OTheRS

Optical Thermal Regulation System

Critical Design Review

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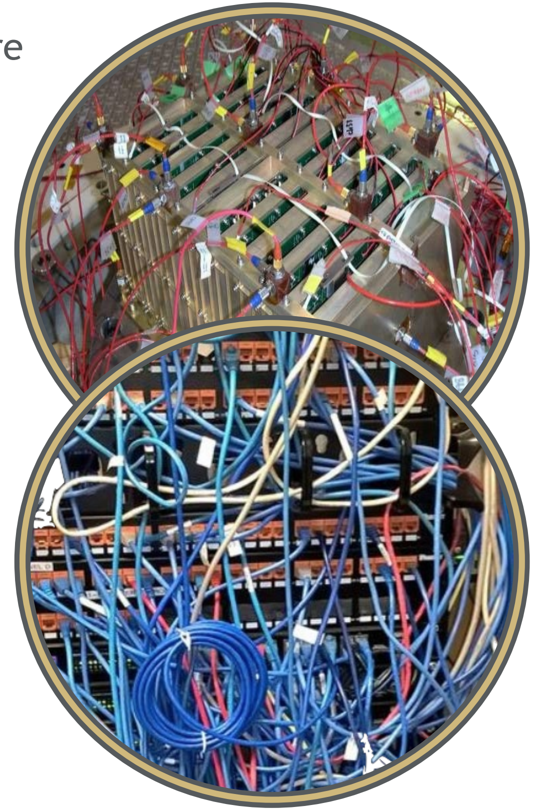
Project Purpose & Objectives

Project Motivation

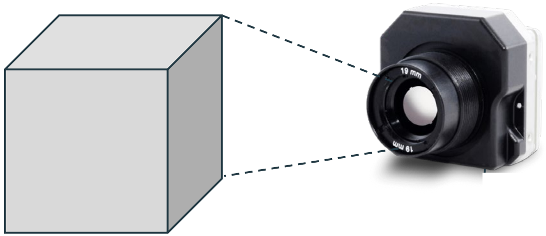
- Satellites operate in a harsh environment with large temperature fluctuations.
    - Thermal regulation is critical to operation of subsystems
- Current thermal sensing solution: Large number of thermal sensors
    - Increased wiring & harnessing complexity
    - Increased number of satellite bus inputs
- Small satellites = compact systems



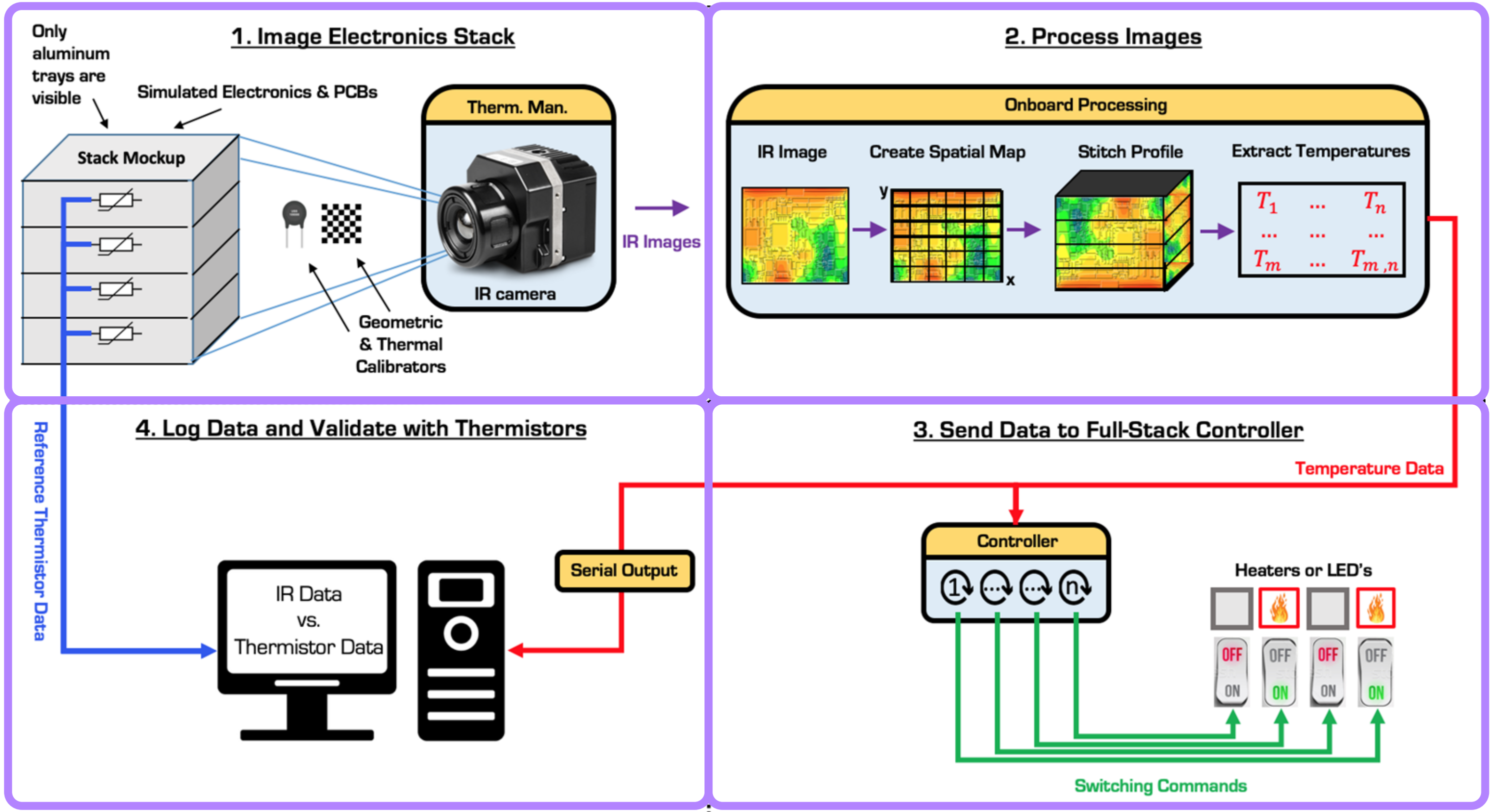
Need a new and innovative solution for small satellite thermal regulation systems...

Project Concept

The **O**ptical **The**rmal **R**egulation **S**ystem is a **variable parameter test bed** modeled after a General Atomics satellite **avionics bay**. The test bed will test and validate the viability of **Long Wave Infrared (LWIR) sensors as a replacement for traditional discrete temperature sensors**. The test bed will be used to explore the capabilities of the system and seeks to determine the efficacy of LWIR sensors in small satellite thermal regulation.



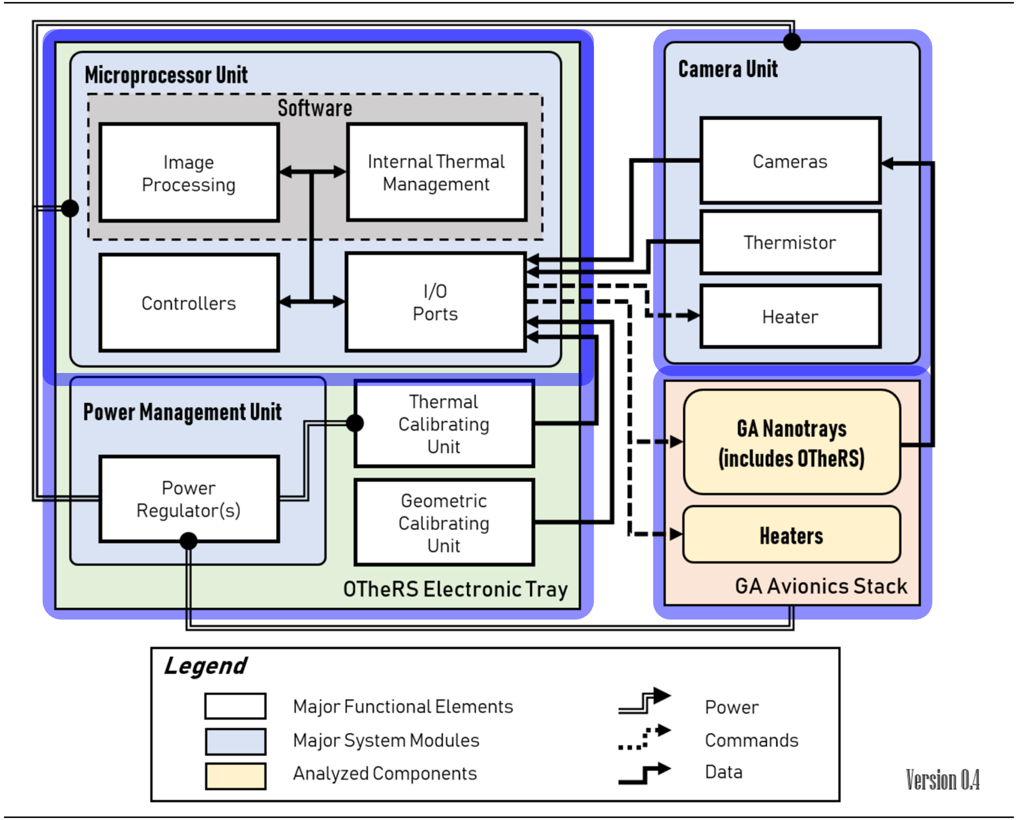
CONOPS



1. Image Electronics Stack
Only aluminum trays are visible
Simulated Electronics & PCBs
Stack Mockup
Therm. Man.
IR camera
Geometric & Thermal Calibrators
IR Images
2. Process Images
Onboard Processing
IR Image
Create Spatial Map
Stitch Profile
Extract Temperatures
T_1 … T_n
… … …
T_m … $T_{m,n}$
y
x
3. Send Data to Full-Stack Controller
Temperature Data
Controller
Heaters or LED's
OFF ON OFF ON OFF ON OFF ON
Switching Commands
4. Log Data and Validate with Thermistors
Reference Thermistor Data
IR Data vs. Thermistor Data
Serial Output

Design Solution

Functional Block Diagram

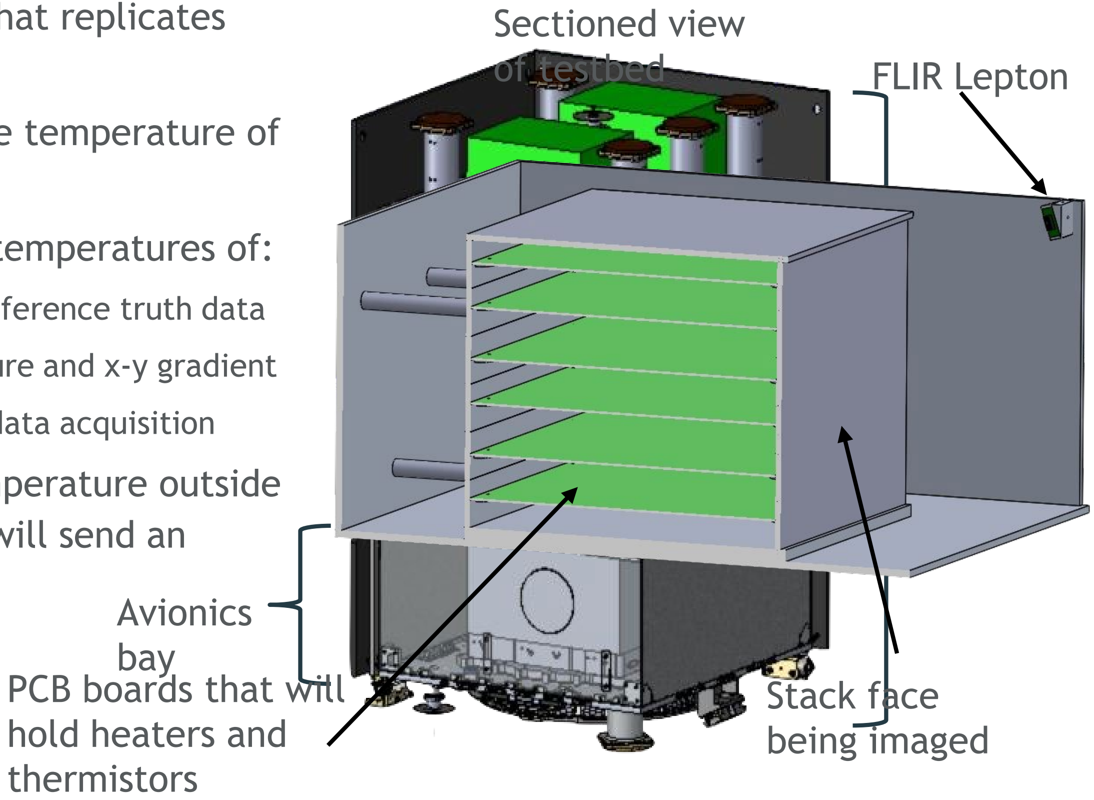


Test Bed Structure

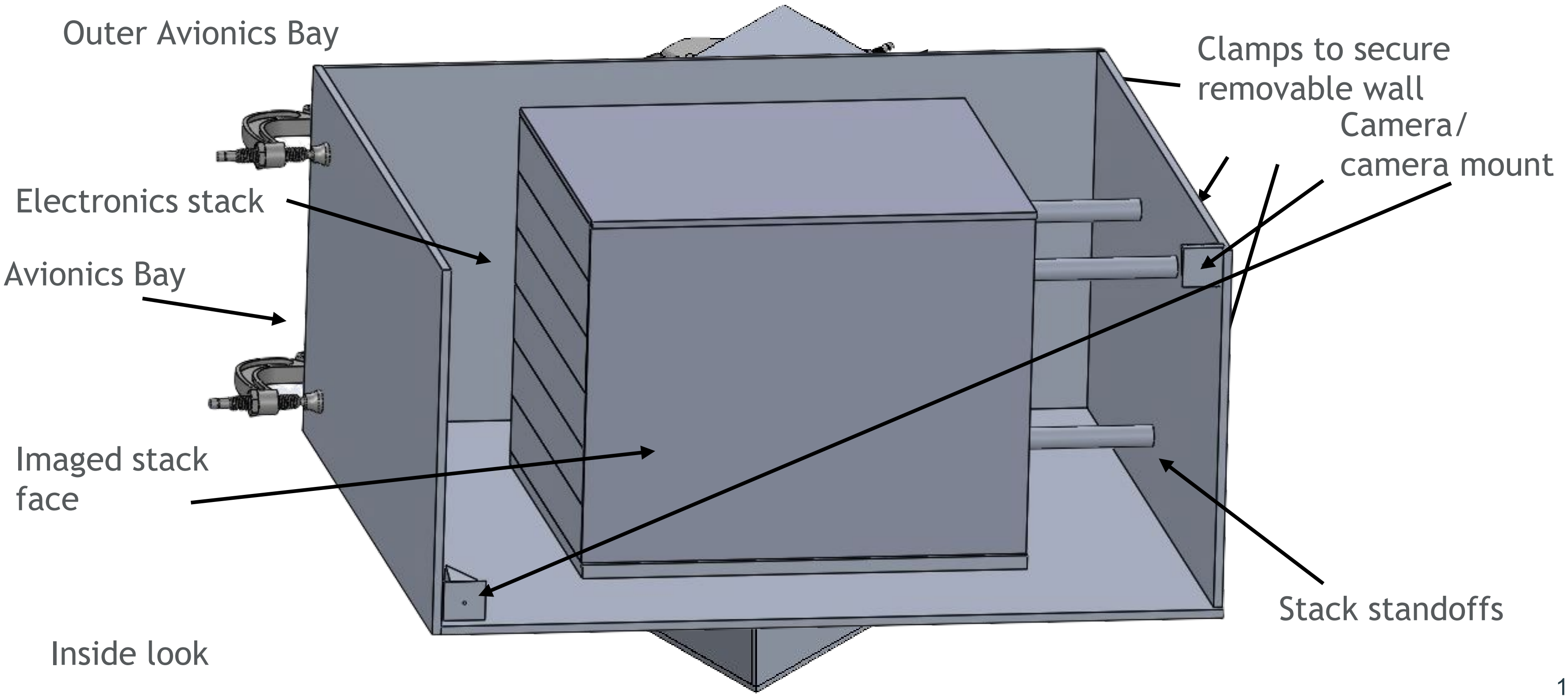
Design Solution

Avionics Bay

- Creating a mock avionics bay that replicates our customers design
- Using LWIR cameras to take the temperature of the walls of the stack
- Using Thermistors to take the temperatures of:
    - Inside of the stack wall for reference truth data
    - Lepton camera for temperature and x-y gradient
    - Microcontroller and ADC for data acquisition
- When the cameras sense a temperature outside of operational range, OTheRS will send an on/off command



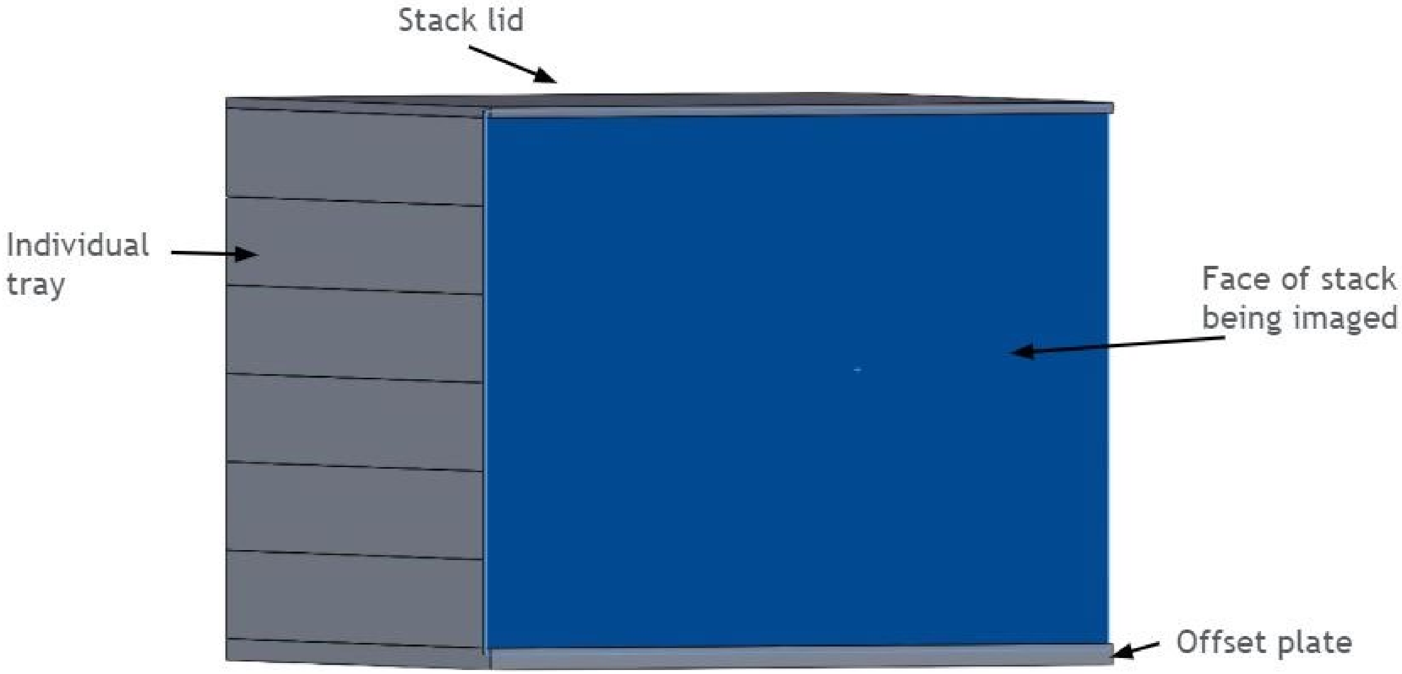
Test Bed



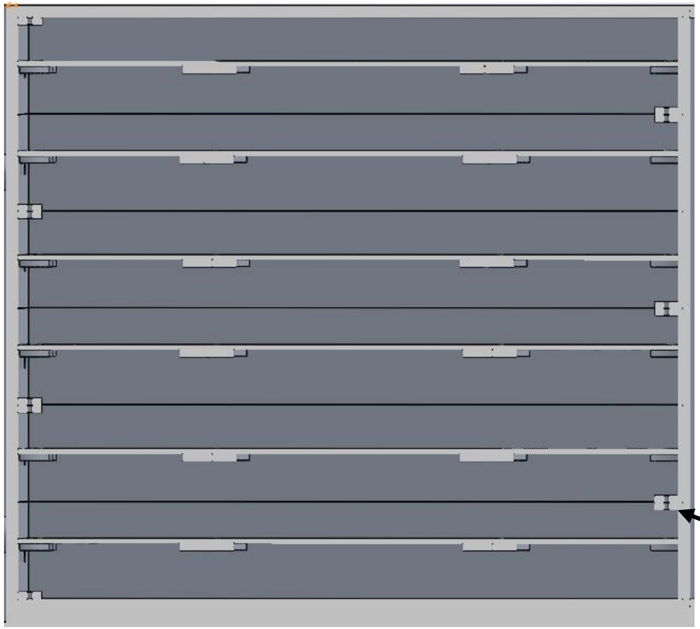
Inside look

Electronics Stack

- Thin plate being imaged can be slid in and out to allow for multiple coatings.
- Grooves in offset plate and stack lid allow imaging of different materials/coatings.

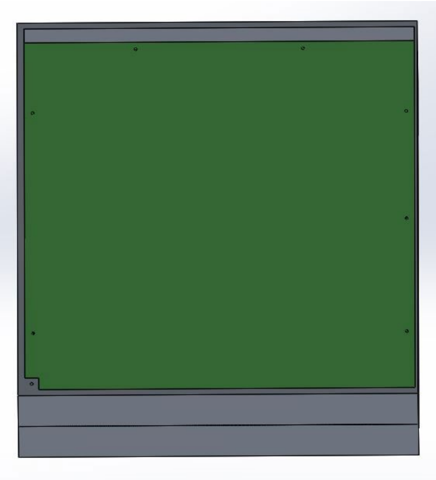


Stack Contents



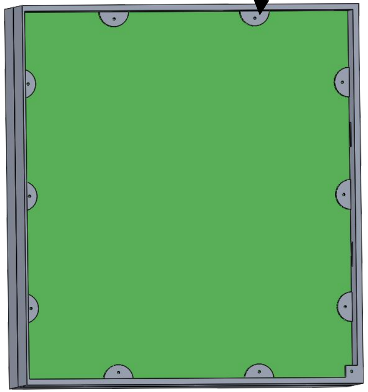
Tray securement tabs

Cross-sectional view of electronics stack



Top of trays

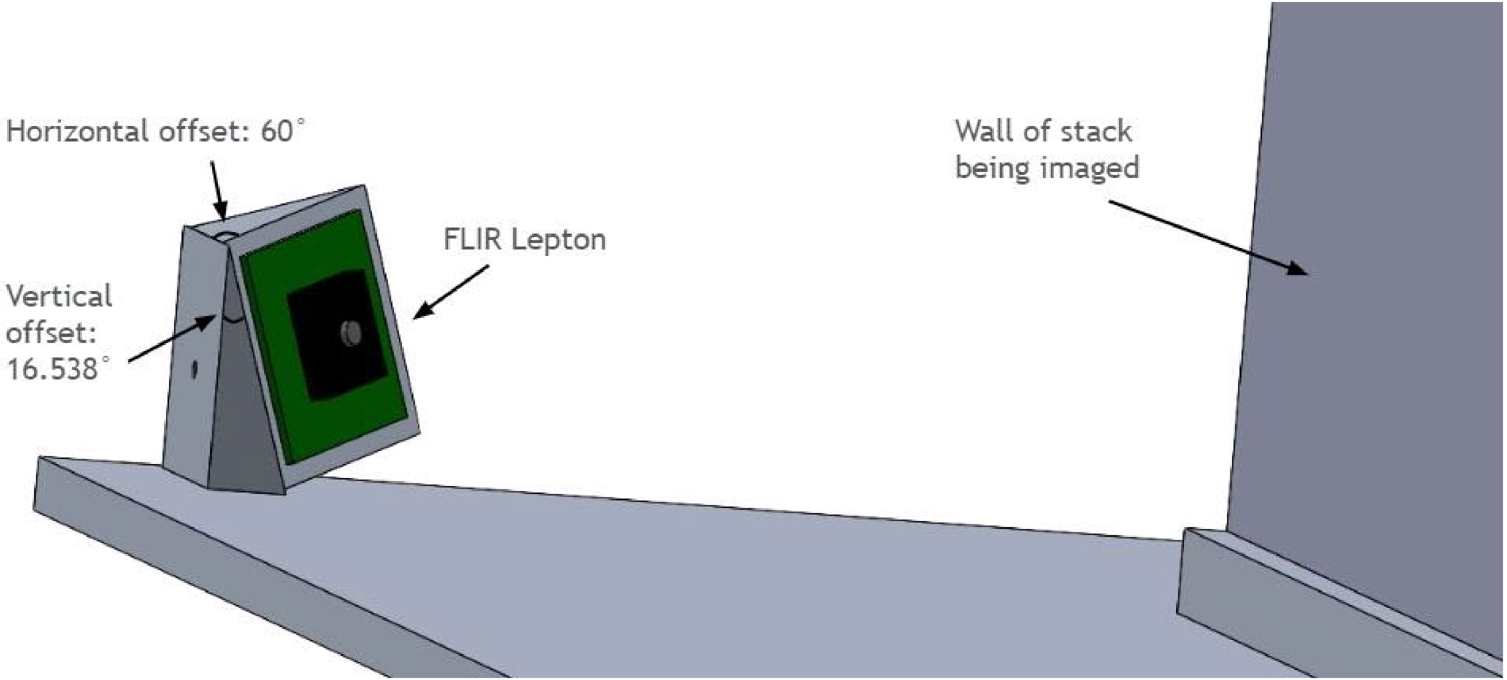
PCB mounting tabs



Bottom of trays

Camera Mounting

Two FLIR Leptons will be mounted in opposite corners that face the side of the stack being imaged



Imaging System

Design Solution

Image Capturing and Processing System

- FLIR Lepton 3.5
  - **Senses wavelengths from 8 to 14μm**
  - **160 x 120 pixels**
  - **Field Of View (FOV)**
    - HFOV = 57°
    - VFOV = 42.33°
    - DFOV = 71°
- Connects to Raspberry Pi 3
  - Pixel stream over 20 MHz SPI
    - Mean data rate 519 kB/s
  - Commands over I2C at 100 kHz
    - Comparatively negligible data rates, commands only sent as required

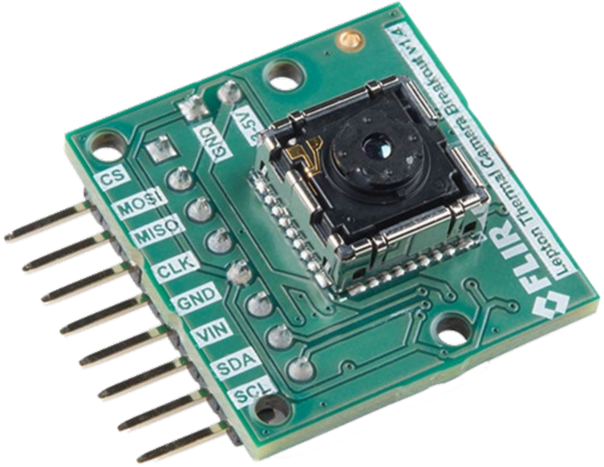


Image Capturing and Processing System

- Raspberry Pi Model 3
  - **CPU:** 4× ARM Cortex-A53, 1.2GHz
  - **GPIO:** 40 pin header, populated
  - **Networking:** 10/100 Ethernet, 2.4GHZ
  - **Product Dimensions:** 85 x 56 x 16mm
  - **Storage:** MicroSD, 32GB
  - Weight: 2.4 oz
- Runs Debian-based OS

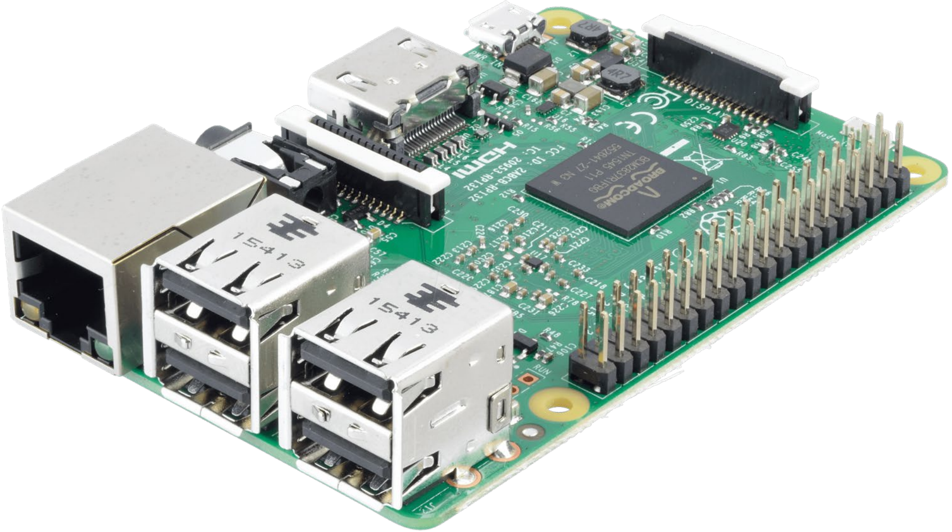
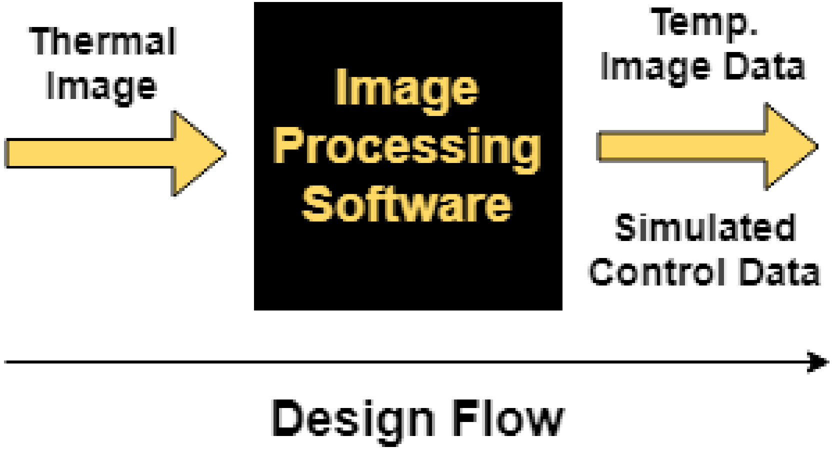


Image Processing Design

- Software Design
  - Input: Thermal image from FLIR Lepton 3.5 camera sensor ➜ Saved in storage.
  - Outputs: ➜ Thermal map of a single-side of the stack ➜ Simulated control data
- Image processing is handled on-board the Raspberry Pi 3
- Microservices architecture for modularized code



Reference Data System

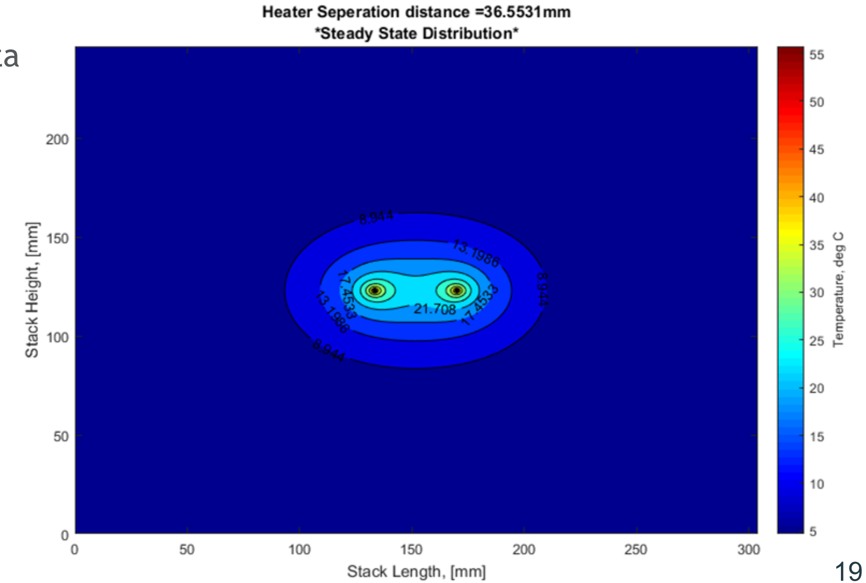
Design Solution

Thermistor Placement

- Driven by the need to compare the thermal image data to truth data
- MATLAB 2D steady state thermal model confirms that power dissipation out of heater should be uniform in all directions along the wall
- Constrained by space and wiring complexity
  - Provides reference data to validate camera data

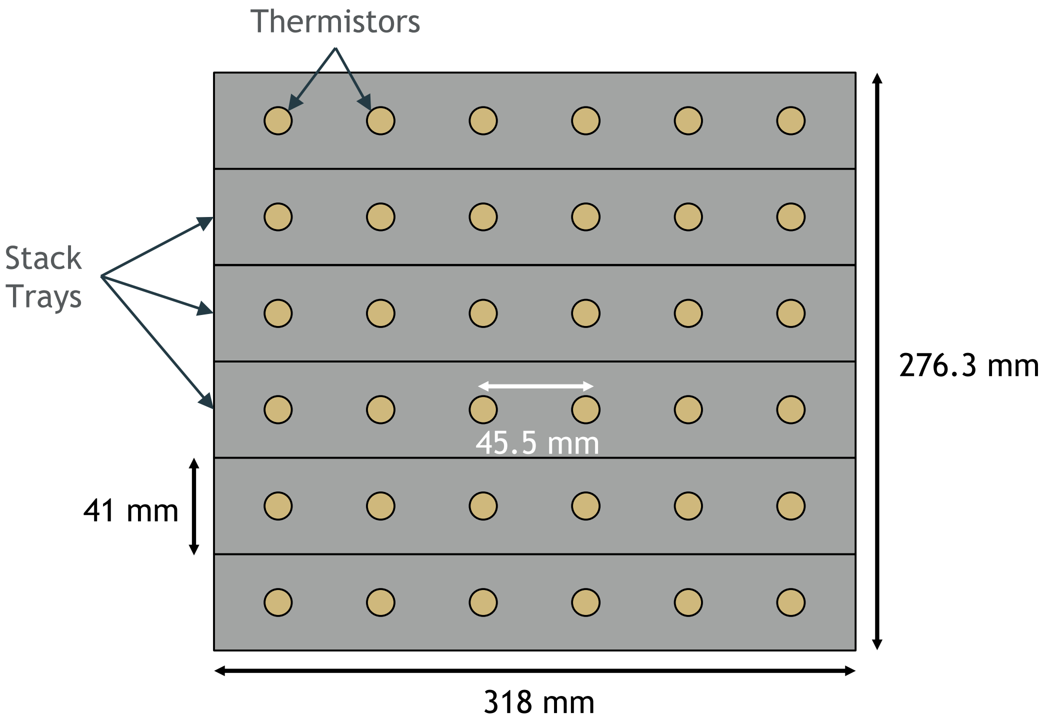
$$Q = \frac{kA\Delta T}{\Delta x} \qquad Q = \epsilon\sigma A T^4$$

$$P = I^2 R$$



Thermistor Placement

- The image processing unit will return the absolute maximum or minimum temperature of each of 6 bins for each tray.
- Thermistors will be placed so that they will return a temperature for each of those bins (shown on figure).
- Each thermistor will have a foam “cap” to block radiated heat



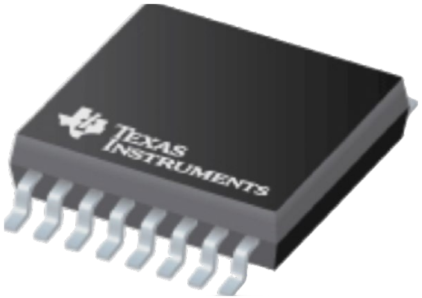
TestBed Thermistor Placement
on Inner Stack Wall

Thermistors as Reference Temperature Source

- Vishay NTCLE413 10 kOhm Thermistors
- Texas Instruments ADC128D818 12 bit ADC
  - 8 channels per chip, up to 72 channels on one I2C bus
- Up to 5 times less uncertainty than FLIR Lepton
  - 0.9 deg C vs 5 deg C

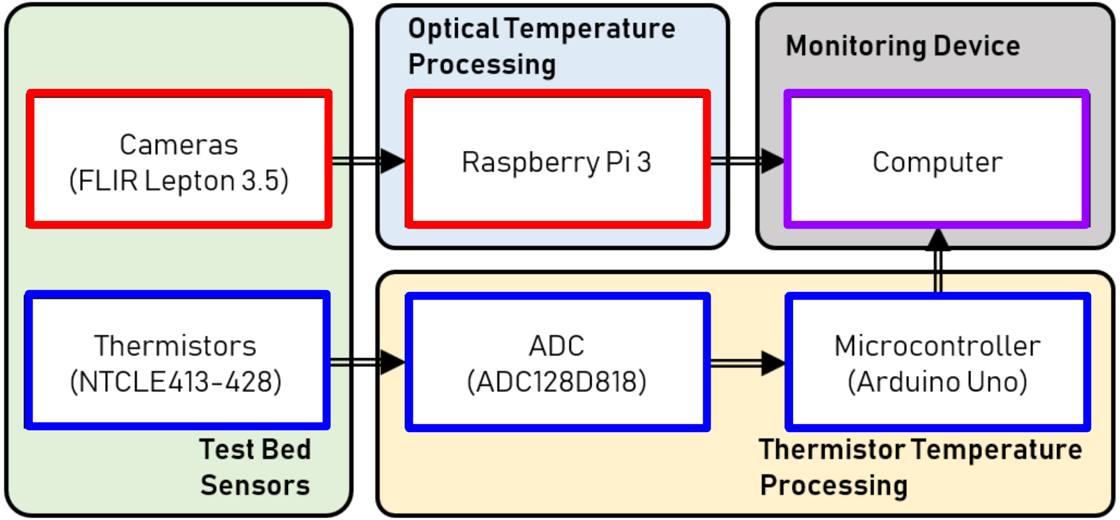
Thermistors

12 bit ADC



Final Testing Data Flow

Thermal Testing Procedure



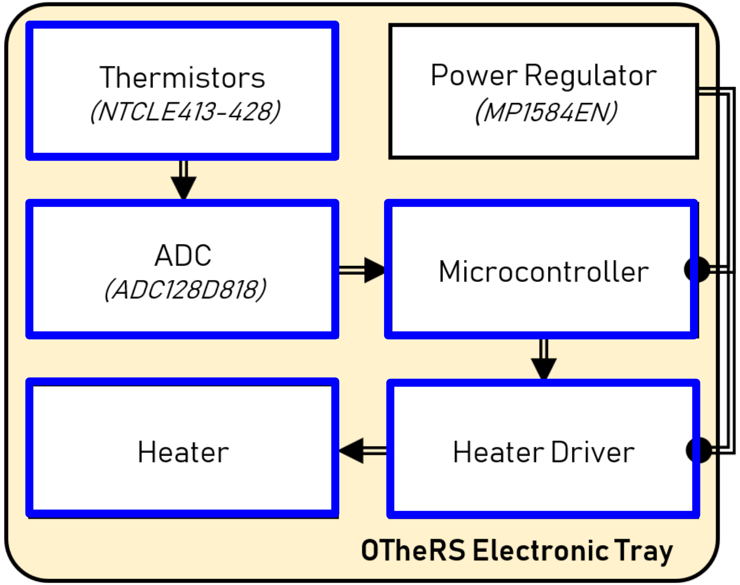
Test Hardware FBD

Simulation Electronics

Design Solution

Simulation Electronics

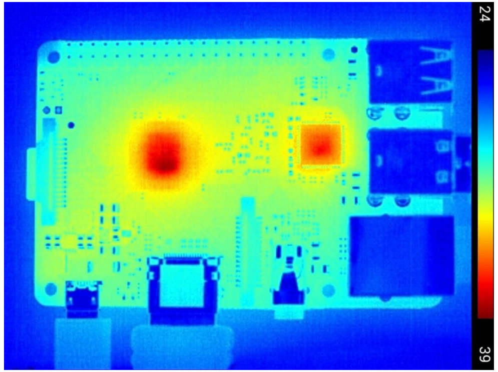
- Power resistors used as heat sources in place of actual avionics
- Constant heat output mode
- Distributed heaters throughout the stack volume



Simulation Electronics

- The test bed will simulate electrical components by the implementation of power resistors. A typical spread of electronic components ranges from 24 to 45 ℃.

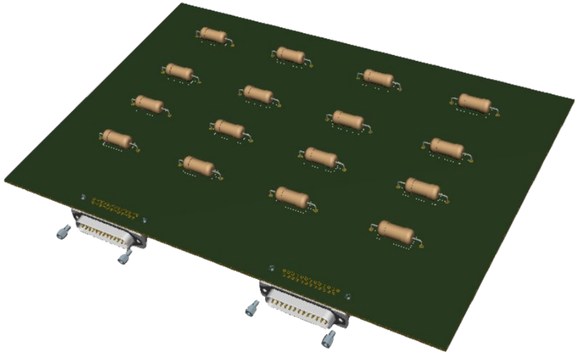
Part	Processor	Board	Port
Typical Usage Temperature	39-43 ℃	28-33 ℃	24 ℃



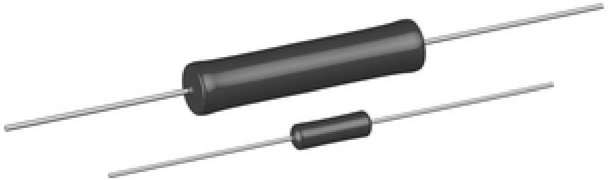
Thermal image of some electrical components

Simulation Electronics

- The power resistors are 10 watt max power dissipation.
- Want to run .5A
- 25 Ohm resistance



Placement of power resistors to simulate electronics



10W 25 ohm Power Resistor

Model: RS01025R00FE73

Critical Project Elements

Critical Project Elements

Critical Project Elements	Description
Image Capture and Processing System	FLIR Lepton and Raspberry Pi, plus associated software
Test Bed Structure	Aluminum test bed
Thermal Control of Camera	Heaters and thermistors to drive and control temperatures of FLIR Lepton
Full-Stack Regulation	Thermal control of Test Bed stack

CPE Explanation

Critical Project Elements	Explanation
Image Capture and Processing System	A thermal camera is a required component of this project. The system must also be able to utilize data from this camera.
Test Bed Structure	Provide a realistic environment in order to test camera and image recognition algorithms.
Thermal Control of Camera	The thermal cameras operating temperature is greater than the minimum temperature it needs to operate in.
Full-Stack Regulation	Need to show whether the thermal camera can successfully control the temperature of elements of the avionics stack

Design Requirements & Satisfaction

Image Capture and Processing

Design Requirements & Satisfaction

Image Processing Software Flow

- 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.

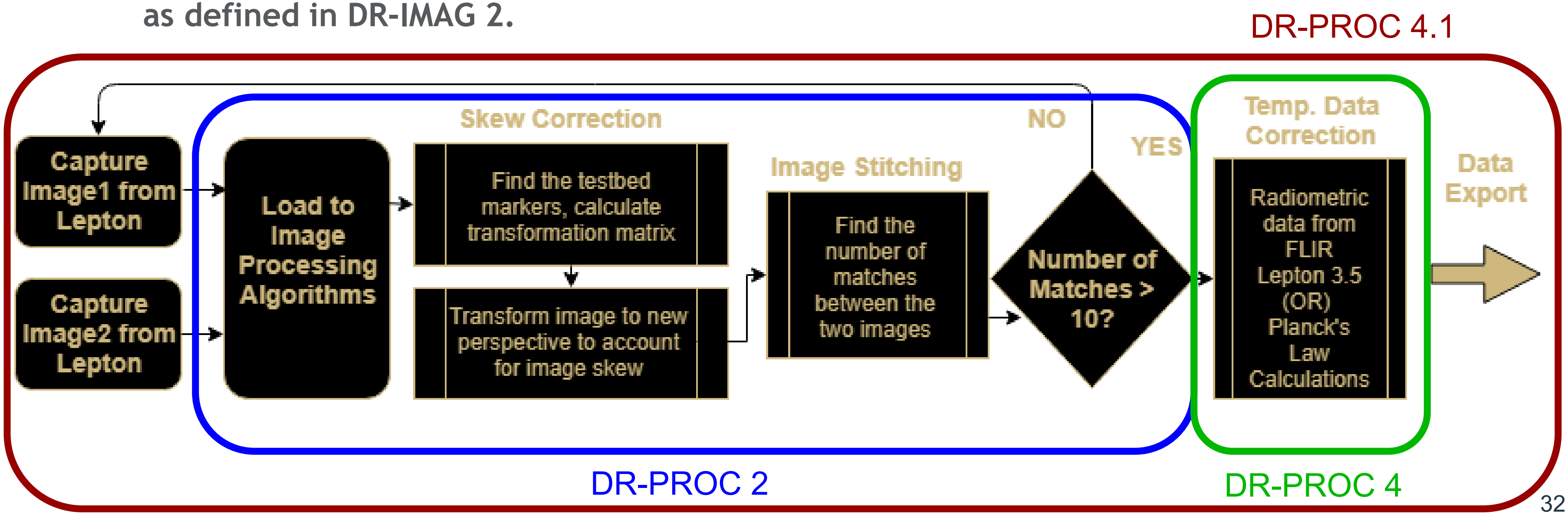
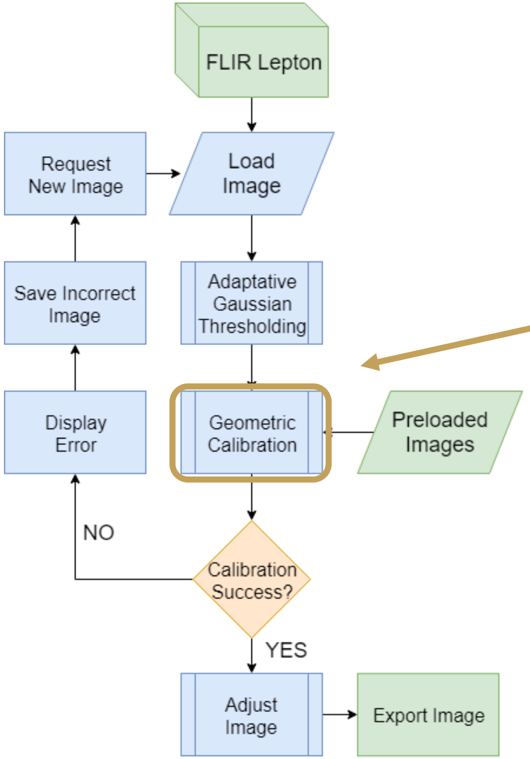


Image Correction



This flowchart showcases how the image correction algorithm is performed.

Geometric Calibration is enhanced via skew correction algorithm.

Skew Correction (1/2)

- **DR-PROC 2: The thermal imaging device(s) shall be both spatially and thermally calibrated with TBD metrics.**

Why?
To correct for the ~60° skew incurred by camera placement to image one side of stack. Image stitching algorithms require a clear image with minimal skew.

OpenCV Perspective Transformation Algorithms

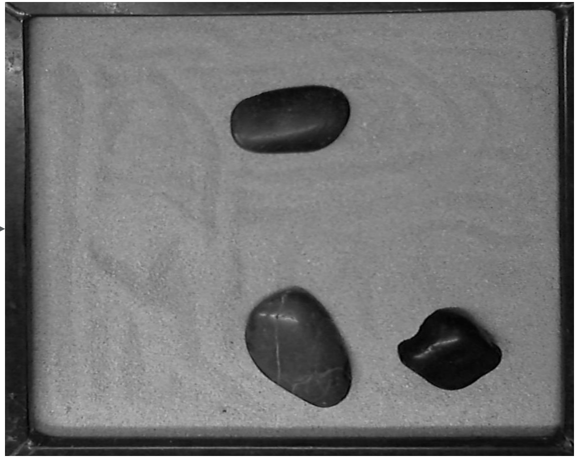
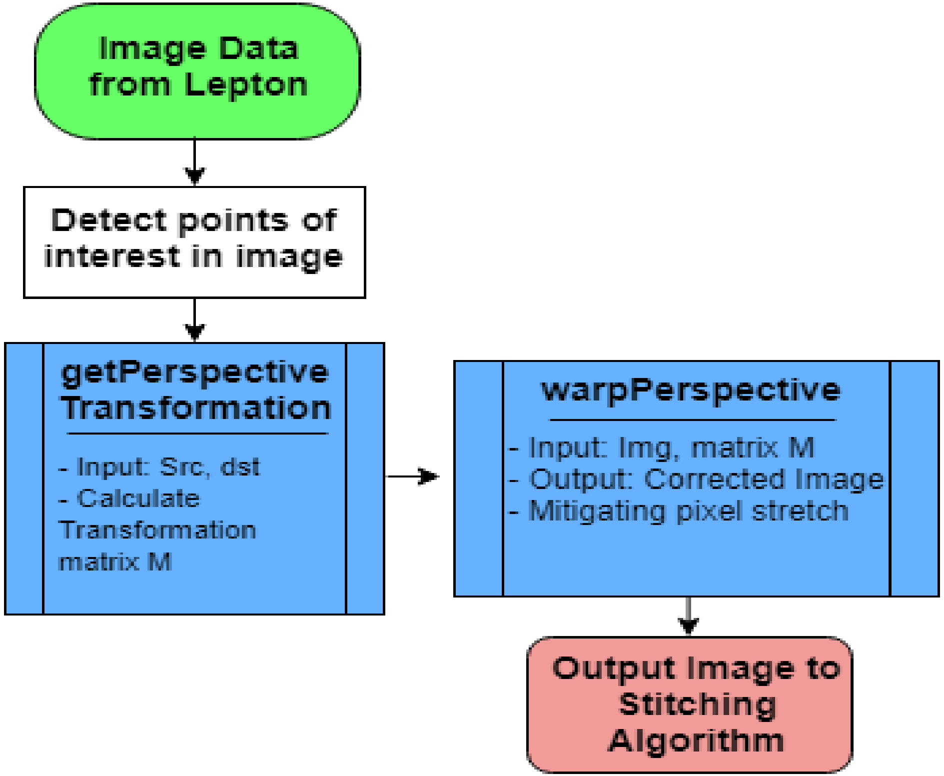


Figure 1. Input image (skewed)

Figure 2. Output image

Skew Correction (2/2)



This flowchart showcases how the skew correction algorithm is performed.

The functions getPerspectiveTransform() and warpPerspective() are common to OpenCV.

Image Stitching (1/3)

- **DR-IMAG 3.1: The field of view (FOV) of the thermal imaging device(s) shall contain at least a single side of stack.**

Why?
Stitch two images together in order to image the entire side of the stack. Algorithms take advantage of the considerable overlap.

Design Drivers: ORB Stitching technique is the fastest technique available for image stitching. Top 15% best point-matches are selected between the two images to create a new single panorama

Image Stitching (2/3)

Input Image A

Input Image B

Output Image = A + B

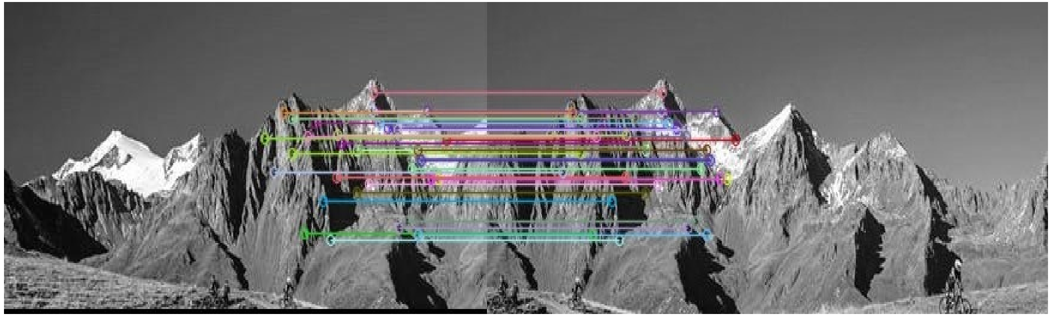
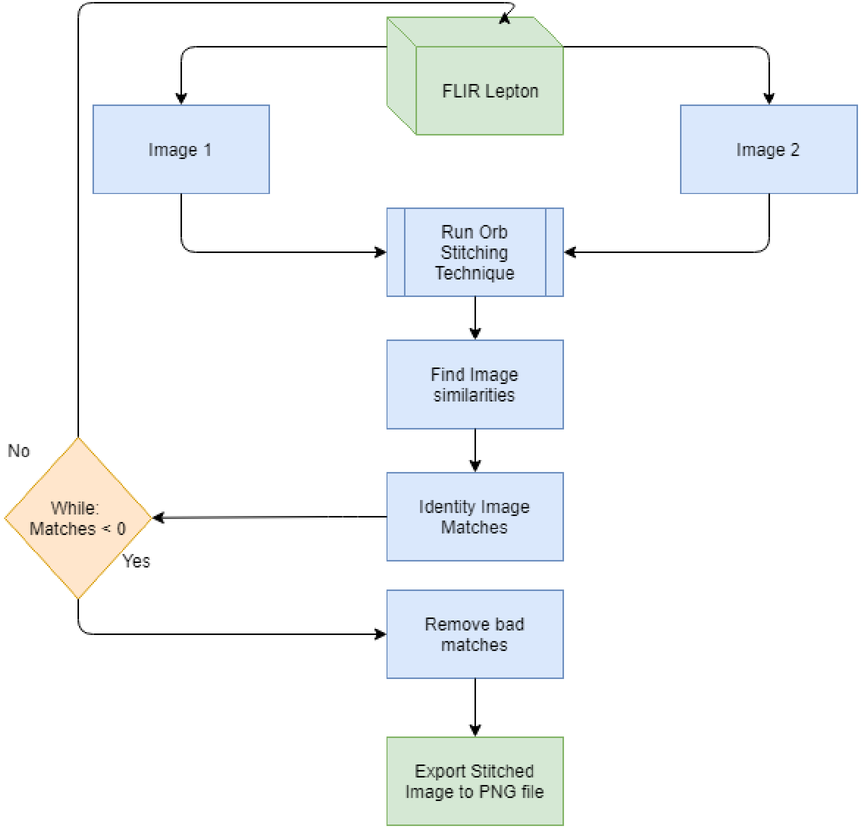


Image Stitching (3/3)



This flowchart showcases how image stitching is performed.

Only the top 15% of detected matches are saved and used in stitching.

Algorithm to stitch two images together via ORB method.

Thermal Correction (1/2)

- **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.**

Why?
Camera output data needs to be transformed into usable temperature data.

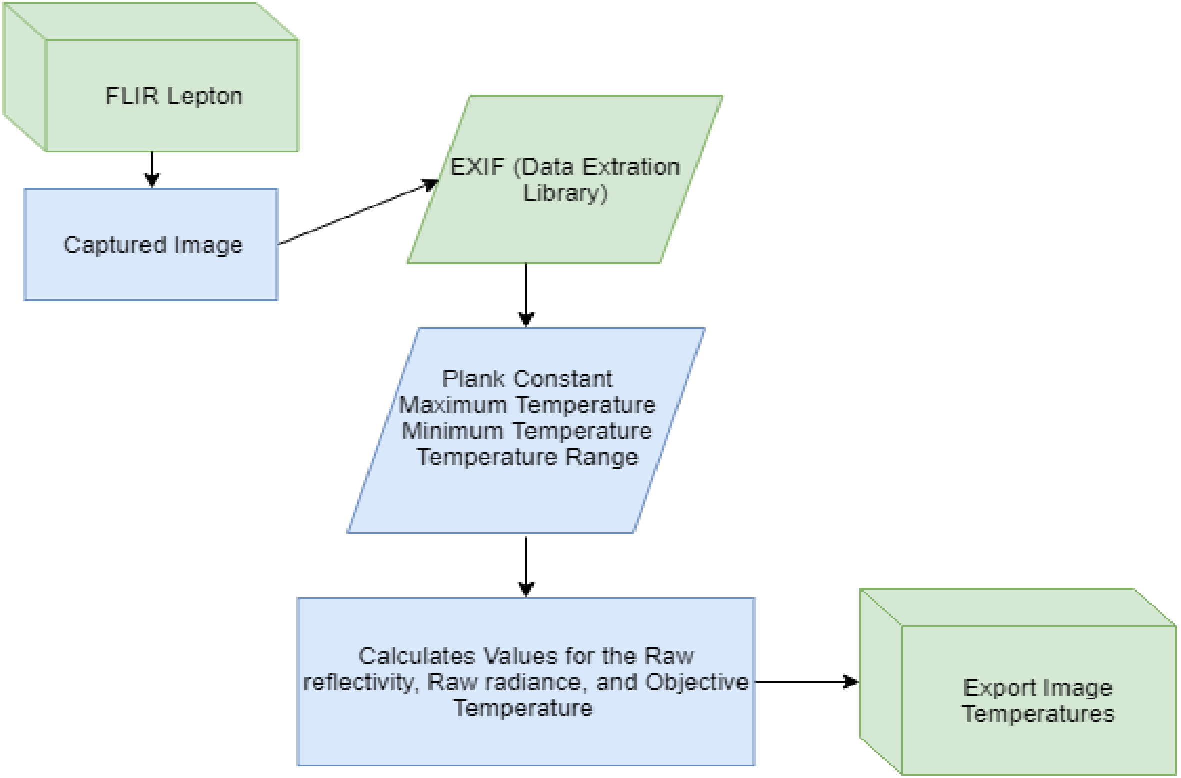
Design Driver:
Radiometry allows for absolute temperature measurements at each pixel location in the image output from the FLIR Lepton 3.5.

Backup methods

→ Planck's Law calculations (applies to any thermal image)

→ High emissivity calibration points

Thermal Correction (2/2)



Electronic Hardware: Microcontroller (1/2)

- **DR-IMAG 2: Images of the stack shall be taken at 90 second intervals.**
- **DR-PROC 3: Internal processing shall control internal thermal regulation of the OTheRS.**
- **DR-PROC 4.1: Automated image processing shall be completed between image captures as defined in DR-IMAG 2.**
- **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.**
- The system requires a microcontroller that can handle processing and communication for the OTheRS.

Raspberry Pi

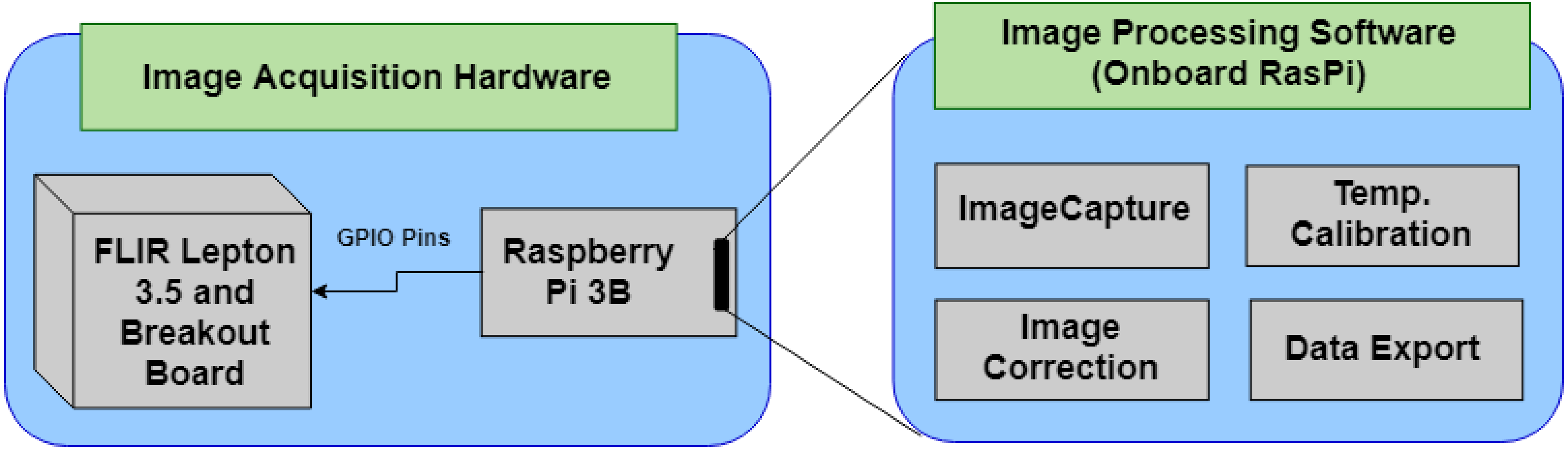
Electronic Hardware: Microcontroller (2/2)

- The Raspberry Pi 3 runs the Image Capture, Image Correction, Temp Calibration, and Data Export through python.
- Initial testing showed that the Raspberry Pi 3 could sufficiently handle the above algorithms. The worst case timings for these algorithms are provided below.

Software Task	Algorithm Complexity	Running Time (ms)
image_capture()	Ơ(1)	235.0
image_stitching()	Ơ(n^2)	538.8
image_correction()	Ơ(n)	435.4
temp_calculations()	Ơ(n)	0.750
calibrate_temp()	Ơ(n^2)	885

Camera/Microcontroller Interaction

- **DR-PROC 4: Temperature data shall be extracted from the thermal image.**
- The Raspberry Pi needs to be able to interface and obtain the data from the cameras.
- Communication between the microcontroller and the Lepton takes place over I2C and SPI.



Hardware/Software Interface Diagram

Design and Functionality

- **DR-PROC 4: Temperature data shall be extracted from the thermal image.**

Pin Name	Interface Type	Number Required	Number Available
SDA	I2C	1	1
SCL	I2C	1	1
MOSI	SPI	1	1
MISO	SPI	1	1
CLK	SPI	1	1
CS	SPI	--	15+
VIN	Power	1	2+
GND	Power	1	8

Connections Required Between
Raspberry Pi 3 and *FLIR Lepton* Breakout Board.

Peripherals	GPIO	Particle	Pin #			Pin #	Particle	GPIO	Peripherals
3.3V			1	X	X	2	5V		
I2C	GPIO2	SDA	3	X	X	4	5V		
	GPIO3	SCL	5	X	X	6	GND		
Digital I/O	GPIO4	D0	7	X	X	8	TX	GPIO14	UART
GND			9	X	X	10	RX	GPIO15	Serial 1
Digital I/O	GPIO17	D1	11	X	X	12	D9/A0	GPIO18	PWM 1
Digital I/O	GPIO27	D2	13	X	X	14	GND		
Digital I/O	GPIO22	D3	15	X	X	16	D10/A1	GPIO23	Digital I/O
3.3V			17	X	X	18	D11/A2	GPIO24	Digital I/O
SPI	GPIO10	MOSI	19	X	X	20	GND		
	GPIO9	MISO	21	X	X	22	D12/A3	GPIO25	Digital I/O
	GPIO11	SCK	23	X	X	24	CE0	GPIO8	SPI (chip enable)
GND			25	X	X	26	CE1	GPIO7	
DO NOT USE	ID_SD	DO NOT USE	27	X	X	28	DO NOT USE	ID_SC	DO NOT USE
Digital I/O	GPIO5	D4	29	X	X	30	GND		
Digital I/O	GPIO6	D5	31	X	X	32	D13/A4	GPIO12	Digital I/O
PWM 2	GPIO13	D6	33	X	X	34	GND		
PWM 2	GPIO19	D7	35	X	X	36	D14/A5	GPIO16	PWM 1
Digital I/O	GPIO26	D8	37	X	X	38	D15/A6	GPIO20	Digital I/O
GND			39	X	X	40	D16/A7	GPIO21	Digital I/O

Raspberry Pi 3 Pins

Structure and Environment

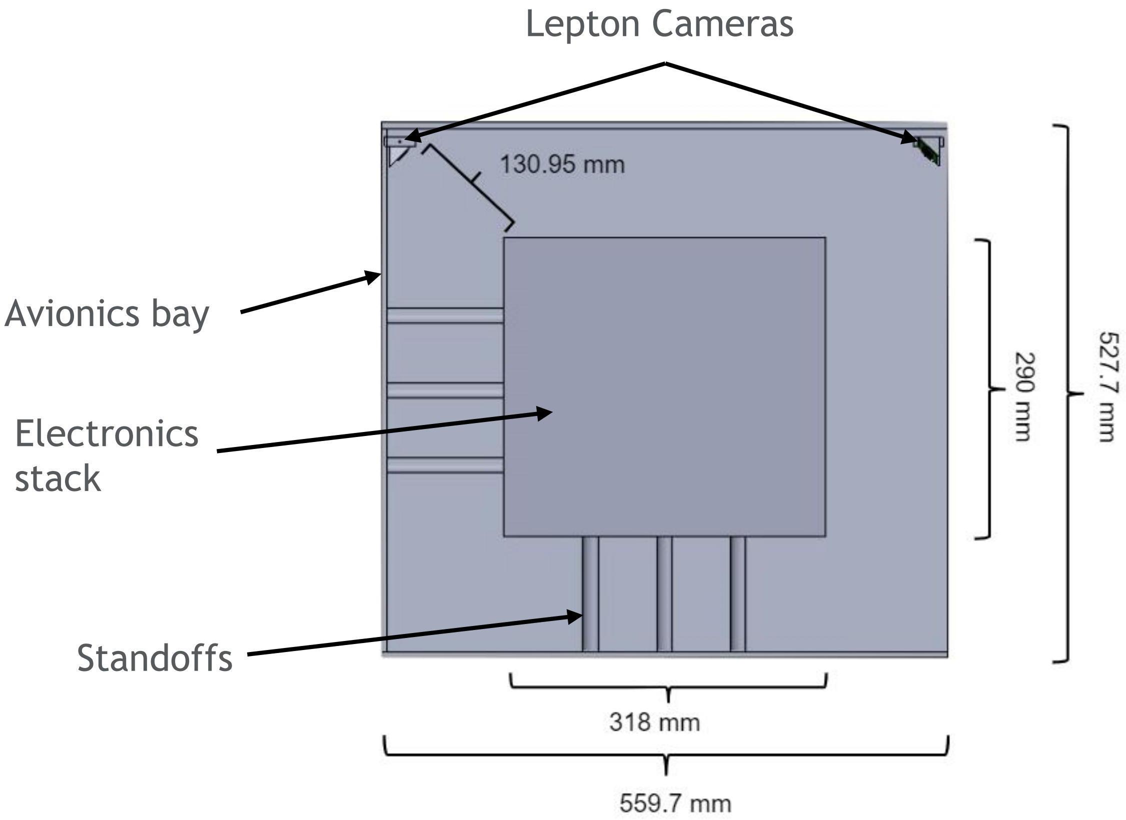
Design Requirements & Satisfaction

Satellite Replication

- **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.**

- Satisfying the above requirements will replicate physical dimensions of the customer satellite.

Stack Replication



Material Replication

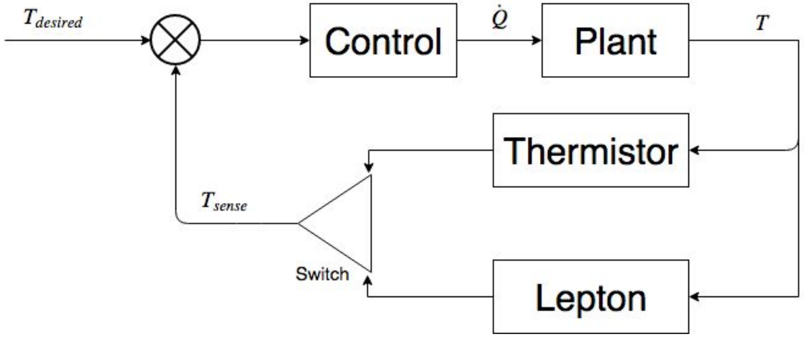
- **DR-TEST 4: Test bed shall replicate material thermal properties of GA's satellite bay.**
- Current chosen material: Aluminum 6061-T6
  - Customer has provided a list of substitute construction materials.
    - Al 6061-T6 falls on the substitute material list.

Full Stack Regulation

Design Requirements & Satisfaction

Full Stack Thermal Control

- **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.**
- Process temperature information from Lepton and make control decisions
- Will also validate control law and the concept of using surface temperatures as a method of regulating avionics by using thermistors as an independent reference source.
  - First, we will show that we can control the surface temperature of a single point.
  - Extend to many points on the surface
  - Will first show that the system can sense, and then respond correctly using physical Indicators (LEDs)



Camera Thermal Control

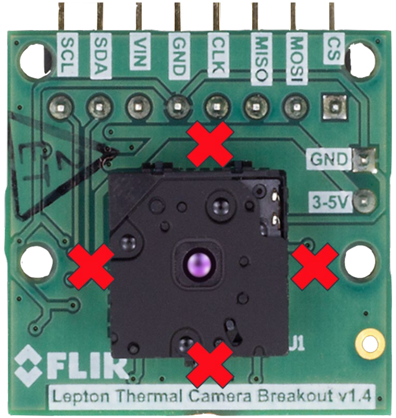
Design Requirements & Satisfaction

OTheRS Thermal Control

- **DR-THER 1: The internal temperature of the OTheRS shall be monitored by at least one thermistor.**
- Components such as the Raspberry Pi and the FLIR Lepton have strict temperature thresholds that need to be met during high temperature and low temperature testing.
- High temperature:
  - Lepton features an over-temperature warning and automatic shutoff.
  - Raspberry Pi downclocks to cool down if above maximum operating temperature.
- Low Temperature:
  - Active temperature control will be required to keep the Lepton and Raspberry Pi above its minimum operating temperature.
  - Need to eliminate temperature gradients horizontally across the components.
  - So long as the temperature is even and in the operable range, the Lepton can internally compensate for varying internal temperatures.

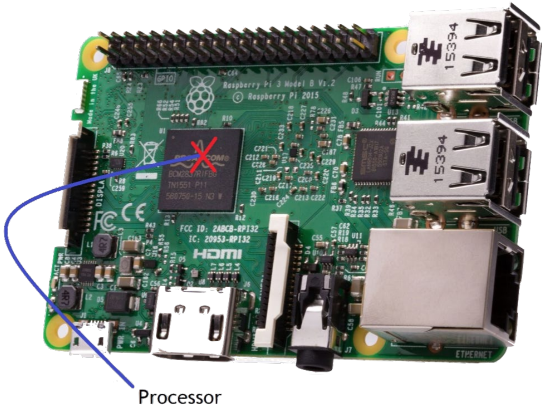
Thermistor Placement

- **DR-THER 1: The internal temperature of the OTheRS shall be monitored by at least one thermistor.**
- Enclosed system combined with IR imaging requires careful monitoring of heat entering the system.
- Camera sensitive to temperature gradients.
- If placed in environmental chamber, the Raspberry Pi will also require monitoring.



Thermistor location

Camera with thermistor locations



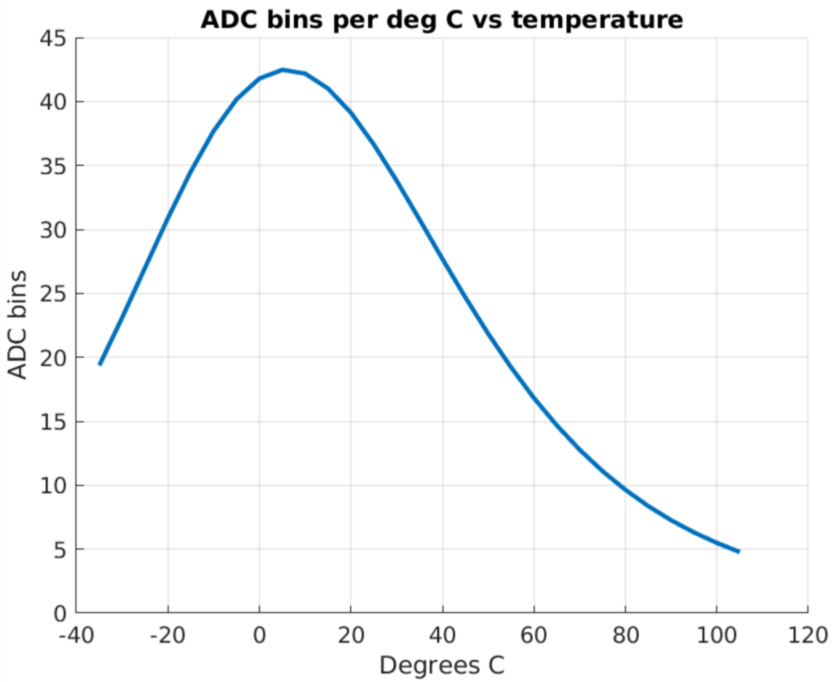
Raspberry Pi with thermistor location

Self Regulation

- **FR 7: OTheRS shall regulate its own temperature**
- Minimum operating temperature of the Lepton is -10 degrees C
- Will need its own heater when tests are conducted at -30 degrees C
    - Approximately 1 W of additional heat is required. Will place heater behind sensor, on opposite side of PCB
- Should multiple heaters be required to counter temperature gradients, they will be controlled by the a microcontroller.

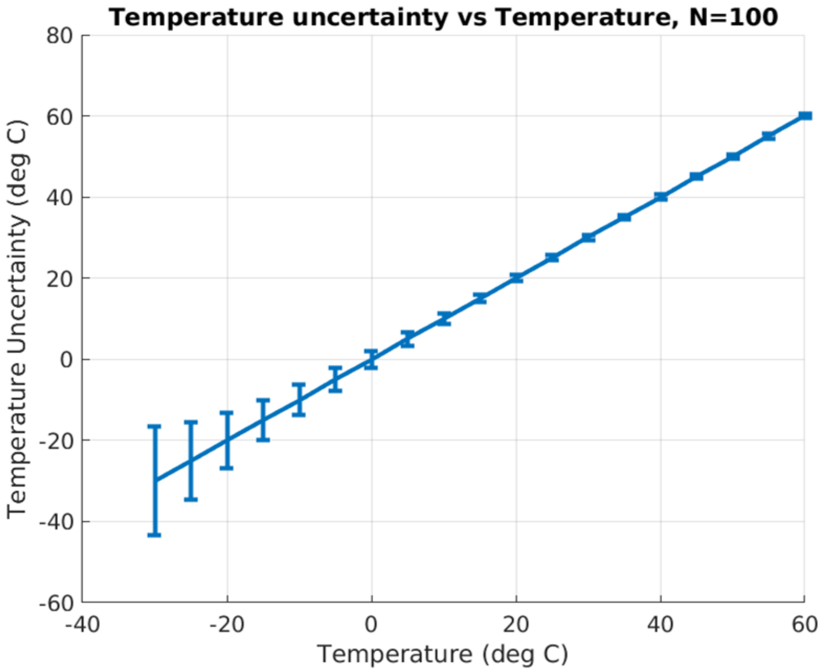
Thermistors: Measurement Resolution

- Vishay NTCLE413 10K 1% thermistors
- Ti ADC128D818 12 bit I2C ADC
- Resolution: 42 bins per degree C at 5C
- Expected signal noise of about 1mV, or about 1.2 LSB
- Better than stated accuracy of Lepton



Thermistors: Error Analysis

- Uncertainties of 0.9 degrees C achievable
- Majority of uncertainty at low temperatures is bias error
  - Not affected by increased sample sizes
- Can be calibrated out, but not affected by sample size or sampling methodology
- Characterize electrical properties of each thermistor in order to reduce bias errors



Project Risks

Risk Assessment

Risk	Description	Likelihood	Severity	Total
MAT-1	Surface IR reflectivity compromises data	5	5	25
IP-1	Trays can’t be individually distinguished	4	4	16
IP-2	Image stitching fails in combining views	2	4	8
CTRL-1	Control system failure to close the loop	2	2	4
THERM-1	Inaccurate surface-to-PCB temp. mapping	4	5	20
ELEC-1	Static discharge kills electronic component	3	5	15
TEST-2	Fogging/condensation occur on lens at low T	2	3	6

Risk Before Mitigation

High

Severity

CTRL-2		ELEC-1	THERM-1	MAT-1
	IP-2, THERM-2	THERM-3	IP-1	
VAL-1	TEST-2			
	MAT-2, CTRL-1			TEST-1

Low

Likelihood

High

Mitigation Strategies

Risk	Description	Mitigation Strategy
MAT-1	Surface Reflectivity	Increase surface roughness, add coating, change stack material
IP-1/2	Tray determination / image stitching fail	RANSAC → Top 15% of best matches
CTRL-1/2	Temperature control fails	Failsafe power switch + test observing
THERM-1	Inaccurate PCB temp. mapping	Use truth data, modeling, testing to resolve errors
ELEC-1	Static discharge	Grounding from camera to test bed, test bed to earth
TEST-2	Fogging or condensation	CO2 dry gas purging

Risk <u>After</u> Mitigation

Severity (High to Low) vs. Likelihood (Low to High)

CTRL-2, THERM-1 ELEC - 1				
	IP-1 IP-2	THERM-3		
THERM-2		MAT- 1		
TEST-2	CTRL-1	TEST - 1		
MAT-2 VAL-1				

High
Severity
Low
Likelihood
High

Verification & Validation

Thermal Regulation Testing

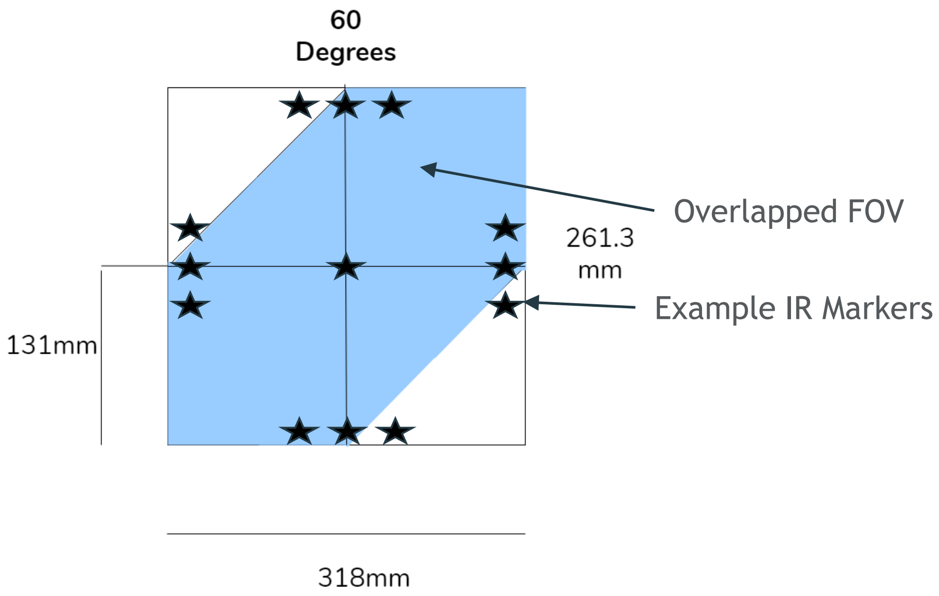
- **FR 7:** OTheRS shall regulate its own temperature.
  - Initial verification
    - Test cases to verify controller functionality
  - Final verification
    - Check functionality in chamber test environment

- Measurements:
  - Thermistors and internal temperature monitor on Lepton
- Measurement Issues
  - Precision difficulties at low temperatures
    - Uncompensated thermistor uncertainty is greater than potential temperature gradient on Lepton

- Provided Capabilities
  - Keeps the Lepton above minimum temperature
  - Assure even temperature across Lepton

Ambient Testing

- **FR 6:** The thermal imaging device(s) shall image critical stack electronics on at least a single side of the stack.
- **FR 8:** Test bed shall mimic the GA satellite.



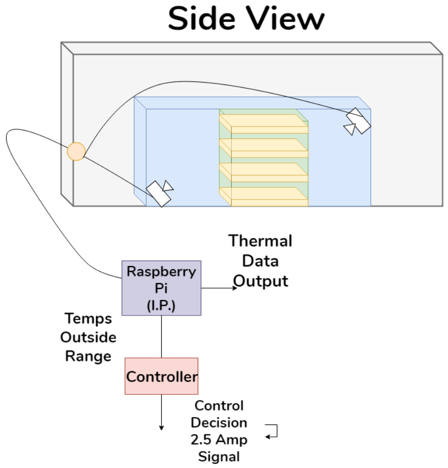
Ambient Testing

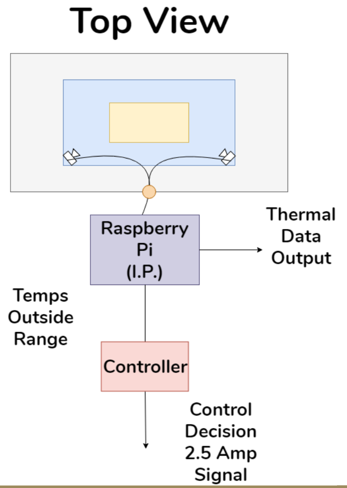
- Measurements:
  - Dimensions
    - Physical dimensions
    - Distance between markers
- Measurement Issues
  - Increased sources for reflectivity
  - Accuracy of measuring device(s)

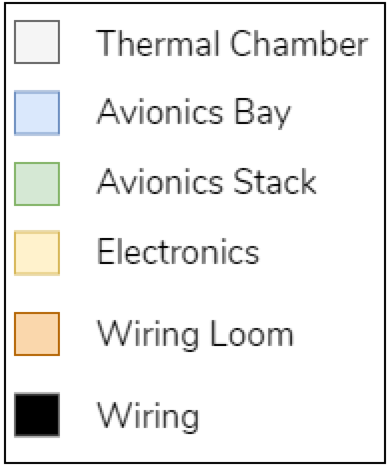
- Provided Capabilities
  - Can observe reflectivity of the system, useful for coatings testing.
  - Can compare temperature data from the camera to thermistor data.
  - Can prove that image processing algorithms operate within the system.

Thermal Chamber Testing

- **FR 1:** OTheRS shall return thermal data map for multiple components between -30°C and 60°C.
- **FR 2:** OTheRS shall provide regulatory commands when components are outside -20°C to 50°C.
- **FR 5**: OTheRS shall be able to switch a 2.5A load as needed to control an externally powered heater or representative indicator.





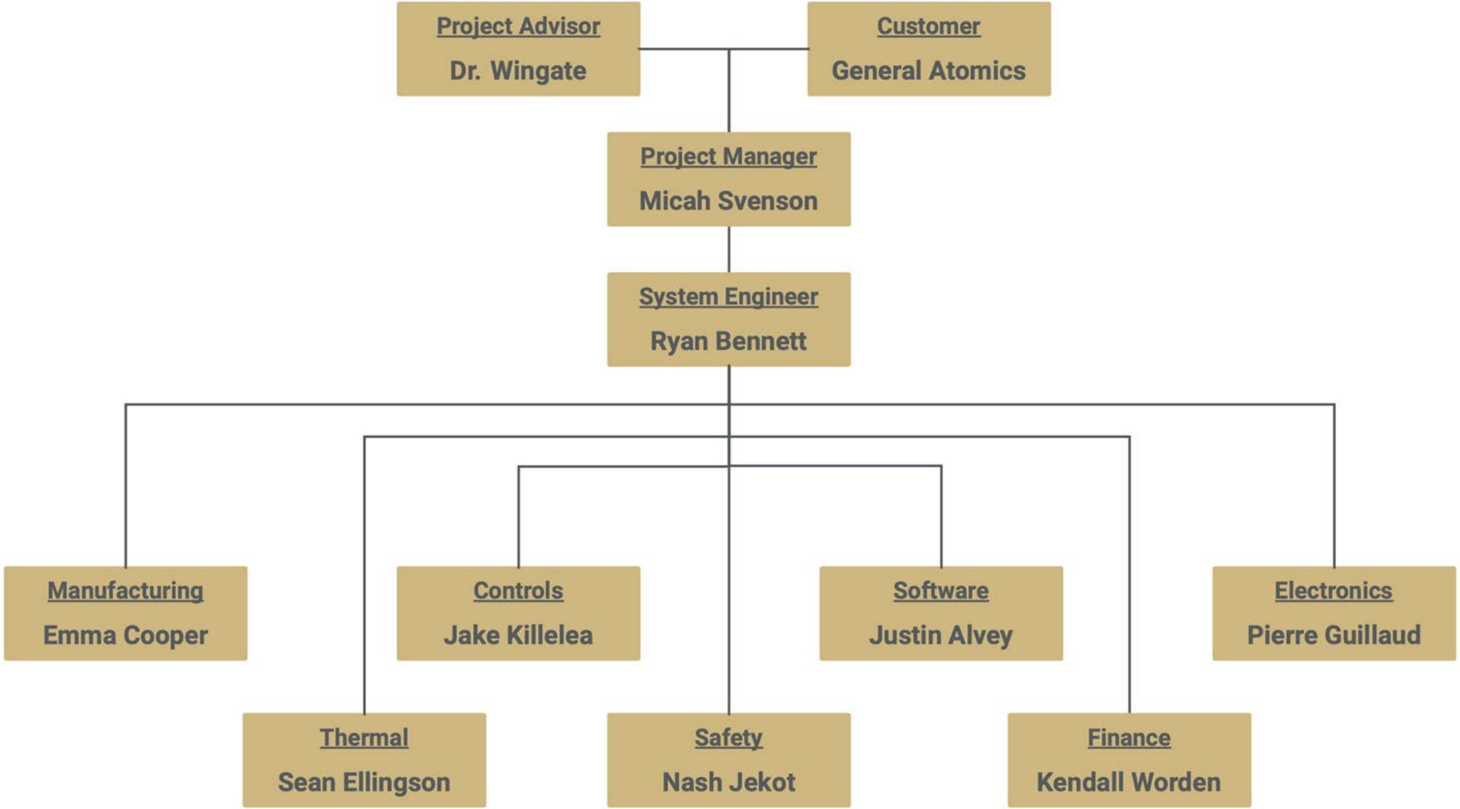


Thermal Chamber Testing

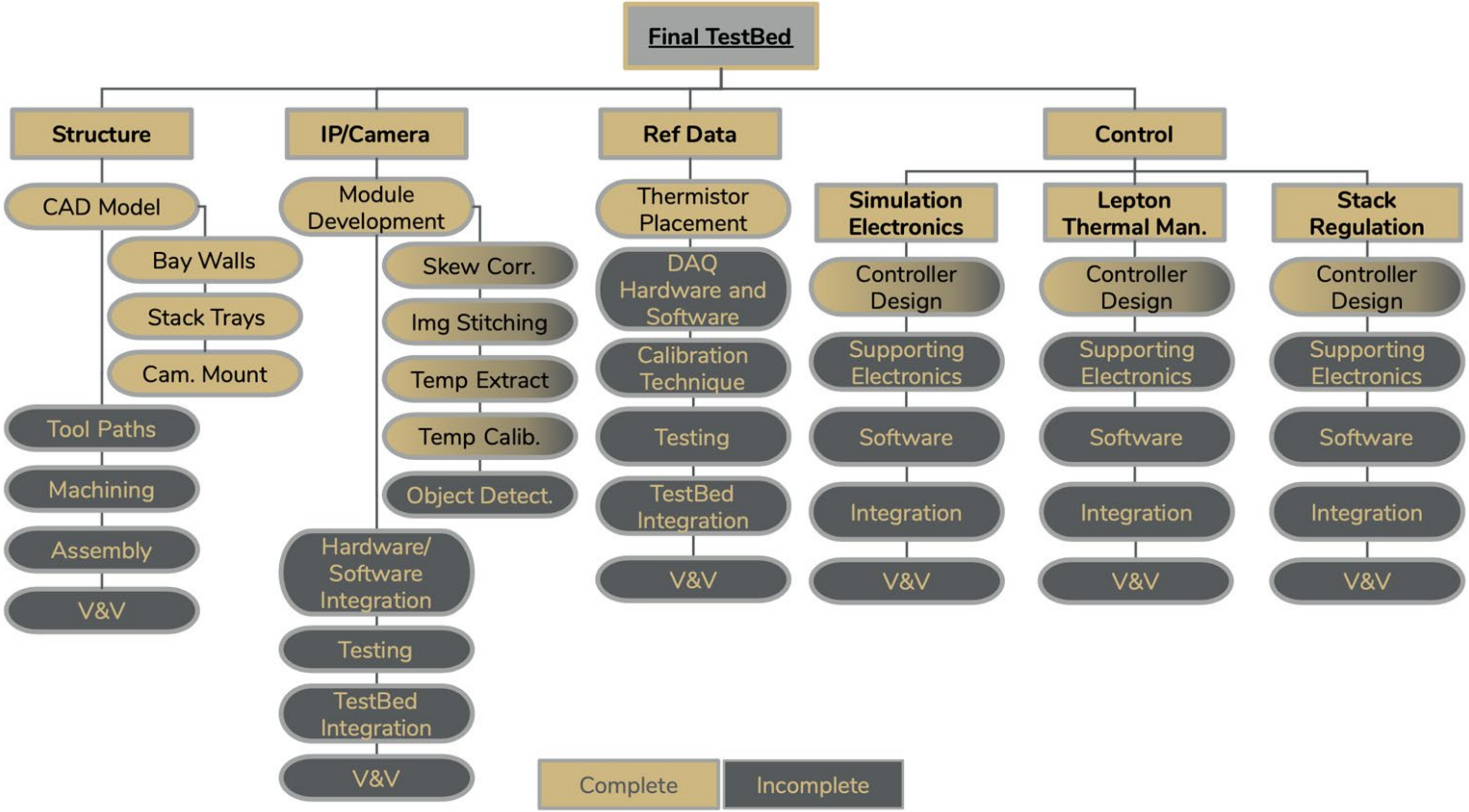
- Measurements:
  - Thermal Measurements
    - Lepton and Thermistors
  - Output Amperage
    - Heater current
- Measurement Issues
  - Poor thermistor uncertainty at low end of testing range
  - Incident heat from internal heaters on thermistor
  - Reflectivity of surface
    - Incorrect temperature measurement
  - Multimeter accuracy
- Provided Capabilities
  - Thermal range can be measured
    - Both Lepton and thermistors
  - ADC gives high sensitivity to thermal changes
  - Controller provides regulation commands
    - Representative indicators or actual components
  - Image processing runs on the PI
    - Object identification
  - Drive customer defined heating element

Project Planning

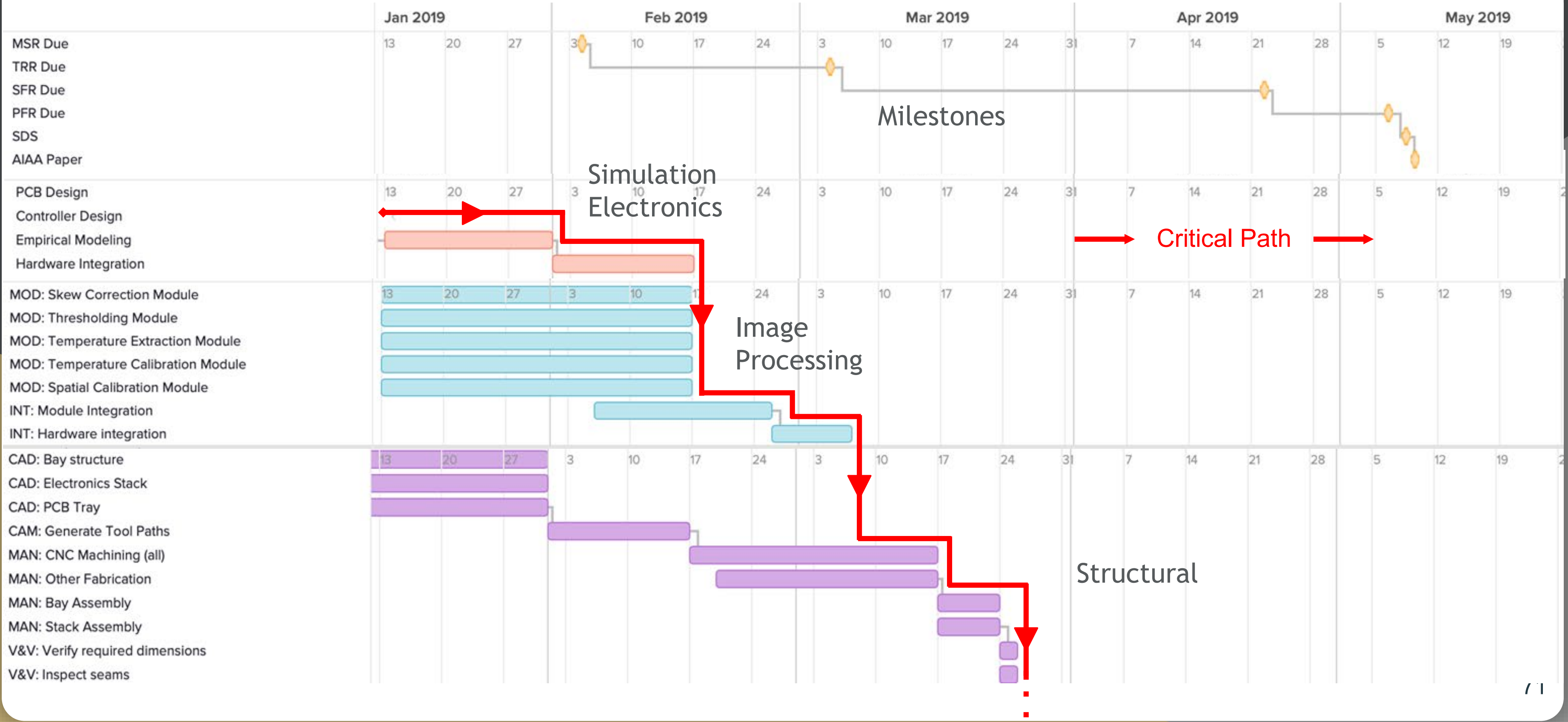
Organizational Chart



Work Breakdown Structure - Final TestBed

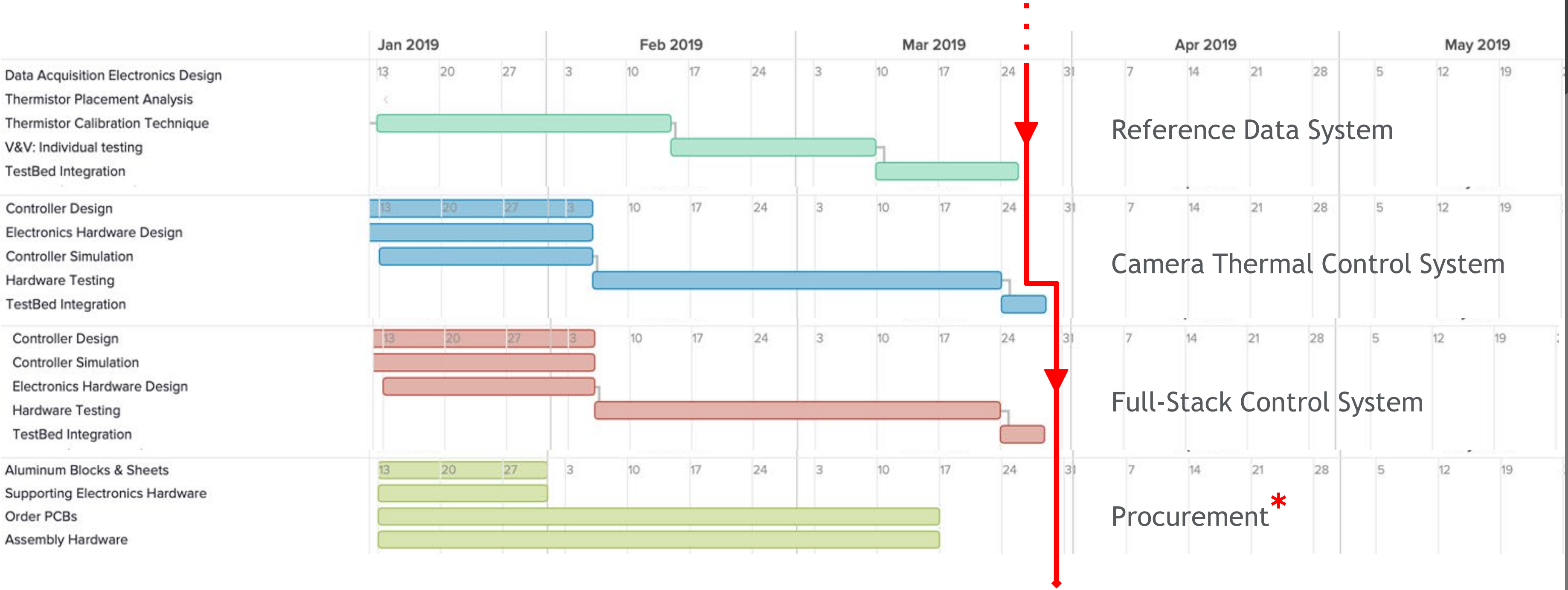


Work Plan



Jan 2019
Feb 2019
Mar 2019
Apr 2019
May 2019
MSR Due
TRR Due
SFR Due
PFR Due
SDS
AIAA Paper
Milestones
PCB Design
Controller Design
Empirical Modeling
Hardware Integration
Simulation
Electronics
Critical Path
MOD: Skew Correction Module
MOD: Thresholding Module
MOD: Temperature Extraction Module
MOD: Temperature Calibration Module
MOD: Spatial Calibration Module
INT: Module Integration
INT: Hardware integration
Image
Processing
CAD: Bay structure
CAD: Electronics Stack
CAD: PCB Tray
CAM: Generate Tool Paths
MAN: CNC Machining (all)
MAN: Other Fabrication
MAN: Bay Assembly
MAN: Stack Assembly
V&V: Verify required dimensions
V&V: Inspect seams
Structural

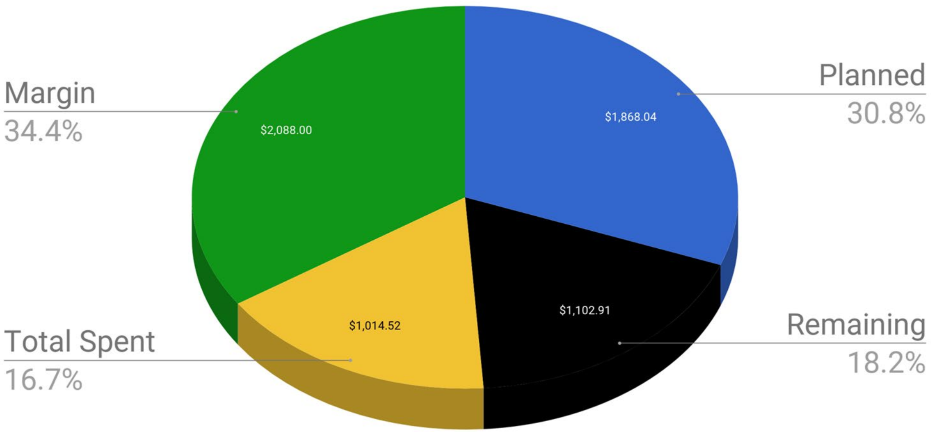
Work Plan



* All procurement activities fall on the critical path with common completion date of Feb 1 or Mar 17

Cost Plan

- Total Cost for Preliminary Test Bed **$1014.52**
- Necessary Components for Final Test Bed
    - Additional FLIR Lepton 3.5 → **$309.01**
    - 10 More 6061 Aluminum Plates for Final TestBed Structure → **$609**
- Coatings (As part of Margin)
    - Acktar Metal Velvet With Adhesive
        - **$260** per bay wall
        - **$132** per stack wall



Test Plan

Datasheet Inspection

Retired Requirements:
IMAG 1, THER 2, COM 2, TEST 2, TEST 4

Testing Date: 1/28/19

Dimension Verification

Retired Requirements:
IMAG 3, TEST 1, TEST 1.1, TEST 1.1.1

Testing Date: 4/1/19

Image Post Processing Check

Retired Requirements:
IMAG 2, IMAG 3.1, PROC 1, PROC 1.1, PROC 4, PROC 4.1

Testing Date: 4/3/19

Control & Comm Verification

Retired Requirements:
*PROC 3, CONT 1, CONT 2, COM 1, COM 1.1, COM 2***

Testing Date: 4/8/19

Final Instrumentation Inspection

Retired Requirements:
*PROC 3, CONT 1, CONT 2, COM 1, COM 1.1, COM 2***

Testing Date: 4/15/19

Questions?

References

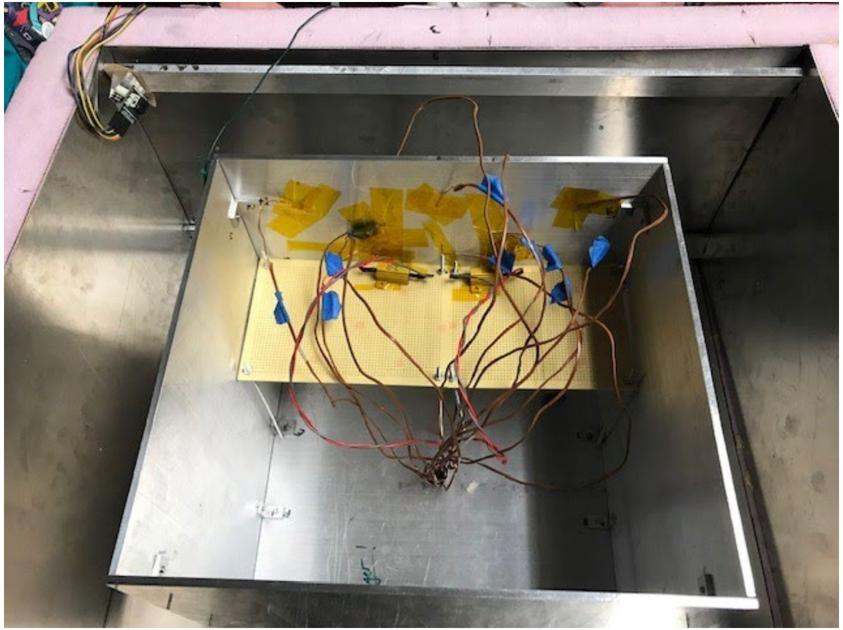
- https://www.unitedaluminum.com/chemical-composition-and-properties-of-aluminum-alloys/
- https://www.makeitfrom.com/compare/2014-T6-Aluminum/6061-T6-Aluminum
- https://www.monolithicpower.com/pub/media/document/MP1584_r1.0.pdf
- https://www.digikey.com/catalog/en/partgroup/lepton-breakout-board/55730?utm_adgroup=Programmers%20Dev&slid=&gclid=EAIaIQobChMIkf6j54WE3wIVFx6tBh1j3gDuEAAYAiAAEgIv9PD_BwE
- https://www.midstateinstruments.com/iriss-small-shaped-high-emissivity-target-labels-4-x-500/

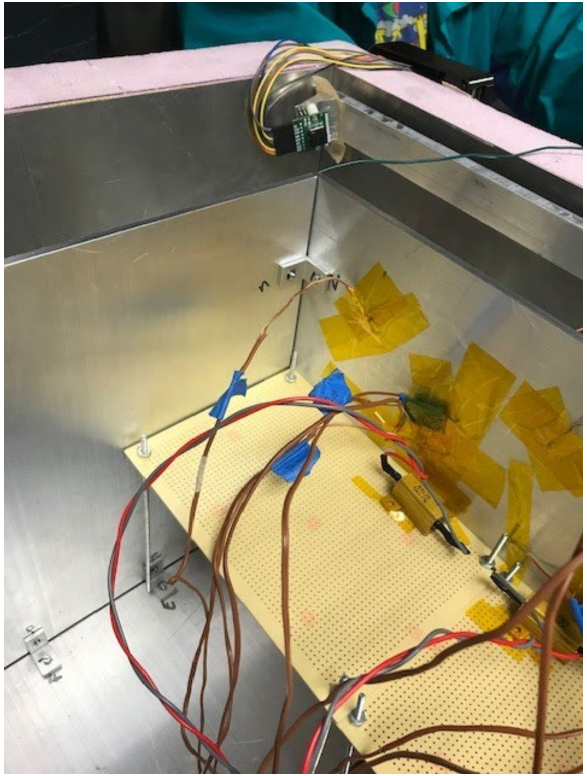
Backup Slide Deck

Initial Test Bed

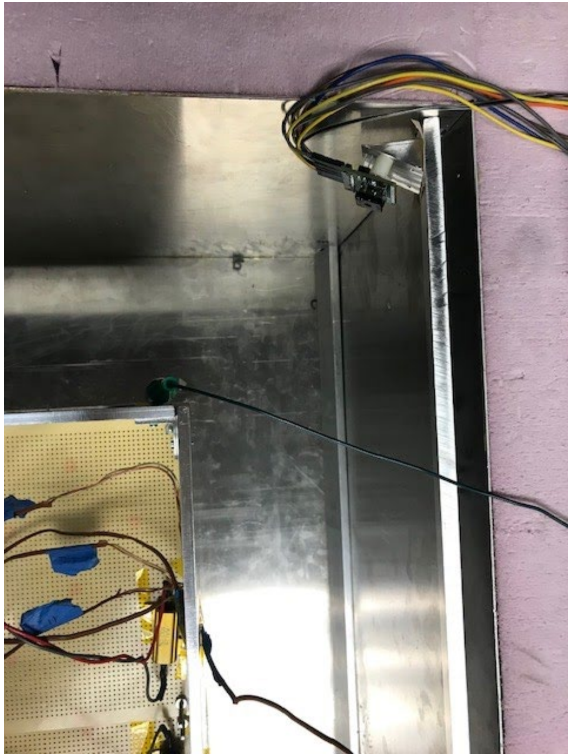
Backup Slide Deck

Initial Test Bed





Initial Test Bed



Initial Test Bed - Reference Data System

- NI 9213 - 16 channel DAQ:

16 Channel DAQ from the ITLL that can resolve thermocouple temperatures within the specified range -40C to 70C to () Accuracy.

NI 9213

- Computer Interface:

The initial test bed thermocouples are displayed on LabVIEW. Their data measured can be saved along with the precise, corresponding time to enable comparison with the thermal images taken.

The final test bed will use thermistors to log the “true” temperature at different points by using a developed C software.

Initial Test Bed - Reference Data Software

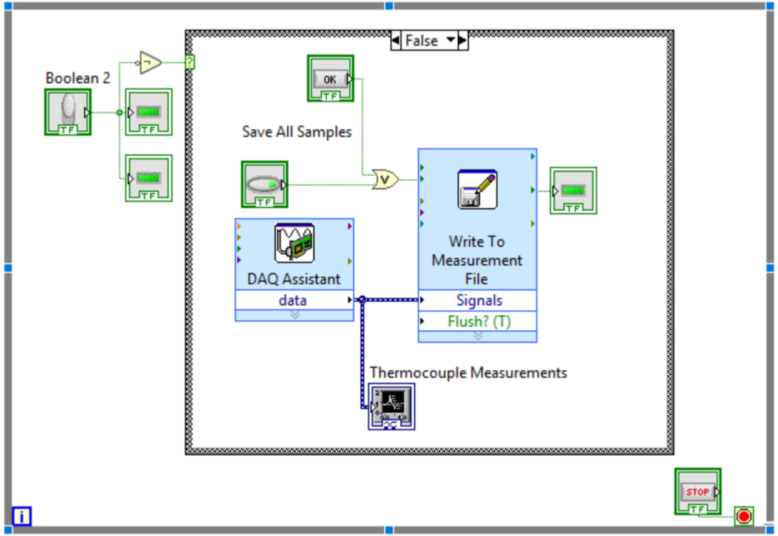
Desired Computer Interface Procedures

Initial testing:

- Save one sample or save continuously.
- Display all 16 thermocouple datas on same plot.
- One thermocouple dedicated to calibration in freezing water to remove offsets.

Final testing:

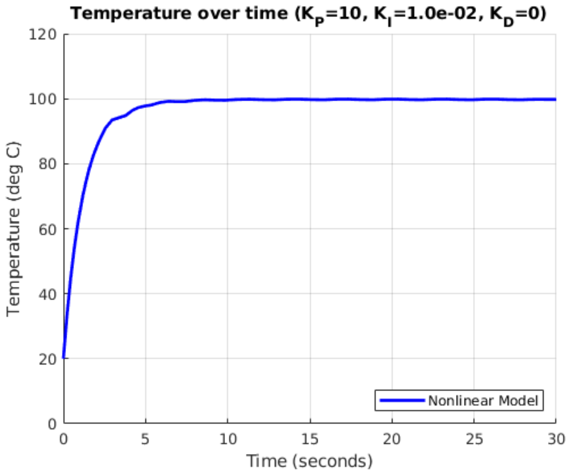
- Side-by-side comparison of measured data from thermocouples and from thermal camera.

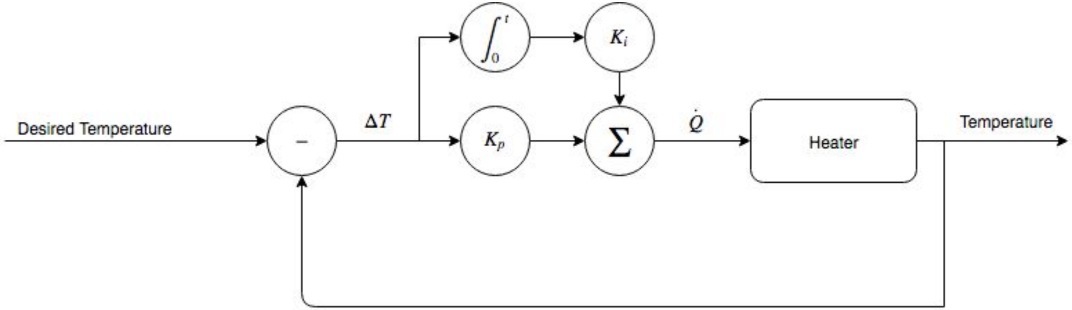


Initial testing LabVIEW flowchart

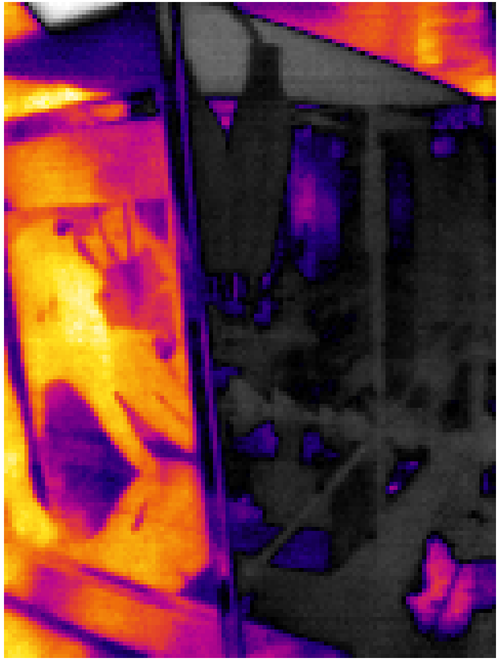
Simulation Electronics: Control

- Modulate heat input using solid state switch
- Gains found and analyzed by simulation
- Power resistors can be reasonably modeled as a first order differential system
- No natural oscillatory modes
- Proportional + integral control is sufficient
- Chassis mount power resistors have time const of approx 600 seconds
- Gains of Kp = 10, Ki = 1/100 validated on nonlinear model





Sample Images from Lepton



- Left: Preliminary test chamber, with lid on
- Right: A hand placed in the test chamber

Hardware Specifications

Backup Slide Deck

Construction Materials

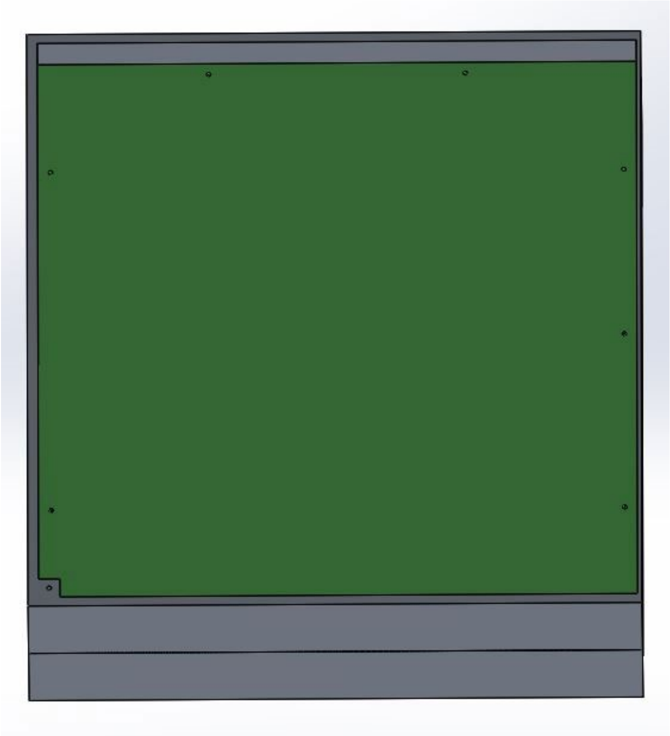
Customer provided list for substitution materials

Standard Substitutions List

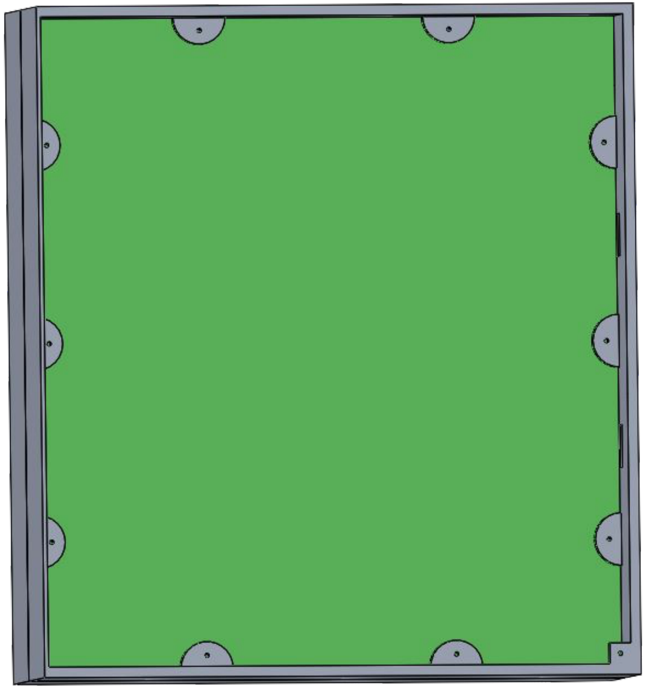
Category	Material	Application	Substitue Material	Notes
Material	AL 6082-T6	Can be subtituted in all situations	AL 6061-T6	
Material	AL 2014 Clad	Can be subtituted in all situations	AL 2024 Clad	
Material	AL 2014-T3		AL 7075-T3/T7351	
Plating			ANODIZE PER MIL-A-8625, TYPE III, CLASS 2, .001 THICK, BLACK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

PCB Mounts

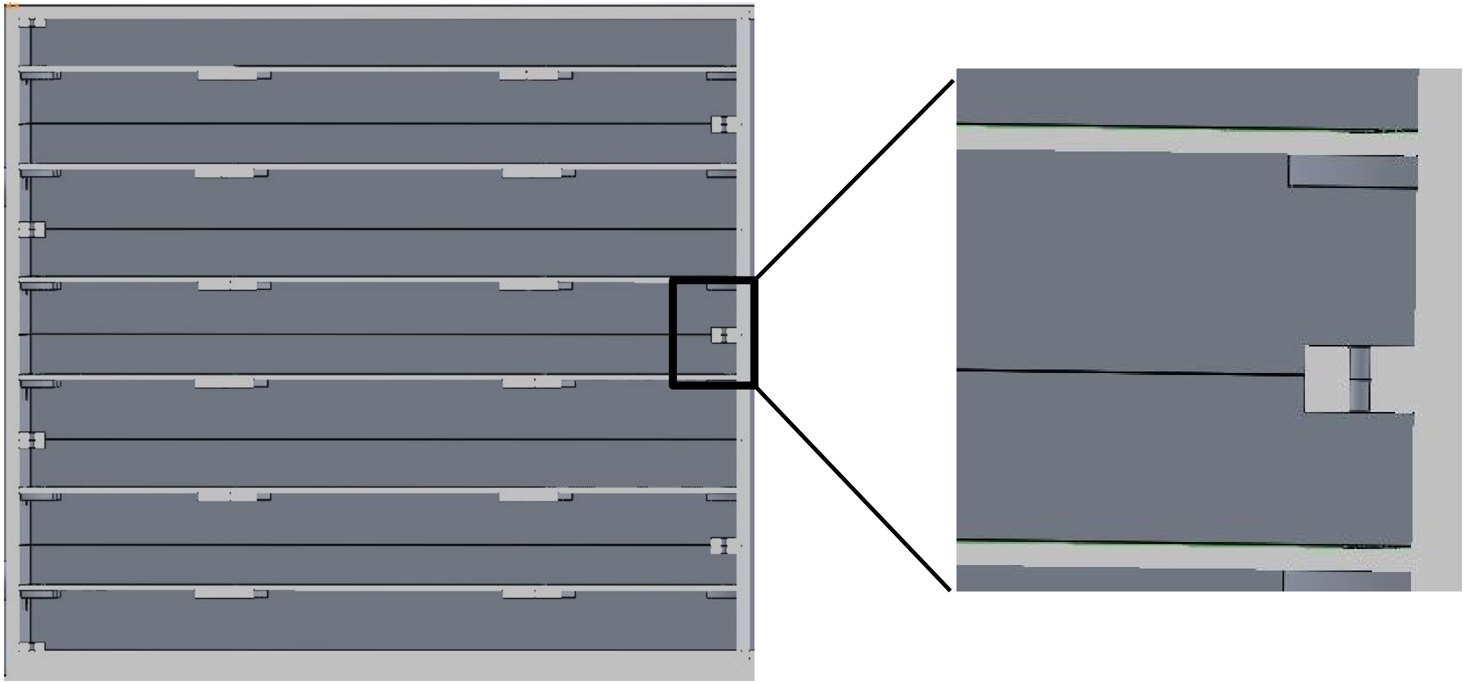
Top View



Bottom View



Attaching Trays

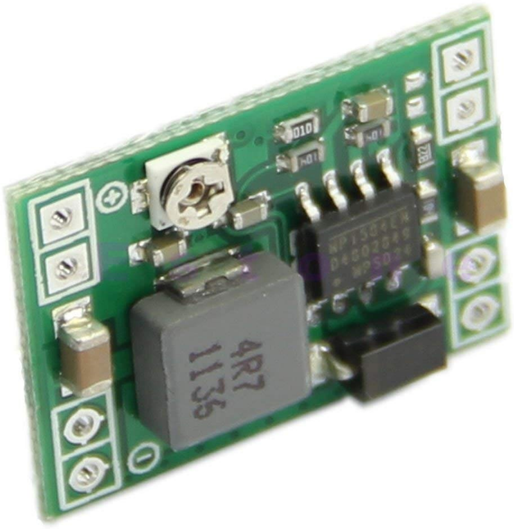


Cross-section of electronics stack trays

Power Converter Selection - MP1584EN

- DC-DC Step Down Buck Converter
- Input Voltage Range: 4.5V to 28V
- Output Voltage Range: 0.8V to 20V
- Output current: 0 to 3A (1.8A typical)
- Switching frequency: 100kHz to 1.5Mhz

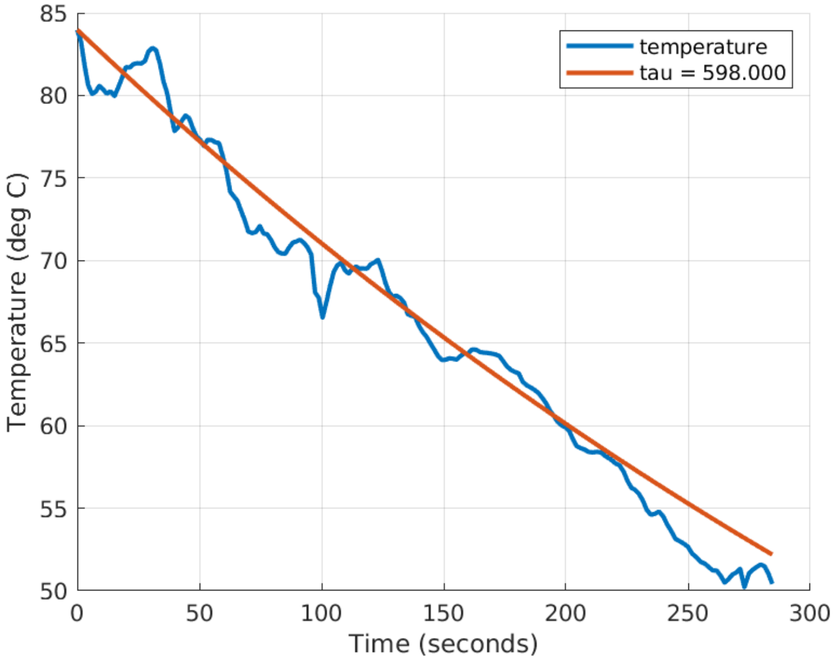
- Temperature rating: -65C to 150C



MP1584EN Buck Converter

Power Resistor Analysis

- Chassis mount, metal clad
- 10 ohms, rated 25W
- 13 grams
- Specific heat approximated as pure Aluminum, 920 J/(kg K) (MIL-HDBK-5J Fig 3.2.1.0 Aluminum 2014-T6)
- Time constant observed to be 598 sec
- Heat dissipation of approx 20 mW per deg C over ambient in current configuration



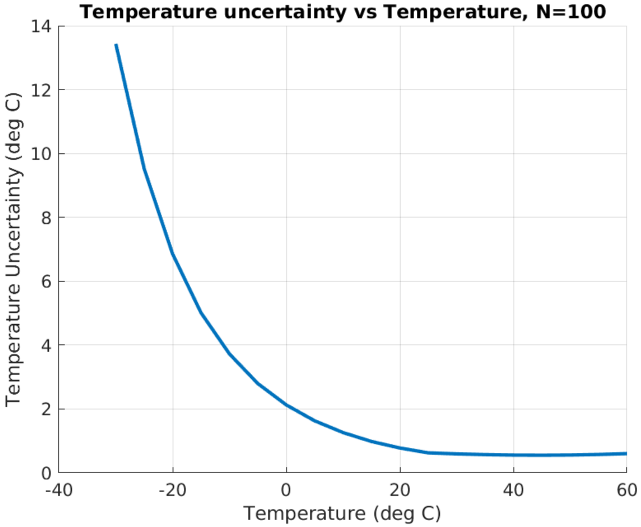
Thermistor Selection - Vishay NTCLE413

Pros

- 10k Ohms = low self heating
- Well documented
- Reasonable precision
- Low price

Cons

- High resistance means lower current, more sensitivity to circuit imperfections, ADC input impedance



ADC Selection - TI ADC128D818

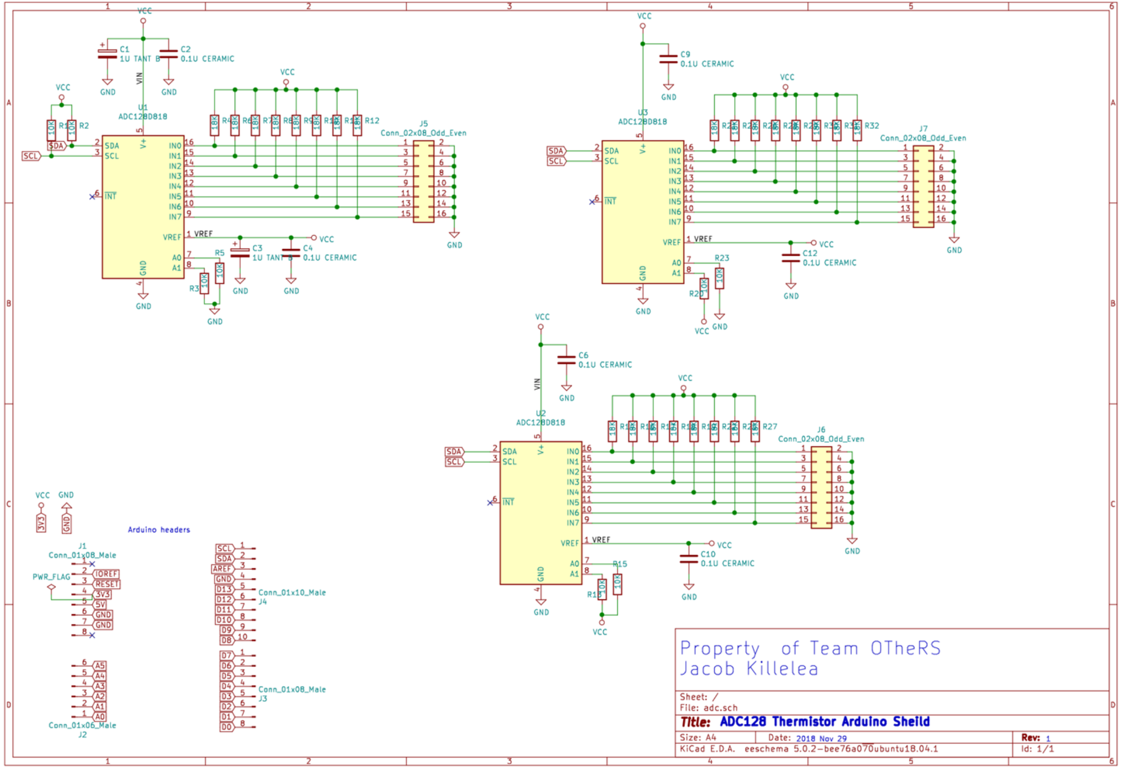
Pros

- Well defined I2C interface
- Nanoamp input leakage current
- Total unadjusted error less than 0.03%
- 98 ms to sample all 8 inputs
- 3.3V and 5V logic compatible
- External Vref
- 0.8 mV per bin

Cons

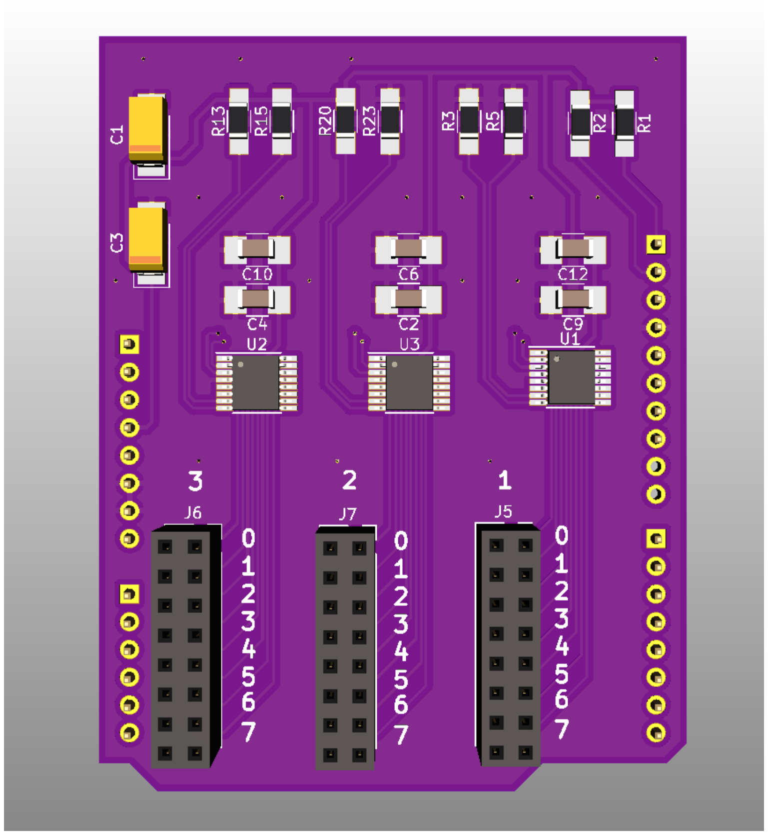
- Many different control and status registers
- Interfacing software is straight forwards, but still development overhead

Preliminary Thermistor ADC Circuitry



Preliminary Thermistor + ADC PCB

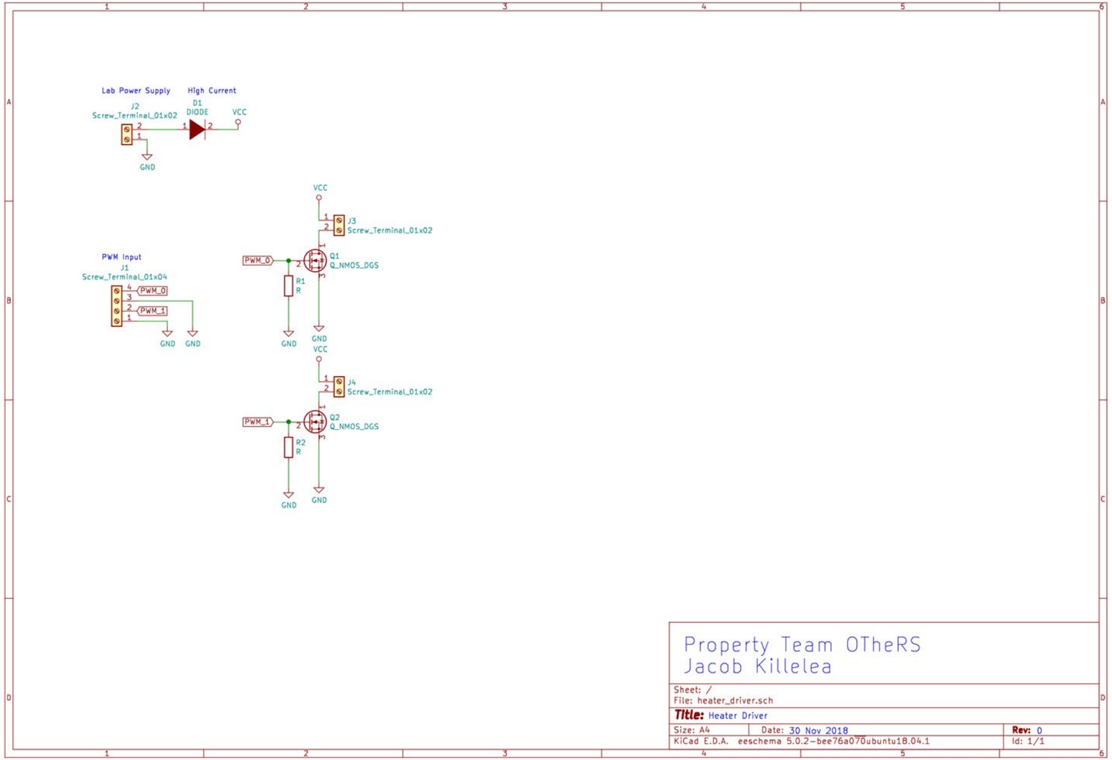
- TSSOP 16 packages necessitate hot air station or reflow oven
- Stackable
- Final revisions upcoming
  - Up to 72 channels on one I2C bus
  - Better analog / digital signal separation
  - Passive low pass filters



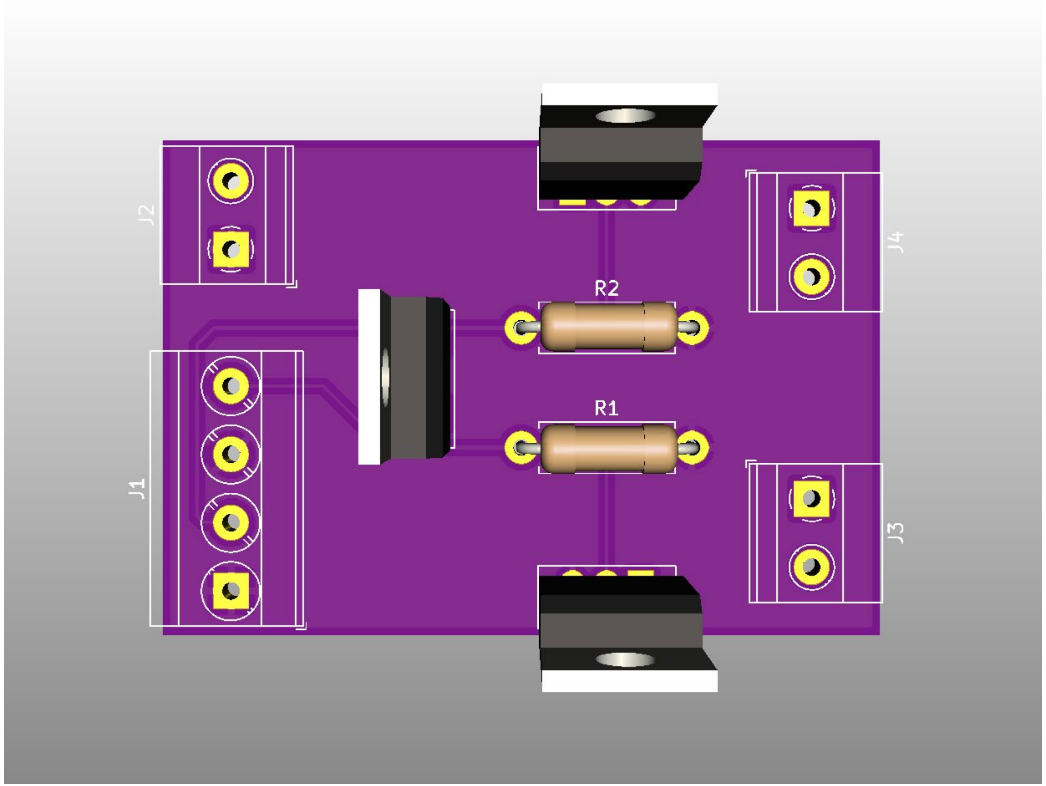
Heater Driver

- Board for input power, input signals, and MOSFETs.
- High current requirements, expecting 0.5A per channel peak
- Traces currently rated up to 4A with a 10 degree C temperature rise (KiCAD PCB Calculator)
  - 2 oz per square foot copper
- MOSFETs and reverse polarity protection diode rated 60+A (with heat sinking)
- Final version extended to 12+ outputs.

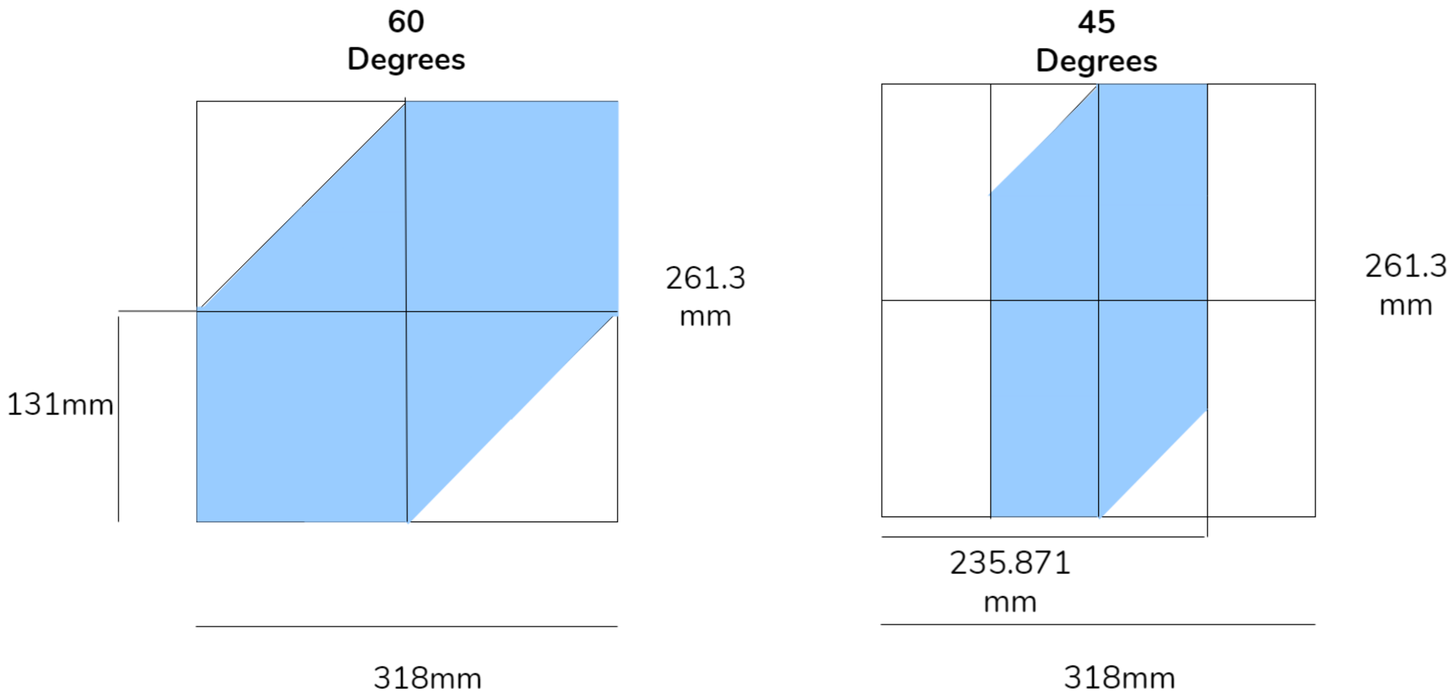
Preliminary Heater Driver Schematic



Preliminary Heater Driver PCB - 2 Channels



Overlap


60
Degrees
261.3
mm
131mm
318mm
45
Degrees
261.3
mm
235.871
mm
318mm

Software Specifications

Backup Slide Deck

IP: Design Requirements

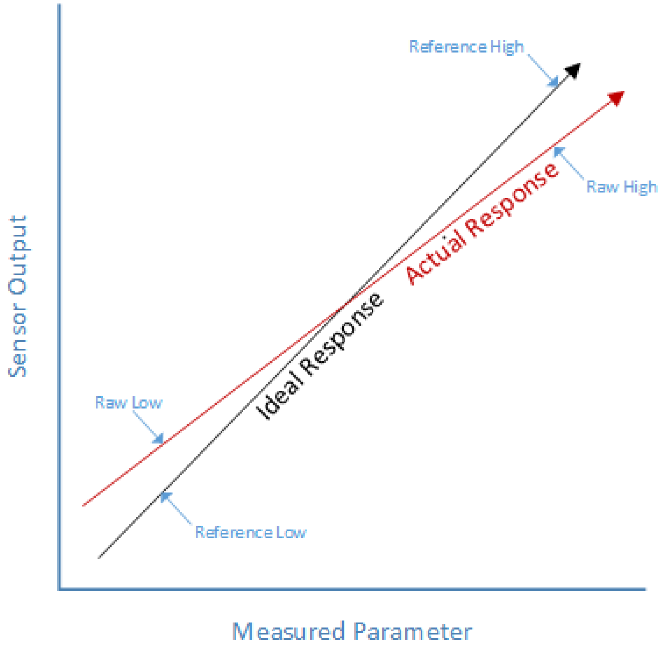
REF ID	Description	Verification Method
PROC 1	The thermal map shall differentiate between objects in stack based on satellite and test bed configurations.	Test/Inspection
PROC 1.1	The thermal map shall distinguish between up to 6 objects (trays) in the stack	Test/Inspection
PROC 2	The thermal imaging device(s) shall be both spatially and thermally calibrated with TBD metrics	Test

IP: Design Requirements

REF ID	Description	Verification Method
PROC 3	Internal processing shall control internal thermal regulation of the OTheRS	Demonstration/Test
PROC 4	Temperature data shall be extracted from the thermal map.	Inspection
PROC 4.1	Automated image processing shall be completed between image captures as defined in DR-IMAG 2.	Demonstration/Test

Camera Calibration: Methodology (1/2)

- Two-Point Calibration Method



Two-point calibration is able to correct both slope and offset errors.

Calibration formula:

CorrectedValue = (((RawValue – RawLow) * ReferenceRange) / RawRange) + ReferenceLow

The calibration slope is applied to the range of raw inputs that range from -30 to 60 degrees celsius (potentially measured in voltage from the reading) to create a temperature value that corresponds to all possible inputs.

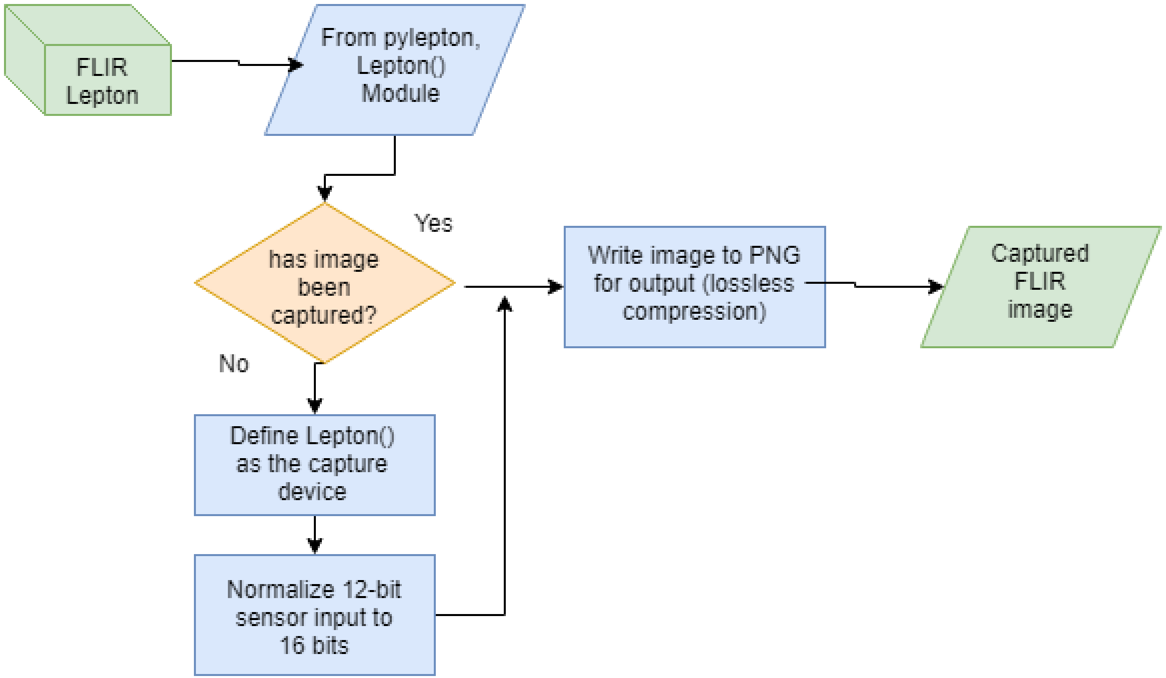
Camera Calibration (2/2)

Temp Calculations Pseudocode

```
def calibrate_temp(thermocouple_data,img):
    # Algorithm inputs
    reflow = Low reference temperature value # define low reference temperature.
    refhigh = High reference temperature value # define high reference temperature.
    rawlow = Low raw temperature value # define low raw temperature.
    rawhigh = High raw temperature value # define high raw temperature.
    Rawrange = rawhigh - rawlow # define raw range.
    Refrange = refhigh - reflow # define reference range range.
    # Calculate the corrected sensor value
    for i in range(0,img.shape[0])
        for j in range(0,img.shape[1])
            CorrectedValue = (((RawValue[i][j] – RawLow) * RefRange) / RawRange) +
RefLow
```

Image Capture Flowchart

Image capture flowchart:



Algorithm to capture an image from the FLIR Lepton

Image Capture Pseudocode

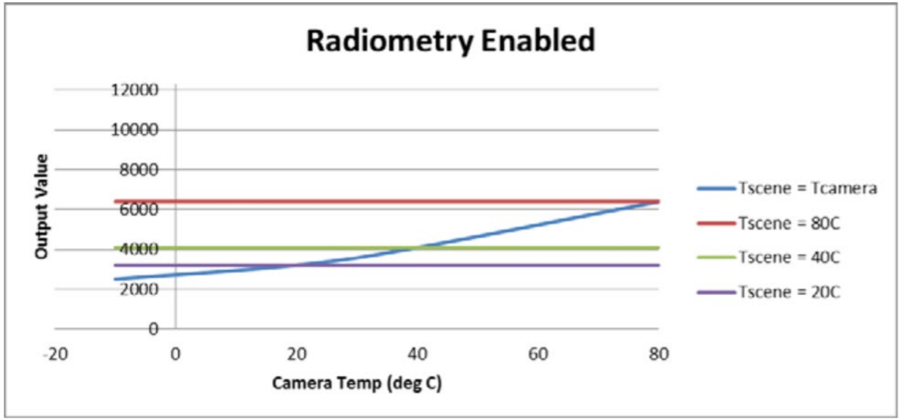
Take thermal image using FLIR Lepton 3.5

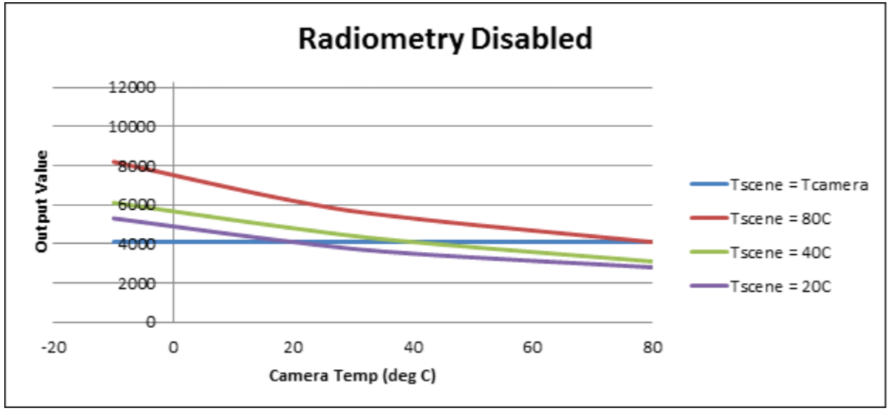
```
def image_capture(Lepton module):
    # Define capture device
    with Lepton as camera:
        # Sensor Data Capture
        data, x = camera.capture()
    # Normalize data (14 bits -> 16 bits)
    cv2.normalize(data,data,0,65535, cv2.NORM_MINMAX)
    # Inputs to normalize() are 1.) input array 2.) output array 3.) lower bound of range
    # 4.) upper bound of range 5.) normalization type to extend image
    # Write Sensor Data to Image (PNG, lossless compression)
    cv2.imwrite("output.png",np.uint16(data))
```

Image Stitching Pseudocode

```
def stitch_two_images(n):
    img1 = cv2.imread('image1.jpg') # load image 1
    img2 = cv2.imread('image1.jpg') # load image 2
    orb = cv2.ORB_create() # Instantiate Feature Detector
    # Find Keypoints that are similar
    kp = orb.detect(img1)
    kp2 = orb.detect(img2)
    # Find descriptors - measure of similarity in the images
    kp, desc= orb.compute(img1)
    kp2, desc2= orb.compute(img2)
    # Find Matches
    matches = locate_match(desc,desc2)
    # Remove "Bad" matches, keep top 15% of
    goodMatches = int(len(matches)*0.15)
    matches_final = matches[:goodMatches]
    # Final Panorama
    plot(matches_final)
```

Radiometry for FLIR Lepton 3.5

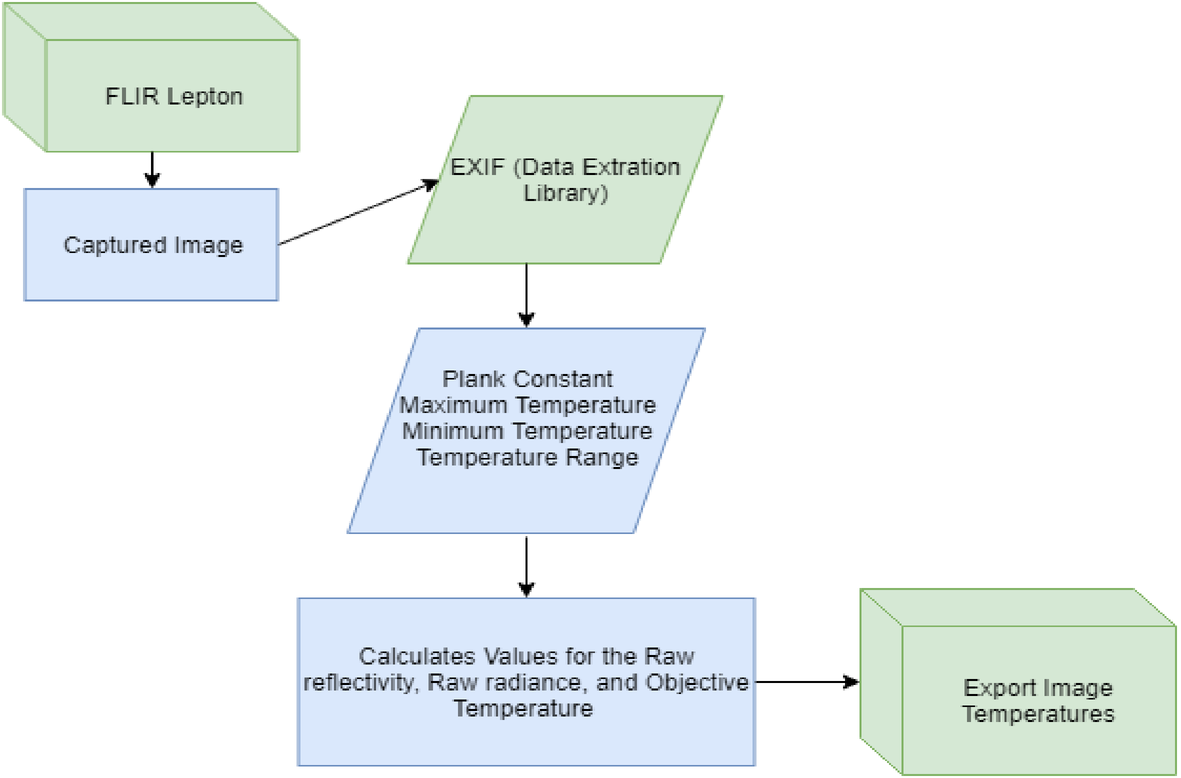




Radiometry feature on camera enables relatively constant absolute temp measurements for the imaged components

Disabling radiometry results in less-accurate temperature results for thermal images

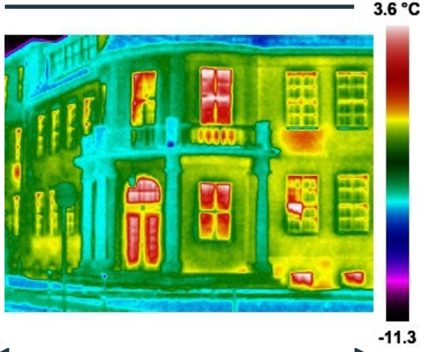
Thermal Correction Flowchart



Thermal Correction: Planck’s Law

Input: Thermal Image

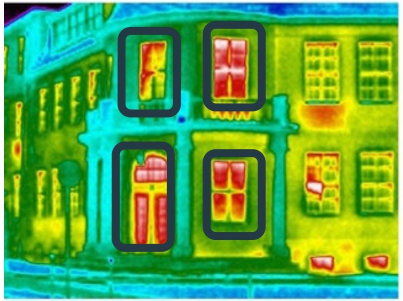
80 px

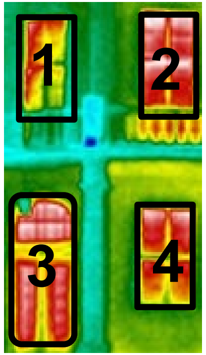


60 px

With the temperature calculated at each pixel location, locate pixel clusters beyond temp. limits

OpenCV Contour Approximations





Export

Backup Method for Temperature Extraction

System shall provide regulatory commands when components are outside -20°C to 50°C.

Thermal Correction: Planck's Law

- This method can be used for any thermal image, not necessary for radiometry
  - Thermal image exports constants for use in Planck's Law calculations
  - Temp. can calculated based on the object's reflected intensity and emissivity of the object in equation
- This method converts the image capture sensor data to a given temp.

$$RAW_{refl} = \frac{R1}{R2(e^{B/T_{refl}-F})} - O$$

$$RAW_{obj} = \frac{S - (1 - Emissivity)RAW_{refl}}{Emissivity}$$

$$T_{obj} = \frac{B}{ln(\frac{R1}{R2(RAW_{obj}+O)} + F)}$$

Metadata:

- Planck Constants: B, F, R1, R2, O (offset)
- S = 16-bit FLIR raw value (camera sensor value)
- T_refl = reflected temp. value in K
- RAW_refl is linear to amount of radiance of the reflected object(s)
- RAW_obj is linear to amount of radiance of the measured object(s)
- Emissivity of object
- **T_obj = object temperature**

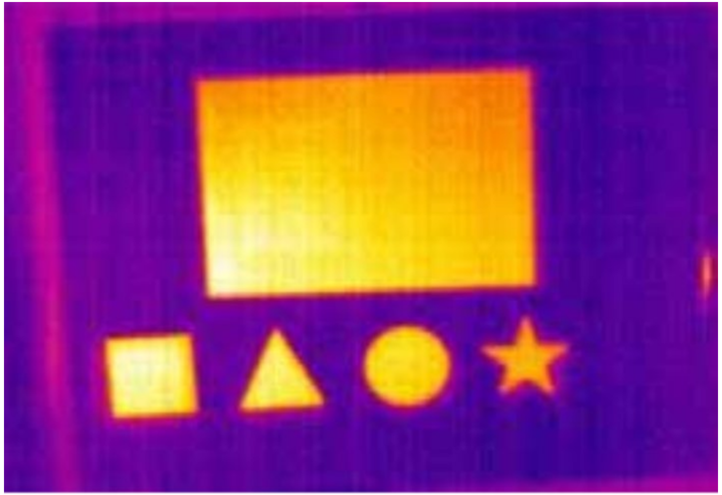
Planck's Law Pseudocode

```
def main():
    img = cv2.imread('image.jpg') # load image 1
    output = np.vectorize(lambda x:
calcTemps(x,Planck_r1,Planck_r2,Planck_b,Planck_o,Planck_f))
    ans = output(img)

def calcTemps(img,Planck_constants,minTemp,maxTemp,deltaT_interval):
    K = 273.15;
    temp = Planck_b / math.log(Planck_r1/(Planck_r2*(pixel+Planck_o)) + Planck_f) - K
```

Thermal Markers

- Provide both thermal calibration and markers for image processing
- COTS Part from Mid-State Instruments
  - IRISS Small Shaped High Emissivity Target Labels
    - Known and constant emissivity
    - Adhesive backing for quick application



OTheR

Backup Slide Deck

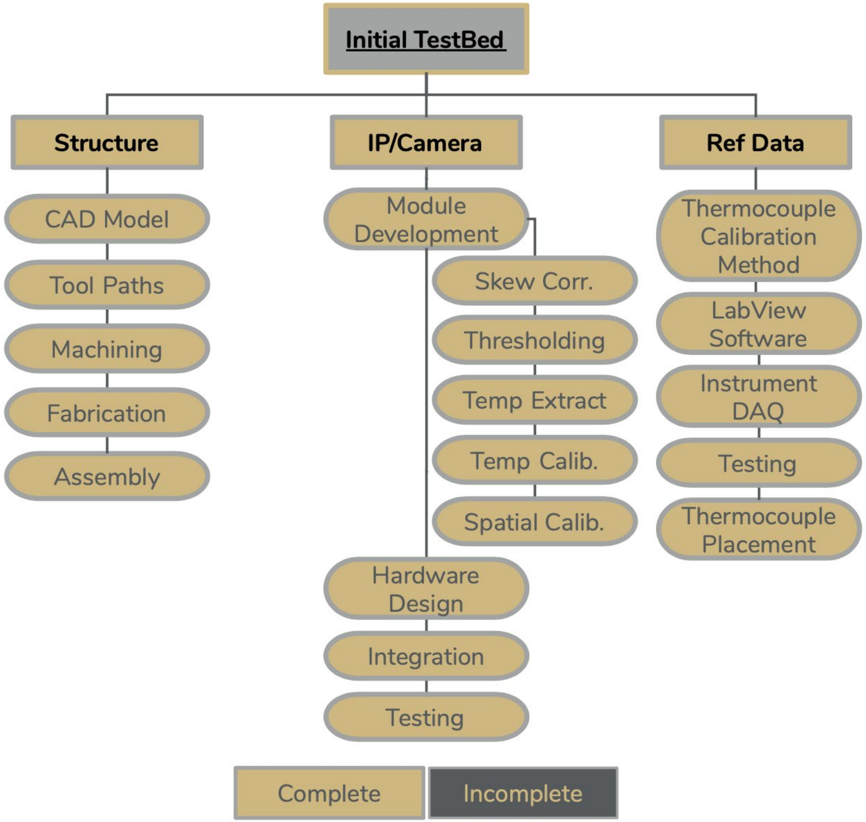
Risk Assessment

Risk	Description	Likelihood	Severity	Total
THERM-2	Thermistors don't provide accurate truth data	2	4	8
THERM-3	Thermal gradient across camera adversely affects output data	3	4	12
VAL-1	OTheRS unable to do thermal chamber testing before customer validation	1	3	3
CTRL-2	System control fails & allows temperatures to exceed safe bounds	1	5	5
TEST-1	Test bed coating/material different from GA design to allow for imaging	5	2	10
MAT-2	Manufacturing accuracy insufficient	2	2	4

Mitigation Strategies

Risk	Description	Mitigation Strategy
MAT-2	Manufacturing accuracy	At the cost of time, use CNC instead of manual milling
THERM-2	Thermistor truth inaccurate	Using heavily supported thermistor supplier, which includes error corrections by temperature and temp. delta
THERM-3	Camera temperature gradient	System of heaters, heat sinks, and thermistor temperature monitoring
VAL-1	Thermal chamber testing	GA thermal chamber & RALPHEE scheduling ongoing
TEST-1	Test bed not bare/untreated aluminum	Research and testing of coatings/materials of which space-rated equivalents exist

Work Breakdown Structure - Initial TestBed



Thermal Chamber

GA Chamber

- Tenney TC series Thermal ambient chamber w/ humidity control
- -73 to +200 ℃, ±0.3 ℃
- 20-95% ± 2% RH
- 609.6 x 698.5 x 711.2 mm workspace
- CO_2 Dry gas purge