional requirement. Finally, the replication of the test bed material is defined in TEST 4. This means that the construction materials must be within approximately an order of magnitude of the customer's materials or substitute materials. The substitute material sheet was given by the customer, refer to email or ask for it in the slack if it cannot be found.

6. Deliverables

The deliverables for retirement of the specific requirements will be the physical datasheet with the pertaining section marked up in some way along with an exception log. This will make it simple for approval and recollection of information if needed later in the project. The exception log will be used if the requirement fails so the fail type and component can be tracked if iterations are needed. This will lead to an archival of information so the team can be more organized in the event of a requirement failure.

7. Testing Tasks

The items below do not require extensive time unless a failure occurs. In the event of a failure, notify the project manager and the systems engineer so options may be considered.

1. Mark up datasheets with relevant information to the requirements.
2. Fill in exception log as needed.

8. Environmental Needs

The plan only requires a computer or physical copy of the datasheet so no extra environmental needed are required at this time.

9. Approvals

Role	Name	Date Approved	Requirement(s) Retired
Testing Personnel	Name(s) here	-	-
Systems Engineer	Ryan Bennett	-	-
Project Manager	Micah Svenson	-	-

B. Dimension Verification Plan

1. Testing Prerequisites

The dimensions may be verified as manufacturing takes place but for final acceptance demonstration of these values to the project manager and systems engineer is required. That being said, the prerequisite is the completed test article that will be used for final testing. Also, DR-TEST 4 must be approved, or the overarching test plan, so the material used to machine the test article will replicate the actual system.

2. Design Requirement(s) to be Retired

- **DR-IMAG 3**: The thermal imaging device(s) shall be 100 to 146.73 mm from the stack.
- **DR-TEST 1**: The outer dimensions of the stack in the test bed shall be 246.3mm x 290mm x 318mm.
- **DR-TEST 1.1**: The interior dimensions of the test bed shall be 261.3mm x 515mm x 547mm.
- **DR-TEST 1.1.1**: The overall stack surface material shall be 5mm thick.

3. Introduction

The objective of this test plan is to verify and demonstrate the physical replication of the actual satellite. Resources to complete the requirement verification can be found on campus such that there are no major constraints for the budget. Primarily, the limitation of this test plan will be the accuracy of the measuring devices used which may give less accurate values than desired for exact precision. Due to this it is preferred to be at least within 3% of the required values.

4. Test Articles

The completed, manufactured test structure is the require module needed to compete this test. Also, a measuring device will be needed.

5. Approach

The approach for this plan is to create a repeatable method for measuring these quantities if needed. Many of these measurements are straightforward in nature, if they are ambiguous refer to the develop CAD models for the parts being measured, with a single exception. The exception is for the device placement in IMAG 3. The measurement should take place between the corner of the stack and the mounting position of the camera. The path should approximately be the shortest path to eliminate measuring between the top and bottom of the bay. For example, if the mounting position of the thermal imaging device is near the base of the bay then the measurement should be taken from the corner such that the measuring device is approximately parallel to the base or ceiling. For requirement retirement, the measurements must be within the range defined in the associated requirement, DR-IMAG 3. All mounting positions of the thermal imaging device must be measured for complete retirement. Along this note, all dimensions must be verified for all sides of the bay and stack components.

6. Deliverables

A formalized report is not required for this plan however the numerical values must be provided for approval so they can become a part of the information archive. Included in this must list how the measurements, specifically the device type and units, were taken so repeatability is possible. Also, a log should be submitted for any measurement issues or pertinent manufacturing issues that may affect accuracy. Although measurements must be demonstrated, both the log and measurement report must be submitted to create the archive.

7. Testing Tasks

The only tasks for this plan are the measurements and log if needed. Measurements for the TEST requirements must be made prior to the IMAG measurements so the sizing of the bay is confirmed.

8. Environmental Needs

This plan requires no additional test environments. Testing will take place in available campus rooms, campus labs, or the Aerospace Machine Shop.

9. Approvals

Role	Name	Date Approved	Requirement(s) Retired
Testing Personnel	Name(s) here	-	-
Systems Engineer	Ryan Bennett	-	-
Project Manager	Micah Svenson	-	-

C. Image Post Processing Check Plan

1. Testing Prerequisites

Before the post processing checks can be approved, the previous two test plans must be completed. Also, the camera and interfacing software must be completed to have a system that will be integrated. Finally, the software for all image processing should be written as they are the primary article under test for this plan.

2. Design Requirement(s) to be Retired

- **DR-IMAG 2**: Images of the stack shall be taken at no more than 90 second intervals.
- **DR-IMAG 3.1**: The field of view (FOV) of the thermal imaging device(s) shall contain at least a single side of stack.
- **DR-PROC 1**: The thermal map shall differentiate between objects in stack based on satellite and test bed configurations.
- **DR-PROC 1.1**: The thermal map shall distinguish between up to 6 objects (trays) in the stack.
- **DR-PROC 2**: The thermal imaging device(s) shall be both spatially and thermally calibrated with TBD metrics.
- **DR-PROC 4**: Temperature data shall be extracted from the thermal image.
- **DR-PROC 4.1**: Automated image processing shall be completed between image captures as defined in DR-IMAG 2.

3. Introduction

This test plan is to verify that the algorithms are written to function with the designed, physical test setup. Initially, testing and verification is being completed using test images which is beneficial for core functionality verification but this plan will require the actual images to be used. This places a constraint on budget and resources if initial testing determines if coating will be needed to improve the accuracy and ability of the thermal imaging device(s). Also, markers may be used to improve the recognition and stitching of images which places a constraint of resource, time, and budget is specific ones are required.

4. Test Articles

The completed test structure is the primary article under test but the thermal imaging device(s) are also needed to obtain results. Also, thermistors should be used as truth data to check against for verification of temperatures. In the event markers are required, they will also be used in the testing.

5. Approach

The approach for this plan is the direct testing of the test setup. The test data will be taken as a part of this test plan in the test setup. The test setup will be in an isolated environment such that no external heat sources such as body heat or lights will not introduce uncontrolled sources of heat. The technique of this test will be to automate the system as much as possible to the point of attempting to replicate the method of final testing. Requirements will be retired on a pass/fail criteria to ensure this critical piece of the project is functioning as desired. The various test cases will only be to vary the mounting positions of the thermal imaging device(s) to test the possible angles experienced in final testing.

6. Deliverables

This test plan requires a test report and an exception log for approval. The exception log will contain all redesigns, bugs, and issues found during the testing. The test plan will need to be formalized as it is a vital piece for tracking of the development of algorithms. At a minimum, sections of this report include the following; introduction, development challenges and solutions, preliminary test verification, final testing verification, and conclusion containing which requirements are completed. This report is one of the most important pieces of the project as the customer will likely request this report if they desire to change any objects in the test bed. Also, these algorithms and procedures can be used in a final implementation so this document can be used for extra development documentation.

7. Testing Tasks

1. Complete preliminary verification with arbitrary test images.
2. Setup the test scenario with the verified dimensions from previous test plans. Dependent on the previous step.
3. Create exception log and fill as needed during iterations through steps.
4. Images of the test article should be exported during each step in processing that is proving functionality and thus that a requirement may be retired.
5. Write test report and submit for approval. Dependent on successful completion of all previous steps.

8. Environmental Needs

This plan requires no additional test environments. Testing will take place in available campus rooms, campus labs, or the Aerospace Machine Shop.

9. Approvals

Role	Name	Date Approved	Requirement(s) Retired
Testing Personnel	Name(s) here	-	-
Systems Engineer	Ryan Bennett	-	-
Project Manager	Micah Svenson	-	-

D. Controls and Communication Verification Plan

1. Testing Prerequisites

The section will require 2 separate items to be completed. The control loops must be created and tuned if applicable thus they are ready to test the output of the control loop through either the use of test cases or demonstration. For the communication requirements, communication protocols need to be implemented and the peripherals need to be picked. Finally, the test plans that occur before this plan in the CDR plans must be completed.

Please note that if COM 2 fails the initial test plan, it must be rolled into this section and the communication protocol be tested. This makes the initial test plan, Datasheet Inspection, a prerequisite to this test plan.

2. Design Requirement(s) to be Retired

- **DR-PROC 3**: Internal processing shall control the internal thermal regulation of the OTheRS.
- **DR-CONT 1**: A control decision shall be communicated by the OTheRS to turn a heater on or a representative indicator.
- **DR-CONT 2**: A control decision shall be communicated by the OTheRS to turn a component off or a representative indicator.
- **DR-COM 1**: The OTheRS subsystems shall use serial communication to transfer information, signals, etc. with the spacecraft bus.
- **DR-COM 1.1**: OTheRS shall communicate with RS-232 communication protocol.
- **DR-COM 2**: OTheRS shall communicate with a heater communication protocol, if any is needed. **

*** - This needs to be tested only if the requirement fails on the Datasheet Inspection test plan.*

3. Introduction

This test plan will be split into 2 sub-plans, one for the Controls related requirements and one for the Communication related requirements. Both sub-plans are related in how they will be completed but are different for how the testing will take place.

Controls related requirements, PROC 3, CONT 1, and CONT 2, will be verified using test cases or the control system response to a test input. These requirements may have a resource constraint if the associated control hardware is not procured but if they are then this sub-plan will not have constraints with either the budget or resources. For the first control related requirement, PROC 3, the verification will likely be test cases to show the system responds to these inputs in the correct manner. Due to the operating temperature range of many components including room temperature, if more verification is needed then a thermal chamber will need to be used to give the thermal range needed to test this. For the remaining related requirements, these may be verified by simulating an input from other subsystems to initiate a needed control decision. Once this test case is verified, the representative indicator, an LED for example, will be used to verify the correct decision.

Communication related requirements, COM 1 and COM 1.1, will be direct observation of the communication packages being sent between components. This sub-plan will have a resource constraint of a device that can communicate the communication protocol to a computer for verification. This is not a critical constraint as the communication protocol has heritage and was used by the team in previous classes thus verification hardware may exist through campus resources.

4. Test Articles

Controls retirement will require the software or control loops as a critical component. Test cases will also need be be generated for this test and for the CONT sub-requirements, indicators will be required.

Communication protocols and peripherals will be needed for the testing. Also, the ability to view the communicated messages and decode them is needed so a device to transfer the communication to a computer is required.

5. Approach

Controls verification will predominantly be completed using test cases to directly verify the requirements with some observation. The use of test cases is key for this sub-plan to allow for testing of the hardware and software without the need of a thermal test chamber. This may need to be used for the total verification of PROC 3 but is left for another test plan after this one is completed. Test cases will be generated in the form of the output of the output from the thermal imaging device's output and after the output has been processed. For PROC 3, the analysis to initially retire the requirement will be to check the outputs for the thermal regulation control to verify that the operating temperatures are high enough and that no specific thermal properties are failed such as the thermal gradient across a component. The analysis on the other 2 control requirements will be verifying the thermal map should either completely trigger the response or not at all so the function can be initially verified. Once this is compete, an iteration may be needed for each of the components found by the image processing algorithms so the control can be verified for each identified object. The acceptance criteria will be pass/fail as the will either function properly or they will not entirely retire the associated requirements. Scenarios and test cases should be derived from actual data from either the image processing or the thermal imaging device(s) to verify functionality with the components selected for the OTheRS.

Communication verification is also completed with test cases but also will combine the observation of the function. The observation will be through the use of signal observations in lab equipment or the decoding of messages between components. The test data should be derived from actual communications so the true function can be verified rather than a single bit of information being communicated correctly. These requirements will be pass/fail as they must function for the OTheRS to function properly in the test chamber where the process will be automated. Test cases may be run multiple times for the verifiaction although the cases should be derived from actual data from the image processing or thermal imaging device(s).

6. Deliverables

Controls and Communications requirement deliverables are separate items and contain the following; test cases, sample data, an informal test report, and an exception log per each testing sub-plan. The test cases and sample data should be included within the report for completeness. The report will contain multiple sections but it is not required to be a full test report. Sections of the report will be an overview, list of items being tested, testing summary, conclusion noting if the requirement is fulfilled and why, and an appendix containing the test cases and sample data if applicable. The exception log should be used if anomalies or bugs are found during tests and a description of their remedy included. For retirement of the requirements, the test report and the exception log must be submitted.

7. Testing Tasks

Controls:

1. Create test cases and inputs for the control loops.
2. Setup test scenario with representative indicators if applicable.
3. Execute the test cases. This is dependent on the 2 preceding steps.
4. Report the bugs found during testing if applicable and fill the exception log with these test bugs. Dependent on the execution of the developed test cases in the created test scenario.
5. Submit the sub-plan test report and exception log if applicable. Dependent on successful completion of above steps and iterations if needed.

Communication:

1. Compile needed resources to view communications
2. Setup the test environment. This is dependent on the previous task.
3. Generate test messages that conform to the required protocols.
4. Execute the test messages while observing in the test environment. Dependent on all preceding steps in the sub-plan.
5. Report the bugs found during testing if applicable and fill the exception log with these test bugs. Dependent on the execution of the developed test cases in the created test scenario.
6. Submit the sub-plan test report and exception log if applicable. Dependent on successful completion of above steps and iterations if needed.

8. Environmental Needs

An approved thermal chamber may be required if further testing and verification is needed on the PROC 3 requirement. If not, this plan requires no extra environments that are not directly accessible on campus.

9. Approvals

Role	Name	Date Approved	Requirement(s) Retired
Testing Personnel	Name(s) here	-	-
Systems Engineer	Ryan Bennett	-	-
Project Manager	Micah Svenson	-	-

E. Pretest Instrumentation Inspection Plan

1. Testing Prerequisites

The prerequisites for this test plan are for all other CDR test plans to be completed. This plan is placed to be the final check before chamber takes place for the OTheRS. The testing referenced by the title of this test is the acceptance testing by the customer.

2. Design Requirement(s) to be Retired

- **DR-POW 2**: Power shall be transferred and distributed using D-Type connectors.
- **DR-THER 1**: The internal temperature of the OTheRS shall be monitored by at least one thermistor.
- **DR-TEST 3**: OTheRS shall not be mounted to the outer walls or stack of the test bed.

3. Introduction

The goal of this plan is to a final visual check of the instrumentation and design prior to the design being placed in a harsher environment. This is an extremely important check so multiple team member should complete this check and sign off. There are no constraints for either the resources or budget as all material should be procured and received when this test plan is being completed.

4. Test Articles

The test article will need to be the entire test bed in its test ready configuration and nothing else as this is a final check.

5. Approach

The approach of this test is to visually inspect the manufacturing and design of the test bed prior to chamber tests. Test cases may be the mounting of the thermal imaging device(s) mounting system if it is not rigidly fixtured to the test bed. As this is a visual check, there approach is how it sounds and a final check for the team that the other plans are complete and the design will fulfill the requirements.

6. Deliverables

There are no required deliverables unless a requirement is failed. If there is a failure a log will need to be created and filled out listing which requirement, why, and the design decision if applicable.

7. Testing Tasks

If no failures are found, the only task is visual inspection.

8. Environmental Needs

This plan requires no additional test environments. Testing will take place in available campus rooms, or the Aerospace Machine Shop.

9. Approvals

Role	Name	Date Approved	Requirement(s) Retired
Testing Personnel	Name(s) here	-	-
Systems Engineer	Ryan Bennett	-	-
Project Manager	Micah Svenson	-	-

II. Functional Requirement Retirement

A. FR 1

OTheRS shall return thermal data map for multiple components between -30°C and 60°C. This requirement will be retired when multiple other design requirements are retired. The thermal range portion of the requirement will be satisfied when the test chamber is confirmed to achieve the desired temperatures. This is through the retirement of DR-TEST 2. For the thermal data map, temperature data will need to be extracted from the raw images from the thermal imaging device to satisfy the portion of the requirement. This will be done when DR-PROC 4 is retired. The final portion to fully satisfy the requirement will be to identify multiple components. This will be handled by the image processing and thus retired with the satisfaction of DR-PROC 1 and DR-PROC 1.1. The retirement of these design requirements will thus satisfy the functional requirement so the list below compiles the associated design requirements. The final check for this requirement will be that the thermal imaging device will measure this range which is covered in DR-IMAG 1.

- **DR-IMAG 1**: The thermal imaging device(s) shall be sensitive to IR Radiation, measuring between 8.70 to 11.93 microns or -30 to +60°C.
- **DR-PROC 1**: The thermal map shall differentiate between objects in stack based on satellite and test bed configurations.
- **DR-PROC 1.1**: The thermal map shall distinguish between up to 6 objects (trays) in the stack.
- **DR-PROC 4**: Temperature data shall be extracted from the thermal image.
- **DR-TEST 2**: The stack shall replicate the thermal operating range of electronics contained in the stack, as defined in FR 1.

B. FR 2

OTheRS shall provide regulatory commands when components are outside -20°C to 50°C. The thermal range portion of this requirement will be satisfied when the above function requirement is retired or if the associated design requirements are retired. These requirements are all requirements in FR 1. The final portion of this requirement will then be to provide regulatory commands. This is satisfied with the retirement of both DR-CONT 1 and 2 which handle the control decisions. When the list of requirements below are satisfied then this functional requirement is successfully retired.

- **DR-IMAG 1**: The thermal imaging device(s) shall be sensitive to IR Radiation, measuring between 8.70 to 11.93 microns or -30 to +60°C.
- **DR-PROC 1**: The thermal map shall differentiate between objects in stack based on satellite and test bed configurations.
- **DR-PROC 1.1**: The thermal map shall distinguish between up to 6 objects (trays) in the stack.
- **DR-PROC 4**: Temperature data shall be extracted from the thermal image.
- **DR-CONT 1**: A control decision shall be communicated by the OTheRS to turn a heater on or a representative indicator.
- **DR-CONT 2**: A control decision shall be communicated by the OTheRS to turn a component off or a representative indicator.
- **DR-TEST 2**: The stack shall replicate the thermal operating range of electronics contained in the stack, as defined in FR 1.

C. FR 3

OTheRS shall operate on 28V unregulated power provided by the spacecraft.
The requirement will require the successful retirement of DR-POW 1. This is the only requirement that will factor directly into how the power is coming from the spacecraft bus to the OTheRS.

- **DR-POW 1**: The power management subsystem shall provide power distribution to the subsystems within OTheRS.

D. FR 4

OTheRS shall fit within a standard GA nanotray, with dimensions of 18.5cm x 13cm.
This requirement has no related design requirement thus requires a plan to satisfy the requirement. Once this plan is written than this section will reference this plan. At the time being, this is not looked at as an issue as many components are quite small and easily fit within these dimensions.

E. FR 5

OTheRS shall be able to switch a 2.5A load as needed to control an externally powered heater or representative indicator.
This requirement is partially related to design requirements but also has a portion that is not related to the satisfaction design requirements. The related design requirements are for the control so DR-CONT 1 and 2 which will satisfy the portion regarding the control of components or a representative indicator. The remaining portion of this functional requirement is the amperage requirement to drive the example heater load. This will require a short test plan to verify that this current is being driven.

- **DR-CONT 1**: A control decision shall be communicated by the OTheRS to turn a heater on or a representative indicator.
- **DR-CONT 2**: A control decision shall be communicated by the OTheRS to turn a component off or a representative indicator.

F. FR 6

The thermal imaging device(s) shall image critical stack electronics on at least a single side of the stack.
This requirement can be boiled down to satisfying imaging requirements. For the single side of the stack, multiple thermal imaging devices are being used meaning that there must be overlap between the fields of view between both devices. This will satisfied through the retirement of DR-IMAG 3.1. The remaining portion of this requirement is what is being imaged which is satisfied through the retirement of the mounting solution in both DR-IMAG 3 and DR-TEST 3. By satisfying the following design requirements, the functional requirement will be satisfied.

- **DR-IMAG 3**: The thermal imaging device(s) shall be 100 to 146.73 mm from the stack.
- **DR-IMAG 3.1**: The field of view (FOV) of the thermal imaging device(s) shall contain at least a single side of stack.
- **DR-TEST 3**: OTheRS shall not be mounted to the outer walls or stack of the test bed.

G. FR 7

OTheRS shall regulate its own temperature.
The regulation of OTheRS is predominantly tied into the operating range of the components and the ability to control the temperature. Being able to control the temperature relies on the measurement of the components temperature so this is tied into the satisfaction of DR-THER 1. Next, the control of the temperature will be satisfied through the verification of DR-PROC 3. The final piece of this requirement is defining the operational range of the OTheRS which is tied into the satisfaction of DR-THER 2. Thus through the satisfaction of the following design requirements, the functional requirement will be satisfied.

- **DR-PROC 3**: Internal processing shall control internal thermal regulation of the OTheRS.
- **DR-THER 1**: The internal temperature of the OTheRS shall be monitored by a thermistor(s).
- **DR-THER 2**: The minimum operating temperature of the OTheRS shall be determined by the highest minimum operating temperature of other subsystems or components.

H. FR 8

Test bed shall mimic the GA satellite.
This requirement will primarily be concerned with the final construction of the test article. This means that dimensions and materials are the key requirements. The dimensions related requirements fall under DR-TEST 1, DR-TEST 1.1, DR-TEST 1.1.1, and DR-IMAG 3. These will defined the size of the test article as representative of the GA satellite avionics bay. Also, this will define where the thermal imaging device(s) can be mounted within the bay. The other portion of this requirement will be the accurate representation of the material used by GA to construct the satellite as this test bed is meant to allow for testing on a representative object. This will be satisfied in the retirement of DR-TEST 4. Through the satisfaction of the following requirements, the full functional requirement will be retired.

- **DR-IMAG 3**: The thermal imaging device(s) shall be 100 to 146.73 mm from the stack.
- **DR-TEST 1**: The outer dimensions of the stack in the test bed shall 246.3mm x 290mm x 318mm.
- **DR-TEST 1.1**: The interior dimensions of the test bed shall be 261.3mm x 515mm x 547mm.
- **DR-TEST 1.1.1**: The overall stack surface material shall be 5mm thick.
- **DR-TEST 4**: Test bed shall replicate material thermal properties of GA's satellite bay.

I. FR 9

OTheRS shall not include ITAR restriced articles.
This functional requirement does not have any derived requirements that feed into the retirement of this requirement. Overall, this means the satisfaction of this requirement will be to check all components prior to procurement to verify this requirement is met.

III. Anti-Reflective Test Plan

A. Variables Impacting Reflectivity

1. Absorptivity and Transmissivity

If a material can be assumed to be opaque, the transmissivity (τ) will be approximately be zero. This is true for metals but in the event of a varied surface material, transmissivity will need to be considered. If the absorptivity (α) of a material is also known, Eqn 1 can be used to quantify the reflectivity coefficient (ρ). This is a direct metric for the effect on the reflectivity of a surface and be used to quantify the effectiveness of all methods. If the absorptivity and transmissivity can be found or modeled they become known parameters of the thermal environment along with the reflectivity coefficient.

$$\rho = 1 - \tau - \alpha \tag{1}$$

2. Surface Roughness

The preliminary research has shown that the surface roughness will directly affect the reflection pattern of the surfaces. The roughness is defined relative to the wavelengths of the incident radiation meaning that so long that Eqn 2 holds, the reflection pattern will be diffuse and reflect in all directions. This appears be more desirable than a mirror-like reflection from a "smooth" surface. By using a rough surface, the incoming angle of incidence of the rays will not need to be considered due to the reflection type. Testing will show the exact effects of the governing equation but will be quantifiable given the wavelengths already being a known parameter for the system.

$$\lambda_{IR} << h_{surface} \;\; \rightarrow \;\; IR\, Wavelength << Height\ of\ Surface\ Roughness \tag{2}$$

3. Refractive Index and Angle of Incidence

Optical grade anti-reflective coatings tend to list the angles of incidence where they are effective at limiting reflection. This will be an important consideration given the thermal imaging device(s) being mounting with high angles of incidence with respect to the surface normal. The exact values for the skew relative to the surface are known for the chosen thermal imaging device meaning a range of values for the effected angle of incidence can be used to research specific coatings for this range. By limiting coatings to this range, reflections from the surface being viewed will be limited and could increase the accuracy of the thermal imaging device.

Refractive index is typically used for transparent or semitransparent materials. This means thin enough materials may fit this constraint for certain wavelength ranges. Further research must be made into the thickness for an effective film given the wavelengths that will be tested, called out in DR-IMAG 1.

B. Coatings Trade Study

A trade study will be used to determine the flow of the testing for anti-reflective coatings or techniques. The weights will not show which is optimal but rather how the team should proceed through testing of the coatings or methods to decrease the reflectivity.

Table 1: Metric Definitions

Metric	Weighting	Justification
Cost	0.3	The cost of the coatings is a driving factor for being unable implement for the team. The planned budget including margin does not leave much remaining budget meaning the cost constraint will heavily weigh onto what the team can complete without seeking additional funding.
Manufacturing Complexity	0.3	As seen during initial test bed prototyping, the complexity of manufacturing can modify the planned designs. The complexity will also determine if the team can use the coating and apply it or will a lead time need to be included to allow for a supplier to apply the coating. This shows that this metric is also involved with another metric, the manufacturing time.
Manufacturing Time	0.15	The time to complete manufacturing tasks was also a notable discovery in initial prototyping and this was noticed when the shop was not being fully utilized by other teams. This shows that if a coating is rather complex to implement it may not be allowable in the schedule and thus not an effective use of the teams' time to apply.
Space Grade Analogous Coatings	0.1	Space grade coatings are desired by the customer to be used with this temperature sensing method along with the customer's product being a space ready system. The ability to replicate space grade coatings with thus weigh in on the selected coatings to test.
Known Reflectivity Impact	0.15	Knowing the exact parameters that effect the reflectivity will allow for more in-depth testing. Also, the ability to establish trends on variables is important to provide to the customer meaning quantifiable impacts and parameters are desirable.

Table 2: Scoring Matrix

	Scoring Criteria				
Metric	**1**	**2**	**3**	**4**	**5**
Cost	$> \$250$	$< \$250$	$< \$150$	$< \$50$	$< \$10$
Manufacturing Complexity	Must be sent to supplier	Fully implemented with campus resources that require scheduling	Partially implemented with campus resources that require scheduling	Implemented with readily available campus resources in less than 3 hours	Implemented with readily available campus resources in less than an hour
Manufacturing Time	$>$ 3 day lead time	$<$ 3 day lead time	$<$ 24 hrs	$<$ 3 hrs	$<$ 1 hr
Space Grade Analogous Coatings	No space grade similarity exists	Some parameters are recreated with a space grade coating	Most parameters are recreated with a space grade coating	Selected coating may be fully replicated with other coatings	Manufacturer provides space grade coating with same parameters
Known Reflectivity Impact	Parameters are completely unknown	Parameters are known but not agreed on by sources of data	Parameters are known but contain $<$ 30% error	Parameters are known but contain $<$ 10% error	Parameters are well known and modelled

Table 3: Trade Matrix, part 1

Metric	**Weighting**	**Simple, Reversible Coatings (1-5)**	**Surface Roughness Variation (1-5)**
Cost	0.3	5	4
Manufacturing Complexity	0.3	5	4
Manufacturing Time	0.15	5	4
Space Grade Analogous Coatings	0.10	1	2
Known Reflectivity Impact	0.15	1	3
Weighted Totals	1	**4**	**3.65**

Table 4: Trade Matrix, part 2

Metric	Weighting	Surface Material Variation (1-5)	Surface Coatings (1-5)
Cost	0.3	3	1
Manufacturing Complexity	0.3	4	1
Manufacturing Time	0.15	3	1
Space Grade Analogous Coatings	0.10	2	4.5
Known Reflectivity Impact	0.15	4	5
Weighted Totals	1	**3.35**	**1.8**

Simple, Reversible Coatings

The simple and reversible coatings are desirable even without well modelled or know anti-reflectivity qualities. Many of these tests do now cause damage to the initial, prototype test bed meaning they can be testing quickly, with no manufacturing time constraints. The resources for these tests may be as simple as sticky notes, suggested by the customer, or certain materials taped to the surface. Although these tests are quite crude, they make up in speed and modulation meaning trends may be developed quicker and provide further insight for future testing.

Surface Roughness Variation

The modification of the surface roughness is well predicted by current thermodynamics modeling and can be used to limit the reflection of the surface while leaving the other thermal parameters relatively constant. Also, the team already has an extra stack face that requires a few hours to complete machining. This face can then be used to modify the surface roughness while limiting cost impacts. The cost implication would be if an exact grit of sandpaper was needed to provide a known surface roughness but not available through campus resources. With enough available grits, a full curve could be developed to show the accuracy as a function of surface roughness. Although the coatings do not account for a specific surface roughness, this is a technique that may be implemented by the customer to limit changes to the current thermal design of the satellite.

Surface Material Variation

Modifying the surface material will require the final test bed to be built. If the final test bed is built, then this will not play into the manufacturing time and this assumption is made to eliminate this source of uncertainty with full manufacturing time. Each new material will require manufacturing time, but this is assumed to be low as it is a thin sheet with precise dimensions. This will modify the tools used to create the surface material but is not a large issue due to many materials that can be manufactured with campus resources if the raw material is obtained. Dependent on the chosen material, certain parameters may be recreated with a space grade coating, but the material will change many parameters such as the conductivity, absorptivity, and emissivity which may not be modified by the space ready coatings. The thermal parameters are likely to be readily available from suppliers meaning the reflectivity impact can be modeled but may contain errors that are assumed to be negligible.

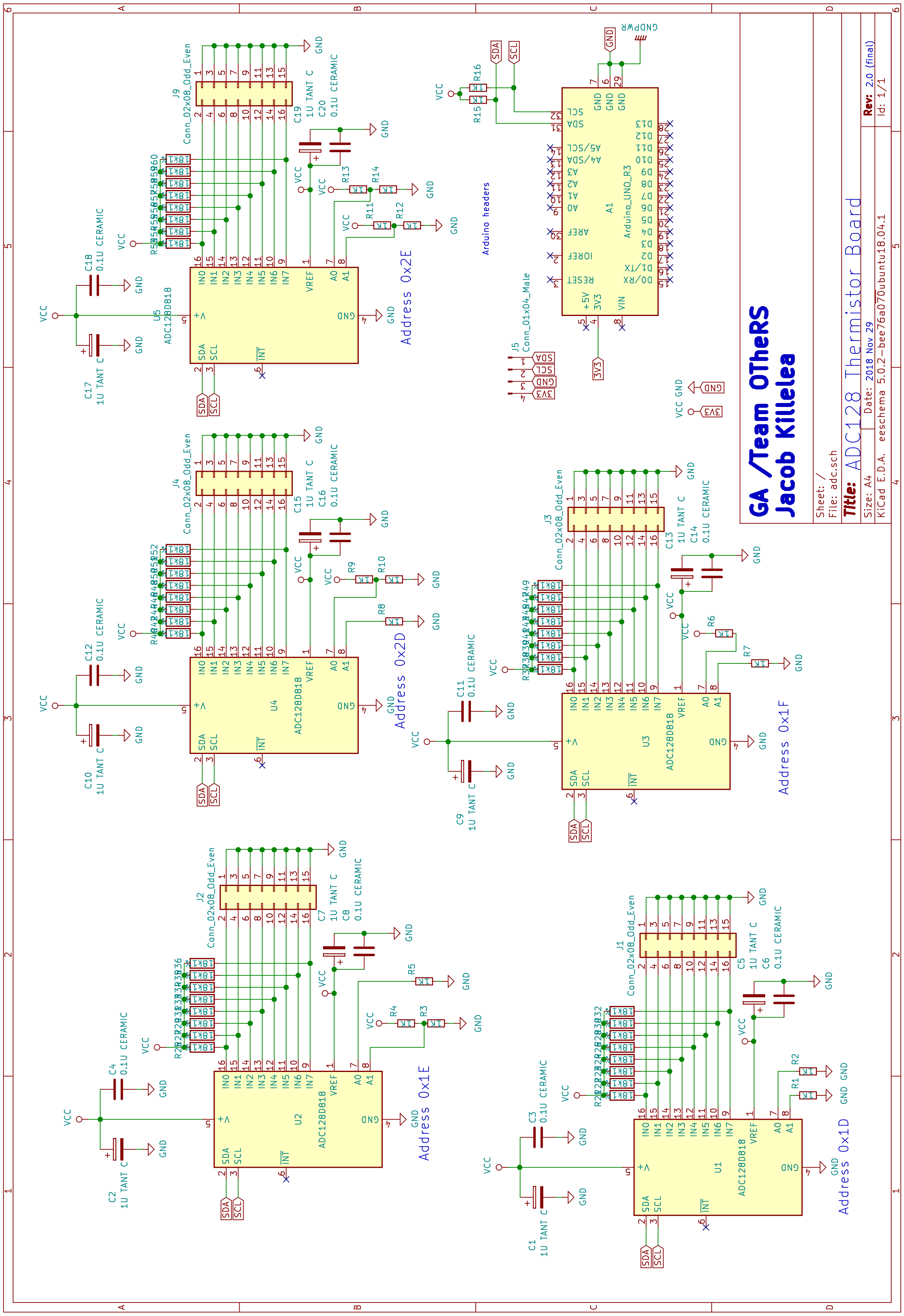
Surface Coatings

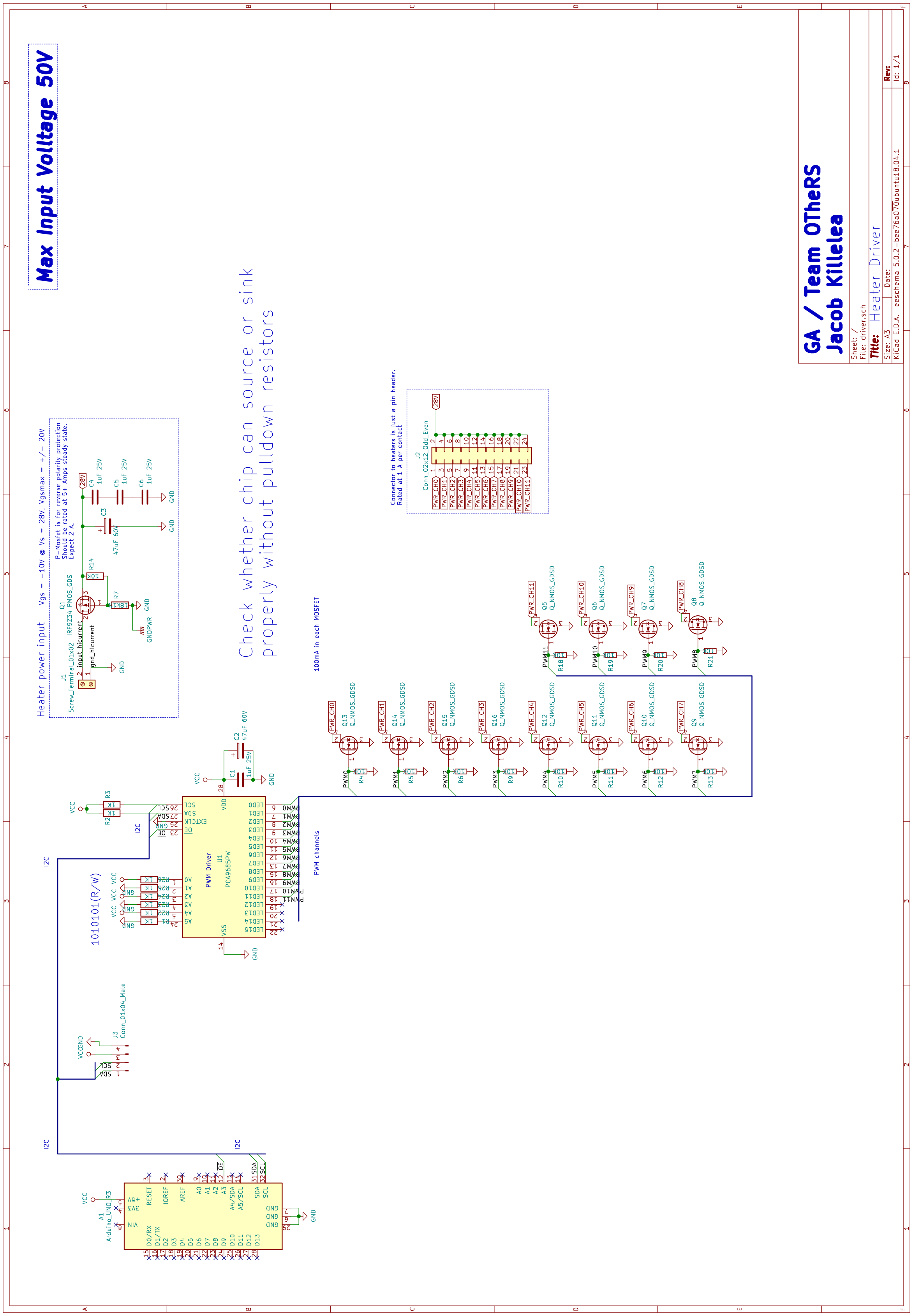
This method is by far the worst option due to issues with the cost, complexity, and time associated with implementation. On the other hand, it is the most desirable for the information that can be provided to the customer and prove useful. This step is the team's goal to complete although this test will contain difficult schedule and cost constraints. Similar to the other tests, there is a high degree of variability in this method but to provide the customer useful data, it should be prioritized to utilize coatings that fit the schedule and budget constraints but also have analogous coatings that are deemed space ready.

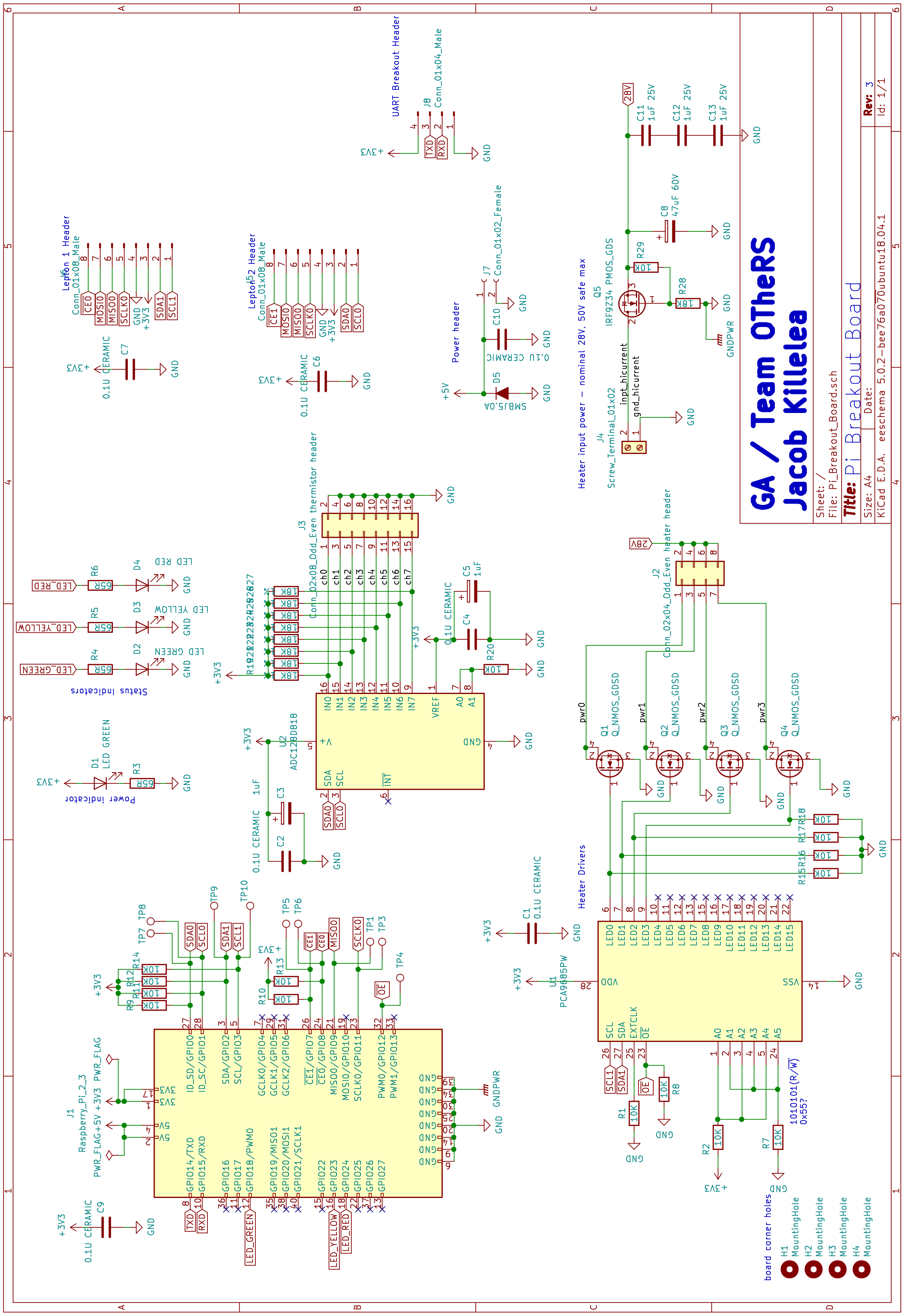
C. Plan Progression

The progression of the tests agrees with the results of the Trade studies in the previous section (See Tables 1 - 4). This will be to start with inexpensive, reversible coating solutions that are also directly available on campus. Next, the tests will move to modifying the surface roughness on a stack wall. This will involve starting with a machined surface and increasing the roughness as tests progress. This will limit the impact on the budget and will increase the speed for repetitive testing. A proposed method for this portion of the test would be starting with a high grit of sandpaper and decreasing the grit to increase the surface roughness. The next step in the progression for coatings testing would be to change the surface material on the stack. This is currently included as a functionality of the final test bed meaning the final test bed is required to perform this testing while minimizing the impact on the full testing environment. Finally, optical grade coatings will be pursued if budget remains to test multiple coatings. These coatings will be paired with possible space grade coatings that the customer can pursue for further testing. A visual representation of the coatings testing flow is shown below in Figure 1.

Figure 1: Test flow for how coatings and anti-reflective methods will be tested


GA /Team OTheRS
Jacob Killelea
Sheet: /
File: adc.sch
Title: ADC128 Thermistor Board
Size: A4
Date: 2018 Nov 29
KiCad E.D.A. eeschema 5.0.2-bee76a0~70~ubuntu18.04.1
Rev: 2.0 (final)
Id: 1/1
Address 0x2E
Address 0x2D
Address 0x1F
Address 0x1E
Address 0x1D
Arduino headers


Max Input Volltage 50V
Heater power input
Check whether chip can source or sink properly without pulldown resistors
100mA in each MOSFET
PWM channels
1010101(R/W)
GA / Team OTheRS
Jacob Killelea
Title: Heater Driver


GA / Team OTheRS
Jacob Killelea
Sheet: /
File: Pi_Breakout_Board.sch
Title: Pi Breakout Board
Size: A4
Date:
Rev: 3
KiCad E.D.A. eeschema 5.0.2-bee76a0~70~ubuntu18.04.1
Id: 1/1
UART Breakout Header
Lepton 1 Header
Lepton 2 Header
Power header
Heater input power - nominal 28V, 50V safe max
Status indicators
Power indicator
Heater Drivers
board corner holes

11.4. Thermistor Specification

$T(°C)$	$R_t(\Omega)$	R_t/R_{25}	$R_{tol}(\%)$	$\alpha(\%/K)$	$T_{tol}(\pm°C)$	$R_{min}(\Omega)$	$R_{max}(\Omega)$
-40.0	190953	19.095	4.24	-5.46	0.78	182848	199057
-35.0	145953	14.595	3.93	-5.30	0.74	140213	151697
-30.0	112440	11.244	3.63	-5.14	0.71	108354	116527
-25.0	87285	8.7285	3.35	-4.99	0.67	84364	902067
-20.0	68260	6.8260	3.07	-4.85	0.63	66164	703557
-15.0	53762	5.3762	2.80	-4.71	0.60	52254	552707
-10.0	42636	4.2636	2.55	-4.57	0.56	41549	437237
-5.0	34038	3.4038	2.30	-4.44	0.52	33254	348227
0.0	27348	2.7348	2.07	-4.31	0.48	26783	279137
5.0	22108	2.2108	1.84	-4.19	0.44	21702	225157
10.0	17979	1.7979	1.62	-4.08	0.40	17689	182707
15.0	14706	1.4706	1.40	-3.96	0.35	14499	149127
20.0	12094	1.2094	1.20	-3.86	0.31	11949	122397
25.0	10000	1.0000	1.00	-3.75	0.27	9900.0	101007
30.0	8310.8	0.83108	1.19	-3.65	0.33	8211.7	8409.7
35.0	6941.1	0.69411	1.38	-3.55	0.39	6845.5	7036.7
40.0	5824.9	0.58249	1.56	-3.46	0.45	5734.1	5915.7
45.0	4910.6	0.49106	1.73	-3.37	0.51	4825.6	4995.7
50.0	4158.3	0.41583	1.90	-3.28	0.58	4079.2	4237.7
55.0	3536.2	0.35362	2.06	-3.20	0.65	3463.2	3609.7
60.0	3019.7	0.30197	2.22	-3.12	0.71	2952.5	3086.7
65.0	2588.8	0.25888	2.38	-3.04	0.78	2527.3	2650.7
70.0	2228.0	0.22280	2.53	-2.96	0.85	2171.7	2284.7
75.0	1924.6	0.19246	2.67	-2.89	0.92	1873.1	1976.7
80.0	1668.4	0.16684	2.81	-2.82	1.00	1621.5	1715.7
85.0	1451.3	0.14513	2.95	-2.75	1.07	1408.5	1494.7
90.0	1266.7	0.12667	3.08	-2.69	1.15	1227.7	1305.7
95.0	1109.2	0.11092	3.21	-2.62	1.22	1073.6	1144.7
100.0	974.26	0.097426	3.34	-2.56	1.30	941.74	1006.7
105.0	858.33	0.085833	3.46	-2.50	1.38	828.62	888.07

Table 20: NTCLE413-428 Specification, $R_{th} = 10k\Omega \pm 1\%$, $R_{25} = 10k\Omega \pm 1\%$, $B_{25} = 3435K \pm 1\%$