OTheRS

Optical Thermal Regulation System

Preliminary Design Review

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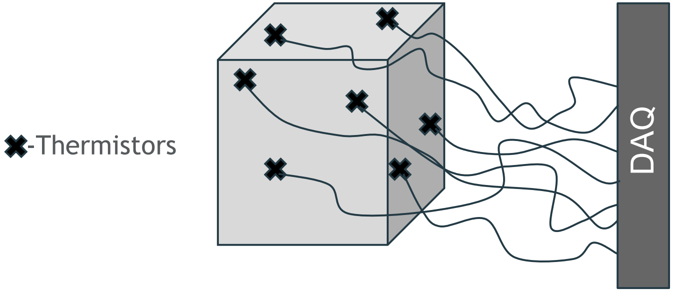
Project Description

Project Motivation

- Current thermal sensing solutions involve placing large numbers of thermal sensors.
- Increased wiring & harnessing complexity.
- Increased number of satellite BUS inputs.
- Small satellites = compact systems.
- Harsh environment & large temp fluctuation

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

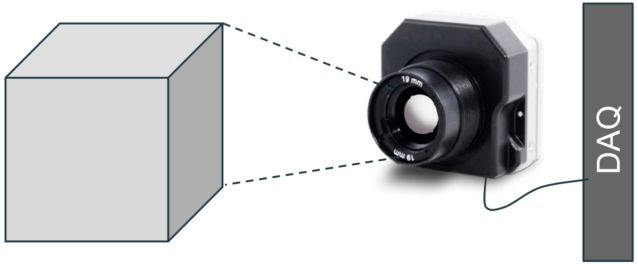
Traditional Thermal Sensing



Project Concept

The OTheRS must be able to **map and accurately sense the temperature** of a mock **electronics stack** within the test bed and provide spatially correlated temperature data through a serial output. Additionally, a controller must receive temperature data then **process and switch on/off commands to heaters or LED’s** to simulate temperature regulation of the stack.

OTheRS Thermal Sensing



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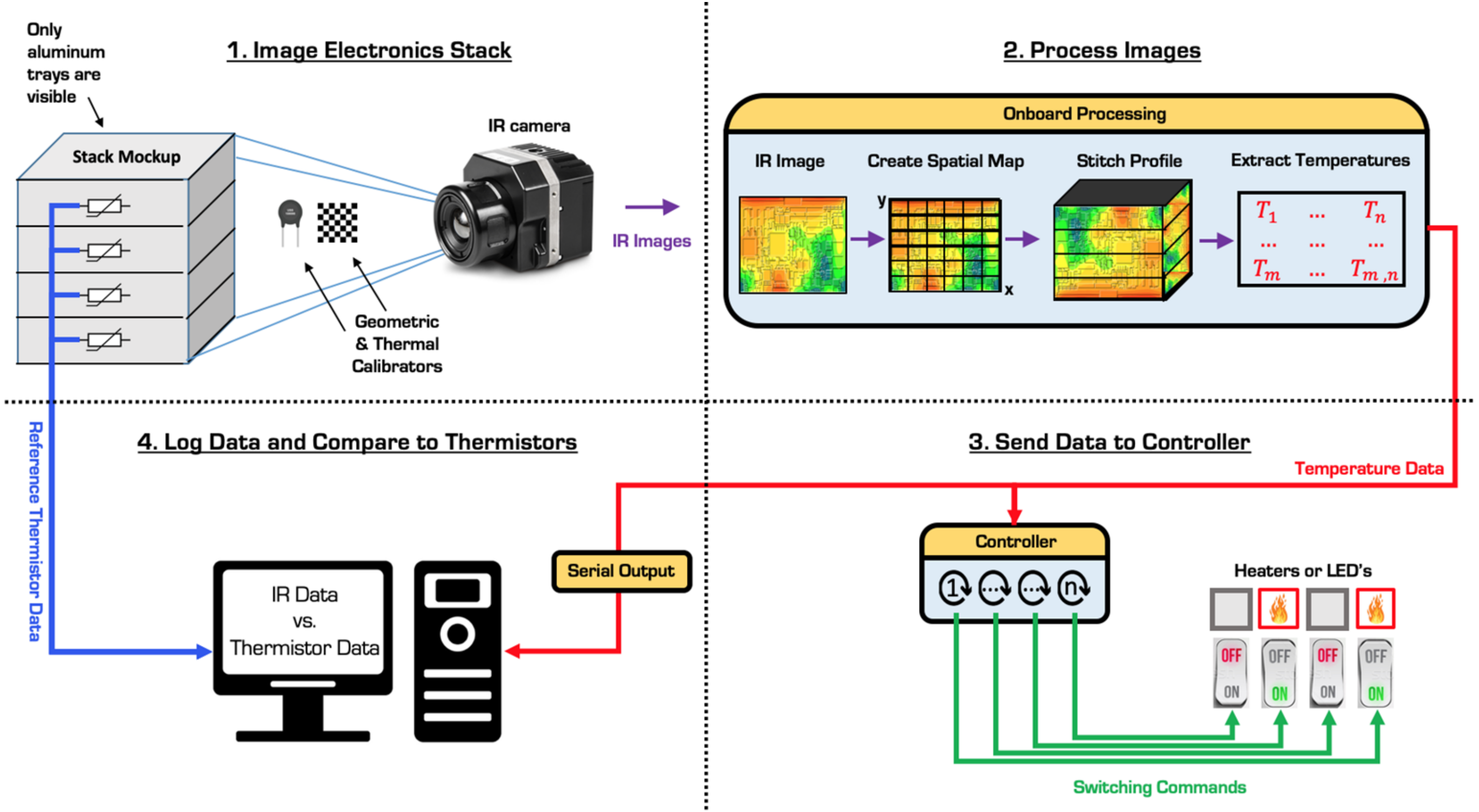
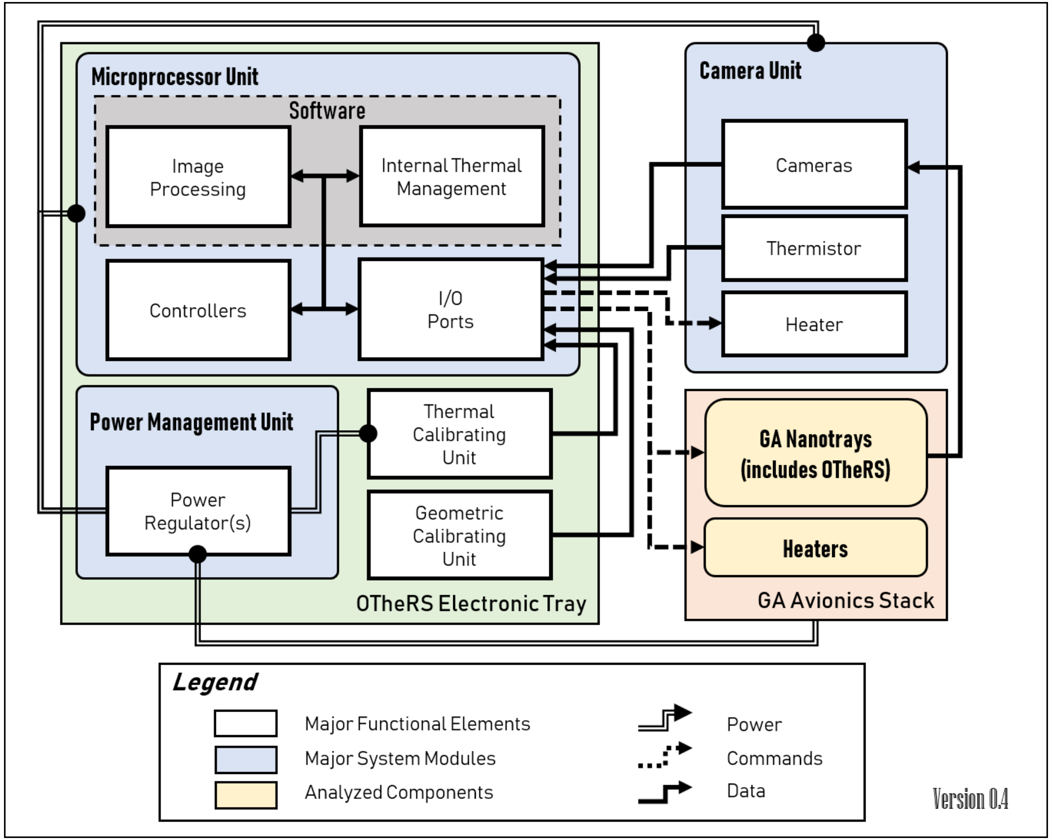


1. Image Electronics Stack
Only aluminum trays are visible
Stack Mockup
IR camera
Geometric & Thermal Calibrators
IR Images
2. Process Images
Onboard Processing
IR Image
Create Spatial Map
Stitch Profile
Extract Temperatures
y
x
T_1 ... T_n
... ...
T_m ... $T_{m,n}$
4. Log Data and Compare to Thermistors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

Functional Block Diagram



Functional Requirements (1/2)

FR 1	**System shall return thermal data map for multiple components between -30˚C and 60˚C.**
FR 2	System shall provide regulatory commands when components are outside -20˚C to 50˚C.
FR 3	System shall operate on 28V unregulated power provided by the spacecraft.
FR 4	**Supporting systems electronics shall fit within a standard GA nanotray, with dimensions of 18.5cm x 13cm.**

Functional Requirements (2/2)

FR 5	System shall be able to switch a 2.5A load as needed to control an externally powered heater or representative indicator.
FR 6	**The thermal imaging device(s) shall image critical stack electronics on a single side of the stack.**
FR 7	**System shall regulate its own temperature.**
FR 8	Testbed shall mimic the GA satellite.
FR 9	**OTheRS shall not include ITAR or EAR restricted articles.**

Design Rescope

Previous Scope	New Scope	Justification
Image all sides of electronics stack	Image a single side of electronics stack	Cost & Camera FOV, Camera Resolution
Uncoated Material	Research and implementation of coatings	High material reflectivity compromises thermal data
Optical Thermal Regulation System	Variable parameter Test Bed to prove concept feasibility	Challenges in sensing methodology does not allow time or budget to develop satellite ready system

Design Rescope: Thermal Imaging Device

<u>Sensor/Camera Choices</u>

Non-contact thermal imaging

ITAR Regulated Sensors/Cameras

- Not allowed

Thermopile Array Sensors

- Small Size
- Low Resolution
- High FOV

FLIR Lepton Camera

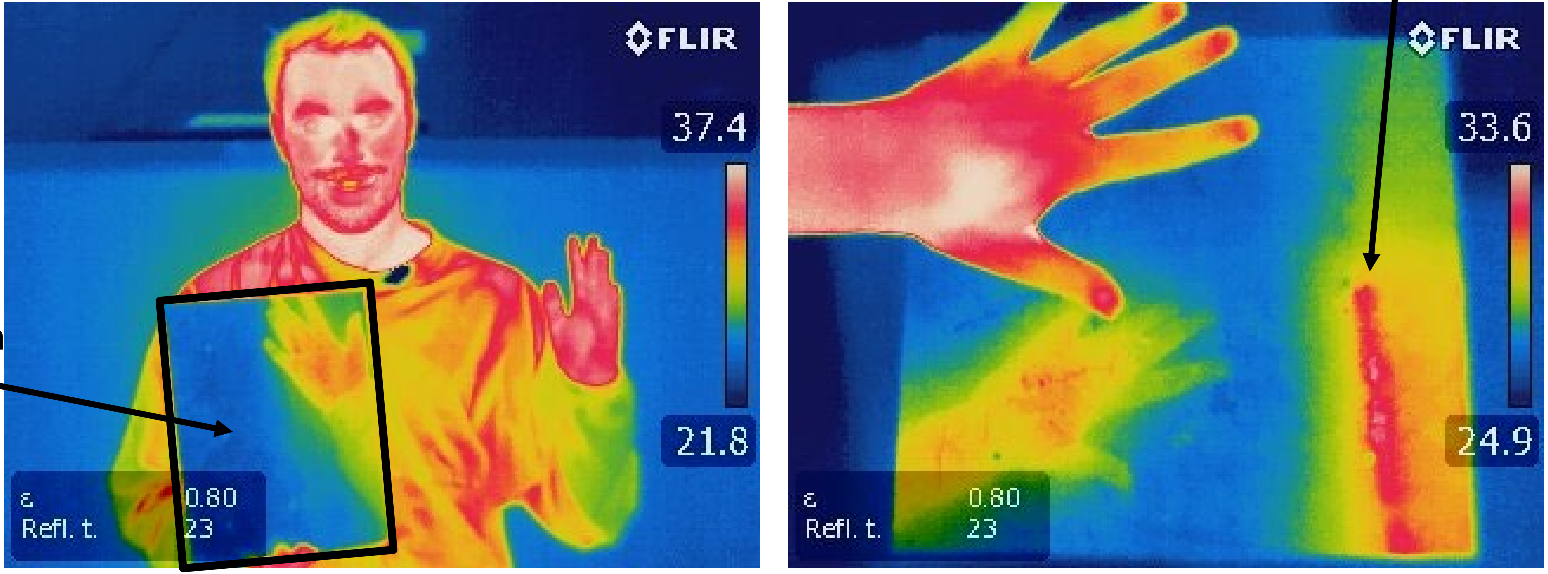
- Small Size
- High Resolution
- Low FOV

Design Rescope: Need for AR Coating

- Untreated, bare aluminum is highly reflective in IR wavelengths!
- Difficult to make accurate readings of surface temperature

Reflection of overhead lights

Aluminum plate



Example of Thermal reflectivity on an aluminum plate

Baseline Design

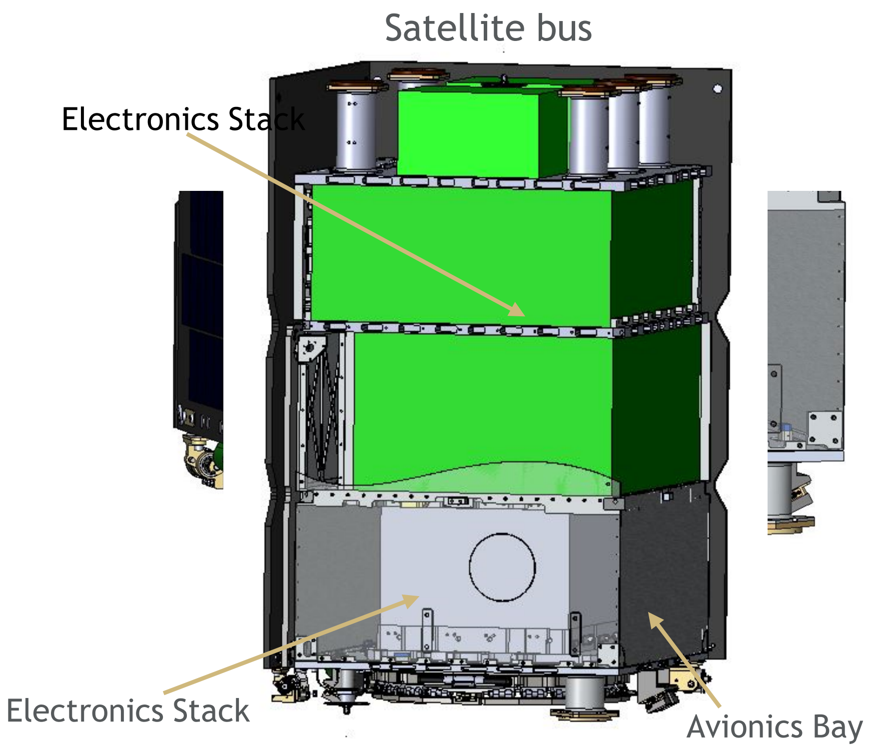
Baseline Design: TestBed

Why?

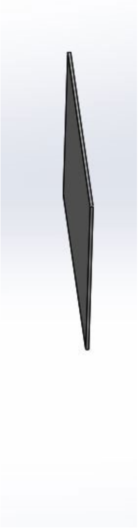
- Goal: Obtain a high resolution surface temperature gradient and map data to heat sources internal to the stack, enabling non-contact thermal regulation.
- Determine system requirements that will enable non-contact thermal regulation.

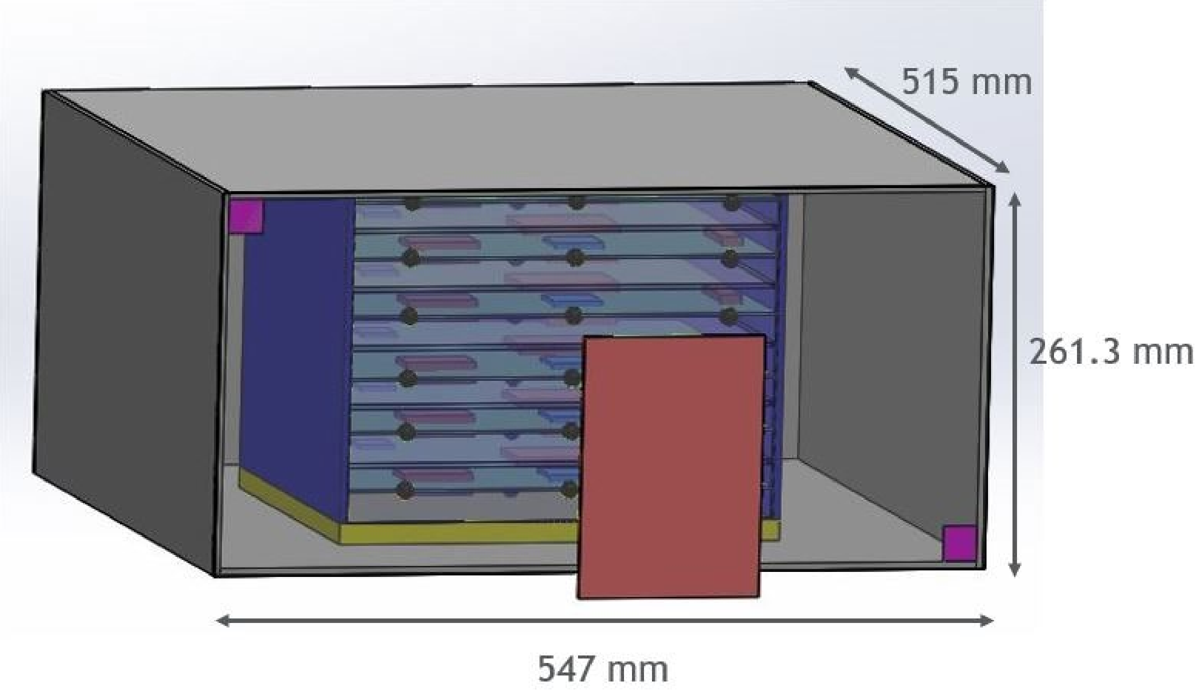
How?

- Mockup avionics bay to determine which environmental factors will affect non-contact measurements.
- Thermoelectric heaters/coolers replicate electronic stack thermal profile.
- Thermistor reference data acts as truth comparison.



Baseline Design: TestBed





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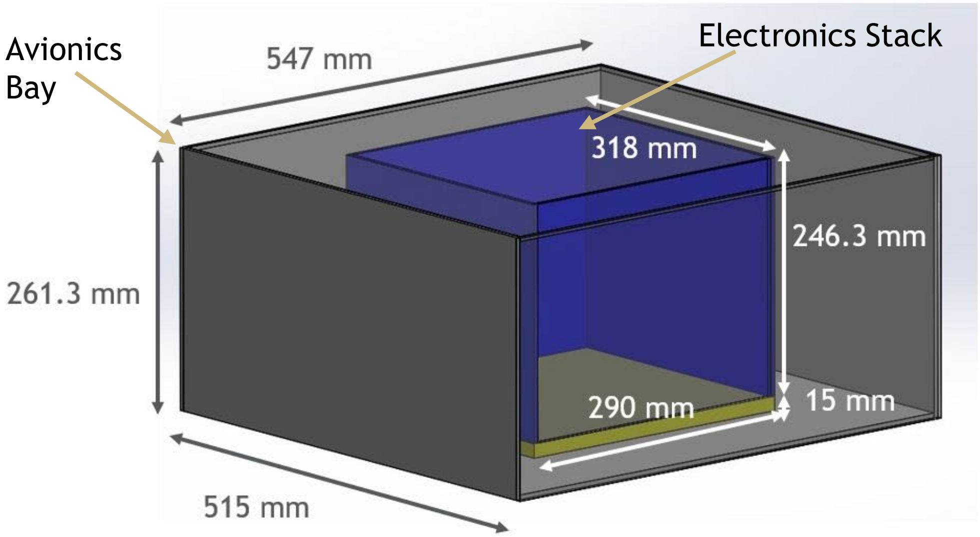
Baseline Design: Structure

Why?

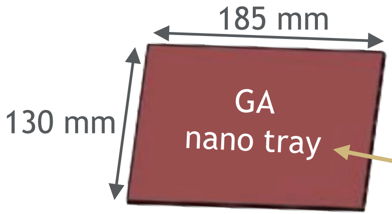
- Mimic avionics bay materials and fabrication methods to collect realistic data.

How?

- Machine electronics stack & avionics bay mockup from aluminum using the same methodologies as the real satellite.
- GA nanotray will hold OTheRS electronics
  - Image processor
  - Controls
  - Power regulation



Walls have a thickness of 5 mm



nano tray not included in test bed mockup of avionics bay

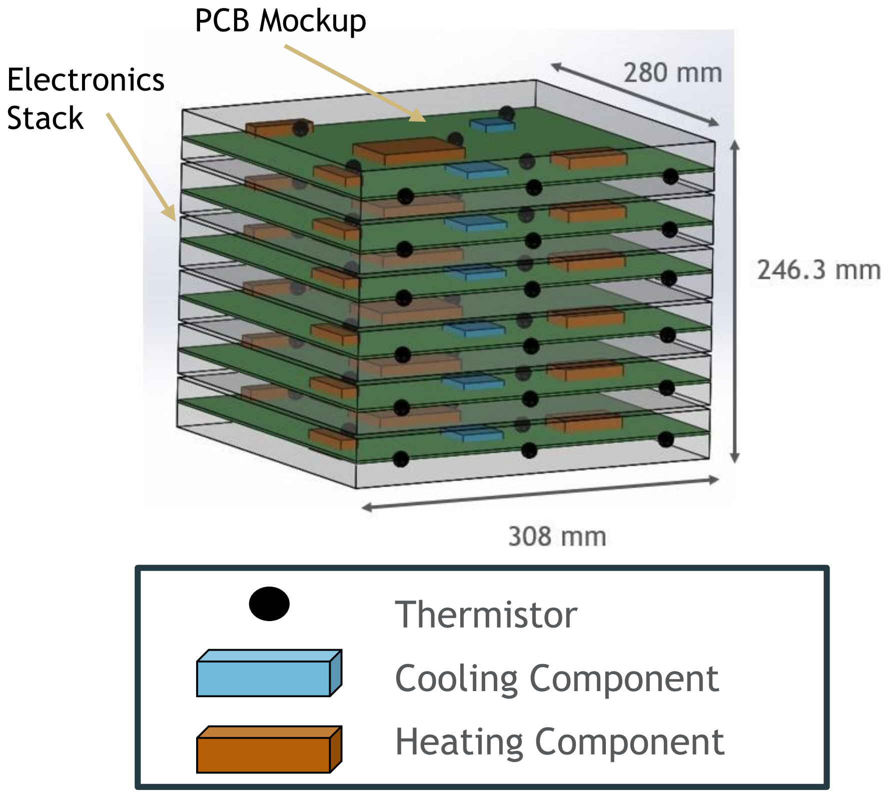
Baseline Design: Simulation & Reference Data

Why?

- Recreate realistic thermal profile of stack electronics for measurement purposes.
- Provide reference data
  - Compare with non-contact data

How?

- PCB mockups made from heating/cooling components.
- Thermistors will provide thermal data of electronics stack
  - Surface temperatures to compare directly to IR image data.
  - Internal temperatures to test OTheRS ability to derive accurate internal temperature profile.



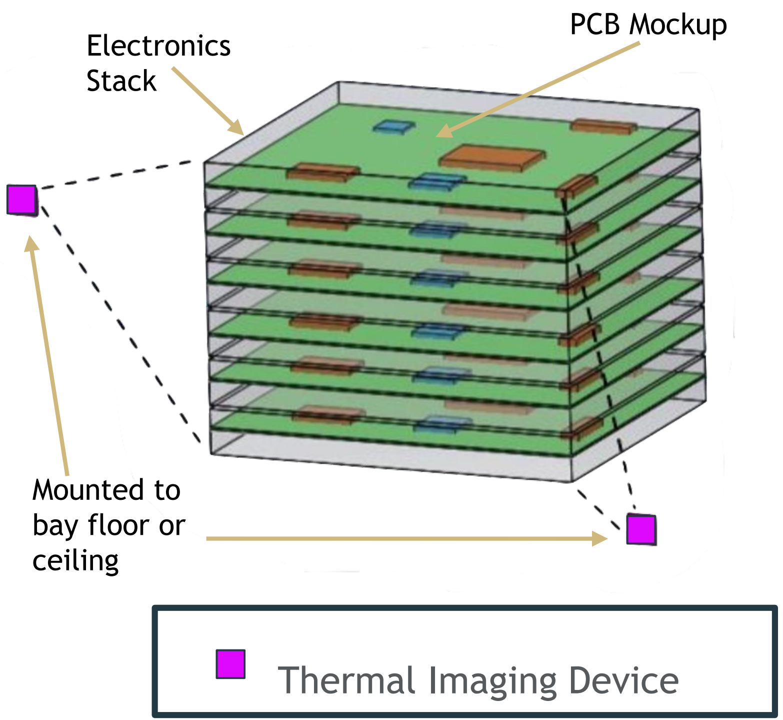
Baseline Design: IR Thermal Sensing Method

Why?

- Image a full side of the stack to measure outer surface temperature.
- Use data to determine internal heat PCB heat profile.

How?

- 2 FLIR Lepton cameras imaging one side of the stack.



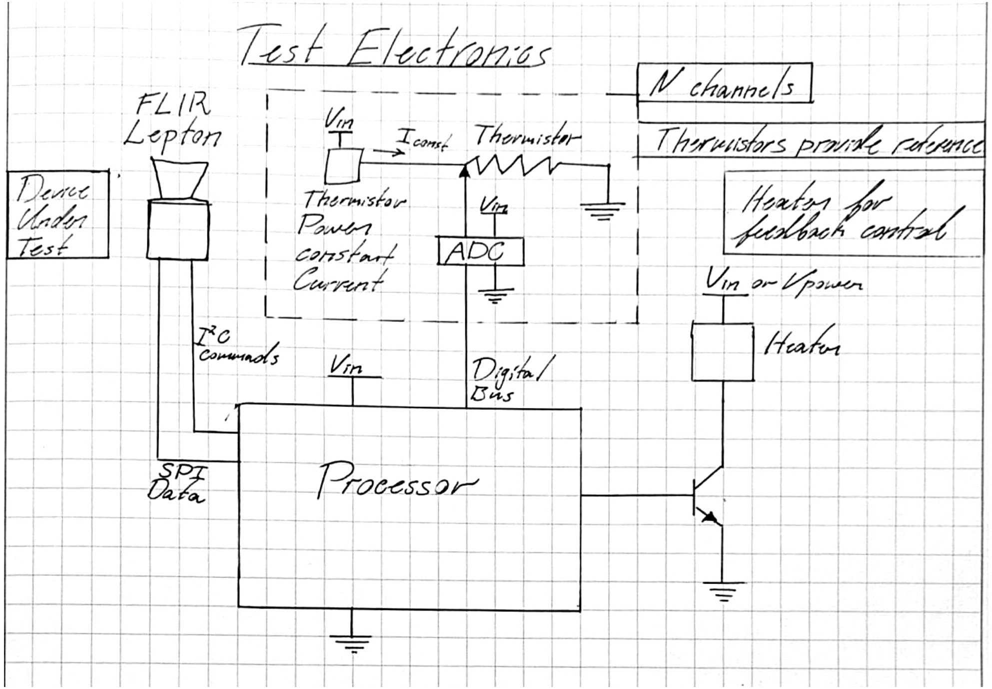
Baseline Design: TestBed Electronics

Why?

- Integrate Sensors and Heater(s)
- Image the stack with the Lepton camera
- Thermistor temperature readings for comparison at N points
- Heater for active control

How?

- Direct connections to processor over digital busses
- Switch/transistor to modulate heater



Electronics layout of the test bed

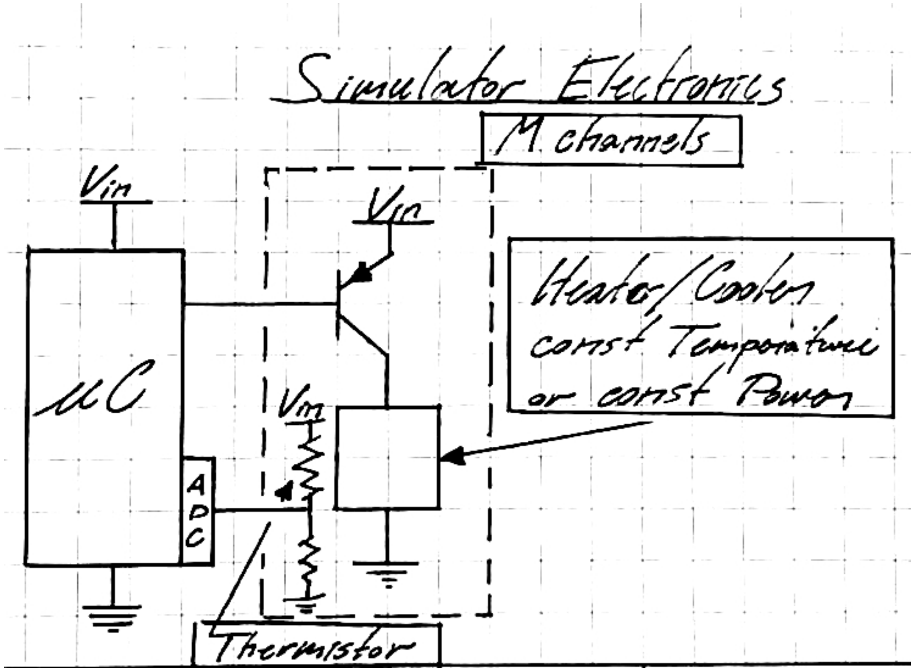
Baseline Design: Simulator Electronics

Why?

- Create a heat profile similar to an actual avionics stack

How?

- M channels of heaters and coolers
- Option for feedback loops
- Separate electronics, power, and code from testbed electronics



Electronics layout of the simulator

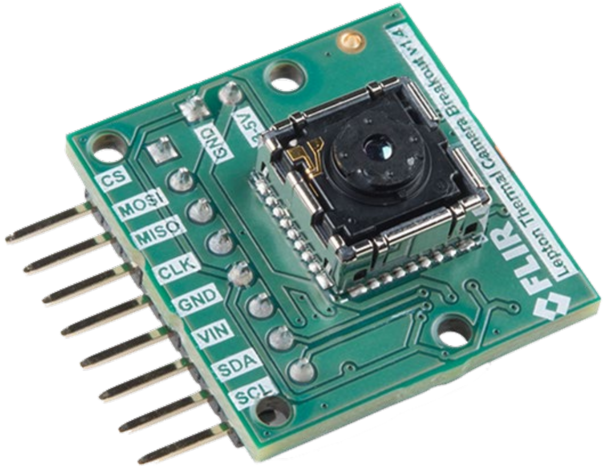
Baseline Design: Thermal Imaging Device

Why?

- OTheRS needs a non-contact thermal sensor in order to take temperatures of the stack.

How?

- FLIR Lepton Camera
  - **Senses wavelengths from 8 to 14μm**
  - **Field Of View (FOV)**
    - HFOV = 51.5°
    - VFOV = 37.8°
    - DFOV = 63.5°
  - Accuracy of up to 0.05℃



FLIR Lepton Thermal Camera Breakout Board V1.4

Baseline Design: Heaters

Why?

- Replicate the heat sources of PCB components.
- Inexpensive compared to other heating methods.

How?

- Uses 50-100W of power to generate heat.
- Number, size, and location of resistors will be tuned to recreate a PCB thermal profile.

Example Power resistor

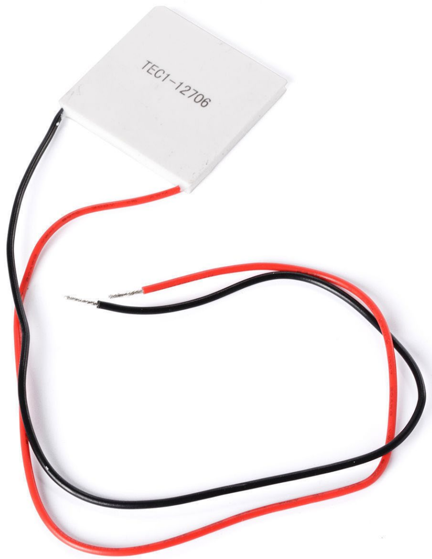
Baseline Design: Thermoelectric Cooler

Why?

- In a space environment, areas of the stack may be far cooler, depending on location.
- Allows for a higher range of temperatures for measurements

How?

- Use electrical power to drive a temperature gradient.
- Works on similar principles as a thermocouple, but in reverse.
- Simple device: just apply power.
- Up to 60W of cooling power
  - Flip it around, and the heating side provides area heating



Example Thermoelectric cooler

Baseline Design: Image Processing

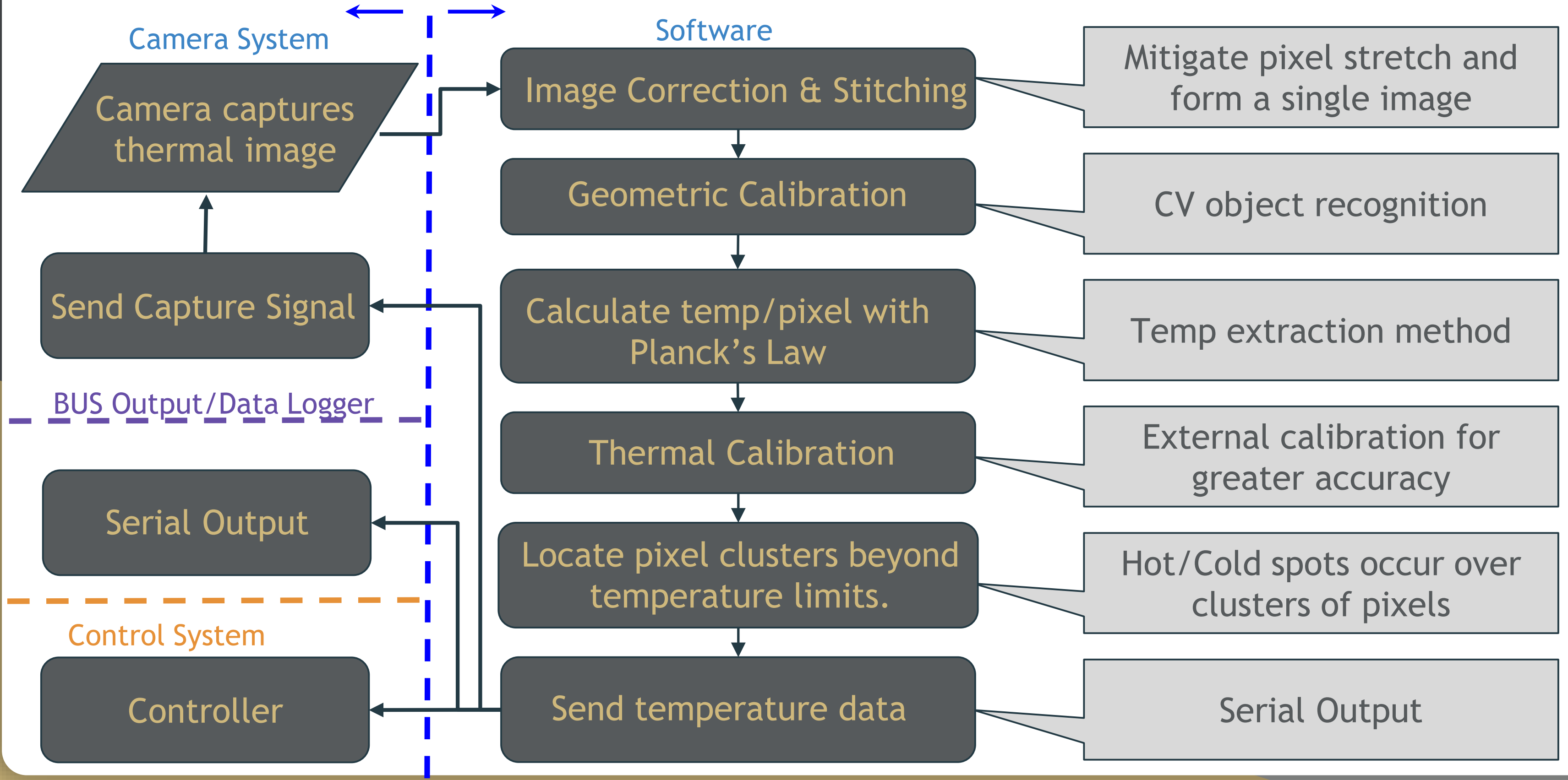
Why?

- Temperature data needs to be calibrated.
- Two cameras means stitching 2 images together.
- Use raw intensity data to find temp data: T_actual.
- OpenCV tools minimize noise, refine edges, adaptive thresholding to minimize error.

How?

- OpenCV Python, Cython libraries
- Extract the compressed intensity data
- Calculate T_actual using Planck's Law
- Calibrate calculated T_actual using 2-point thermistor calibration
- Send thermal map data to controls subsystem
- Parallel processing to simplify the problem

Baseline Design: Image Processing Overview



Baseline Design: Processor

Why?

- Image processing software needs platform to run.
- Internal thermal control software needs platform to run.
- Processor necessary to supply heater control commands.

How?

- Microcontrollers possess CPU with different processing speeds depending on model.
- Microcontrollers possess most of the necessary peripherals necessary to interface with system.

Design Feasibility

Critical Project Elements

Critical Project Element	Description
Camera Layout	Camera System is contained within a limited volume.
Processor	Processor must fit in GA nanotray along with other electronics and run software.
Image Processing	Software must process camera output for temperature data.
Thermal Model	Sensitivity of thermal imaging and power dissipation to maintain thermal equilibrium.

Design Feasibility

Camera Layout

Camera Layout Feasibility

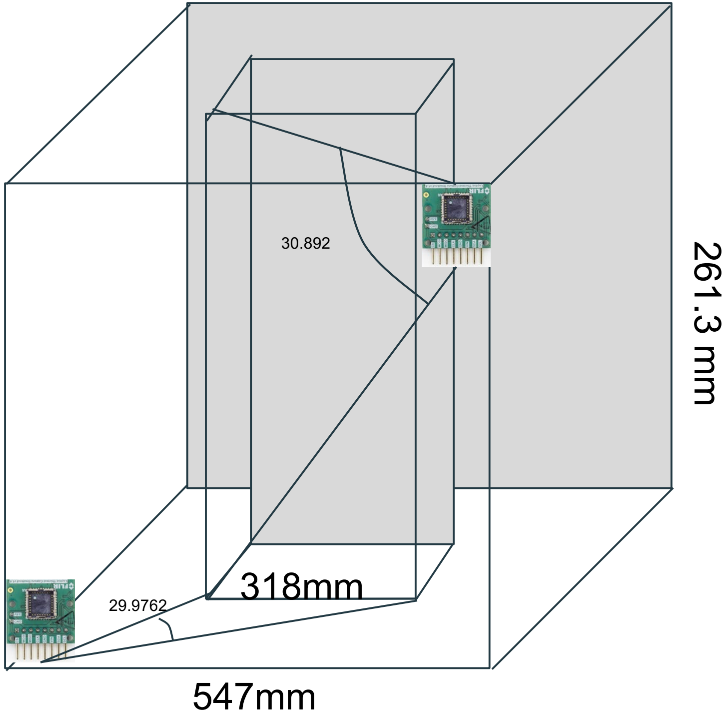
Requirements:

- **FR 6** - The thermal imaging device(s) shall image critical stack electronics on a single side of the stack.
- **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 a single side of stack.

Camera Layout Feasibility

- Cameras will be mounted in corners
    - Need a HFOV of 29.97° and VFOV of 30.892°
- With the FLIR Lepton an entire side can be viewed with two cameras
- Resolution of 6.83mm on the horizontal and 5.33mm on the vertical

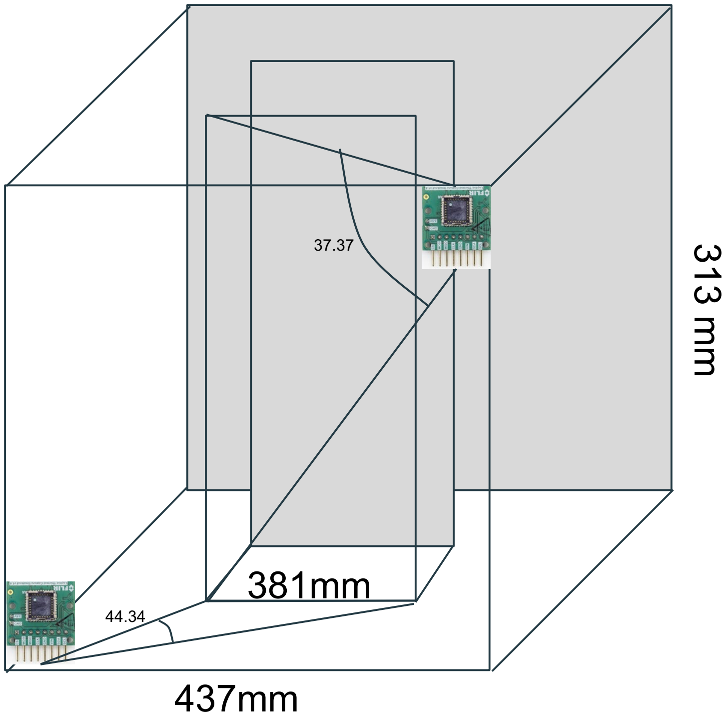
Camera Layout



Camera Layout Feasibility

- Maximum Error
  - Increased Size of Stack by 20%
  - Decreased Size of Walls Surrounding Stack by 20%
    - Required Vertical FOV of 37.37°
    - Required Horizontal FOV of 44.34°
- Feasibility Analysis
  - Current Camera Layout can view the entire side of the stack
  - The Camera Layout can view the entire side of the stack while being 100 to 146.73 mm from the stack
  - Therefore, the layout is **Feasible**

Camera Layout



Design Feasibility

Image Processing

Image Processing Feasibility

Requirements:

- **FR 1** - System shall return thermal data map for multiple components between -30°C and 60°C.
- **DR PROC 2** - The camera subsystem shall be both spatially and thermally calibrated.
- **DR PROC 4** - Temperature data will be extracted from the thermal map.
- **DR PROC 4.1** - Automated image processing shall be completed in 10 seconds or less between image captures.

Image Processing: Study Overview

- **Feasibility Study:** The image processing (IP) software shall create a 2D thermal data map for a single side of the stack between [-30℃ and 60℃] and return extracted temp data from the map.
- This software will be automated and use the OpenCV Computer Vision library along with Python, Bash scripting
- **Key Features:** Image stitching, geometric calibration, building thermal map
- **Theory:** Planck's Law equations

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

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

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

Image Processing: Image Stitching (Python)

- The Scale Invariant Feature Transform (SIFT) is an OpenCV image processing toolbox for stitching an image in Python
- With this library, the image stitching process can be automated
- Lossless compression to create the new image

Test Image 1

Test Image 2

=

Final Image

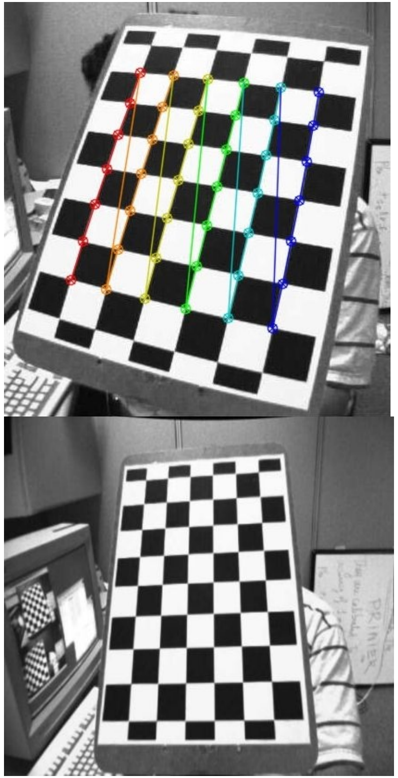
- Based on testing using SIFT, this image stitching technique is: **Feasible**

Image Processing: Geometric Calibration

- Camera will be calibrated geometrically using OpenCV tools to minimize distortions
    - Straight lines appear curved, objects look closer/farther than in reality

- To improve accuracy, a database of 10+ test patterns will be in use to calibrate the camera in order to accurately detect tray overlap and limit pixel stretching

- Based on OpenCV image testing, this geometric calibration technique is: **Feasible**

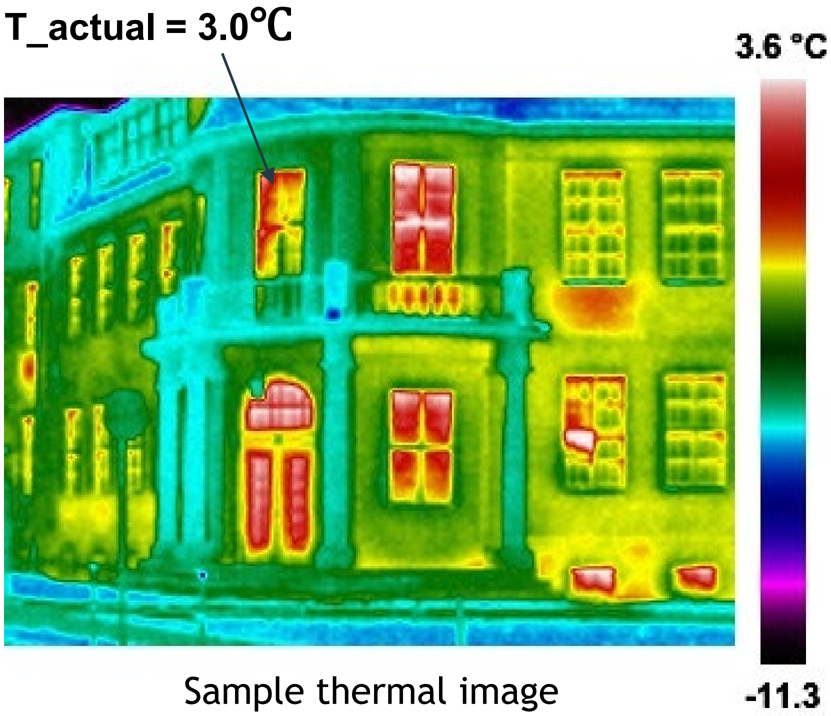


Sample Geometric images

Image Processing: Thermal Map

- Thermal map will be created based on intensity data extracted from image capture for side of stack
- This profile will be created in Python using Exiftool (hidden data extraction) and OpenCV
- Based on analysis of FLIR Lepton image captures and using Planck's Law to calculate temp. data, this thermal map is:

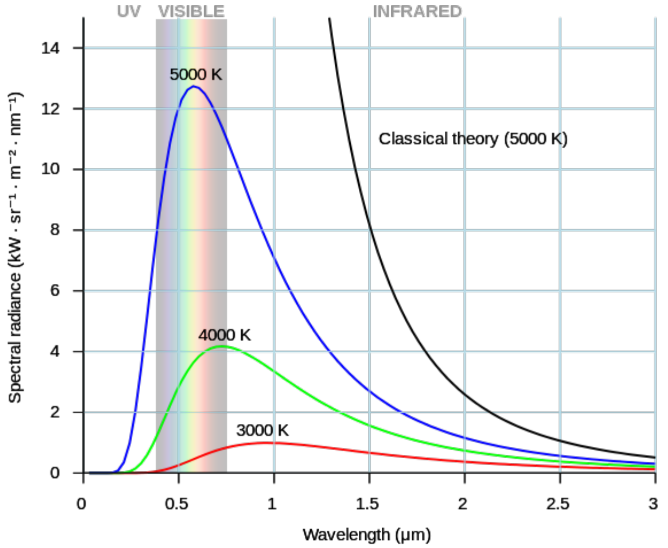
Feasible



Sample thermal image

Image Processing: Planck's Law Theory

- Planck's Law describes the spectral radiance of EM radiation emitted by a black body in thermal equilibrium at a given temp. T
- The spectral radiance of a body B(λ,T) describes the amount of energy a given object gives off as radiation at different wavelengths



$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

c = speed of light

kB = Boltzmann constant

h = Planck constant

λ = wavelength

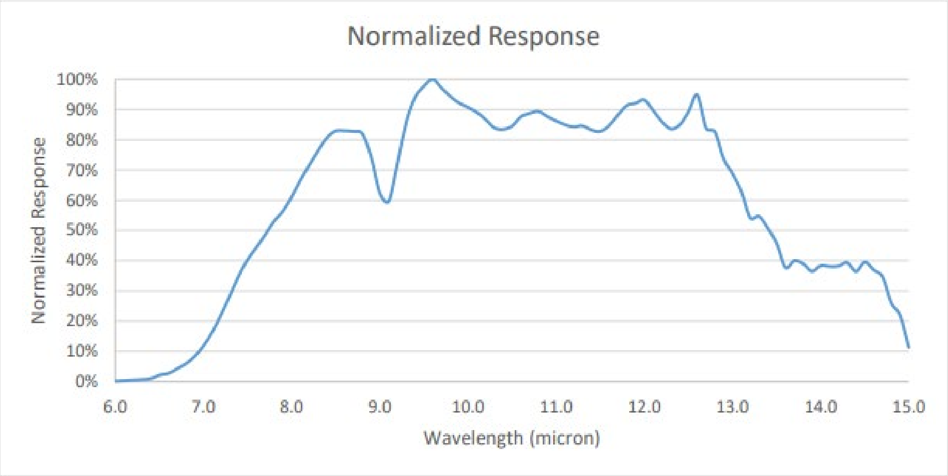
T = temperature

Image Processing: Lepton Camera Sensitivity

- Lepton is internally calibrated for its differing sensitivity over a range of wavelengths.
- Outputs a 14-bit number at each pixel corresponding to received intensity.
- Output is generally linear with respect to small changes around the camera's temperature.
- Sensitivity, S(ƛ) shown at right.

$$intensity(T) \propto \int_0^\infty S(\lambda)B_\lambda(T,\lambda)d\lambda$$

Figure 48 - Normalized Response as a Function of Signal Wavelength for Lepton 3.0 and 3.5



Design Feasibility

Processor

Processor Feasibility

Requirements:

- **FR 4** – OTheRS shall be able to fit within a standard GA Nanotray, with dimensions of 18.5cm x 13cm.
- **FR 9** – OTheRS shall not include ITAR or EAR restricted articles.
- **DR-PROC 3** – Internal processing shall control internal thermal regulation of the OTheRS.
- **DR-PROC 4.1** – Automated image processing shall be completed in 10 seconds or less between image captures.
- **DR-COM 1.1** – OTheRS shall communicate with TBD communication protocol.

Image processing criteria:

- Processor shall be able to run Python, Python Libraries, and OpenCV.

Processor Feasibility

The microcontroller must:

- Fit within 18.5 cm x 13 cm
- Use communication protocols: I2C, SPI (camera), RS232 (serial thermal commands), USB or Ethernet (Test bed)
- Handle 32-bit software (Python, OpenCV)
- Process an image in less than 10 seconds

Processor Feasibility

Feasibility analysis:

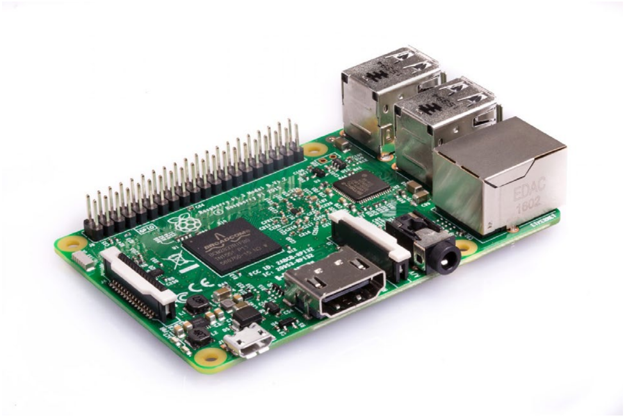
- 32-bit criteria : MCUs can process between 8 bits and 64 bits depending on model.
- Communication protocols criteria: SPI, UART, I2C, USB standard on many microcontrollers
- Size criteria: Many MCUs range in sizes below 10cm x 10cm, but custom PCBs can be used to miniaturize electronics.
- Processing speed criteria: Image processing using given resolution below 1 second using Python, processor speed high enough depending on MCU model.

Therefore the processor requirements are: **Feasible**

Processor Feasibility

Feasible Example: **Raspberry Pi 3 Model B**

- Power: 1.5 W - 6.7 W
- CPU: 1.4 GHz 64/32-bit Quad Core
- Memory: 1 GB Ram
- Communication protocols: UART, I2C, SPI, USB, Ethernet
- Size: 8.56 cm x 5.65 cm
- Weight: 45 g



Raspberry Pi 3 with standard configuration

Design Feasibility

Thermal Model

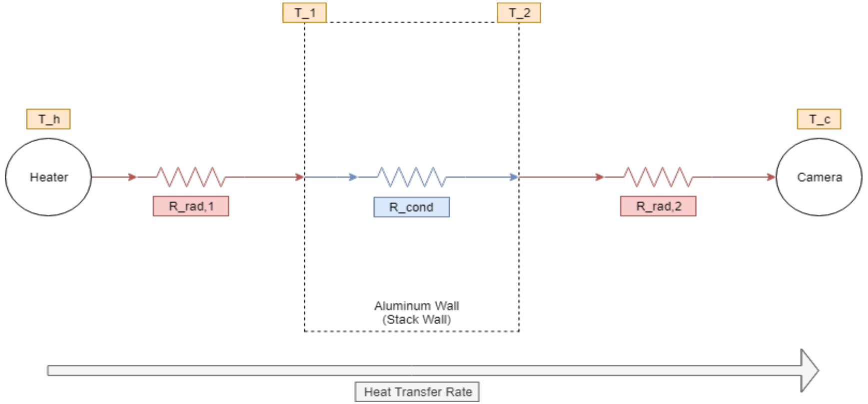
Planar Thermal Model Feasibility

Requirements:

- **FR 1 -** OTheRS shall return thermal data map for multiple components between -30°C and 60°C.
- **DR-TEST 2** - The stack shall replicate the thermal operating range of electronics contained in the stack, as defined in FR 1.

Motivation

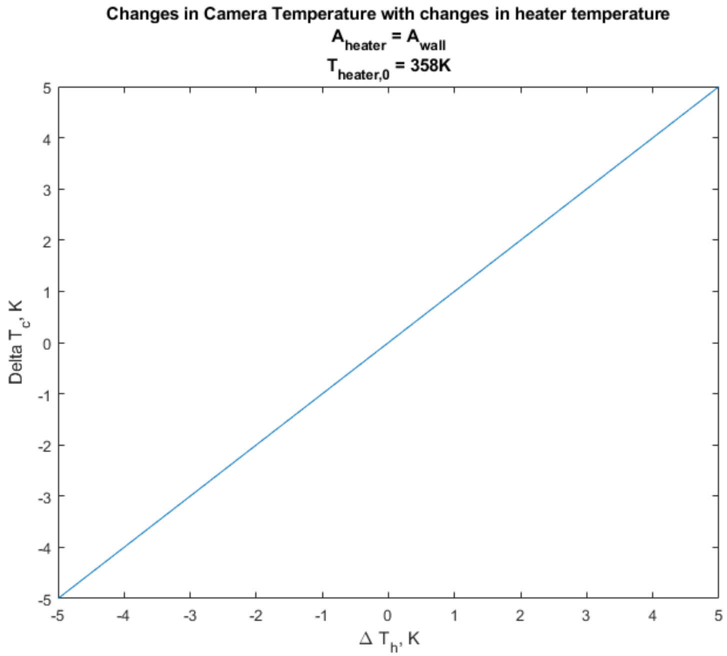
- Camera's sensitivity to instantaneous changes in heater temperature



Planar Thermal Model Feasibility

- Assumptions
  - No view factors
  - No convection
  - Steady 1D heat flow
  - Internal heater is the same size as the stack wall (normal area)
- Known Values
  - Operating Temperatures
    - Camera
    - Stack Surface
  - Thermal Properties
    - Emissivity of stack
    - Thermal conductivity of stack
  - Dimensions
    - Normal Area
    - Thickness

- Results



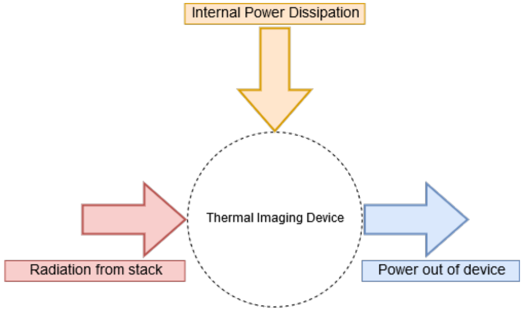
Therefore the sensitivity requirements for the camera are: Feasible

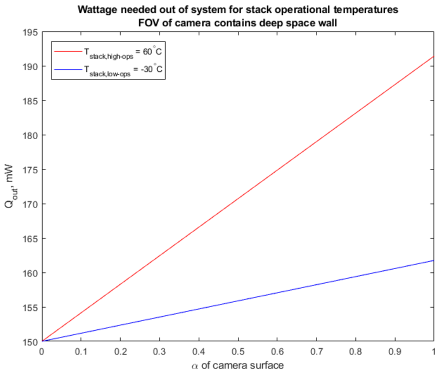
Incident Thermal Model Feasibility

- **Requirements**
  - **FR 1 -** OTheRS shall return thermal data map for multiple components between -30°C and 60°C.
  - **FR 7** - System shall regulate its own temperature.
  - **DR-TEST 2** - The stack shall replicate the thermal operating range of electronics contained in the stack, as defined in FR 1.
- **Motivation**
  - Can the sensor maintain thermal equilibrium in the possible configurations
- **Key Assumptions**
  - Neglect convection and reflection
  - Stack area being viewed is at constant temperature
  - Camera has internally dissipated power
  - Neglect conduction on sunlight wall
  - Camera view factor(F) is ½ of full side between two nodes
  - Camera is at thermal equilibrium
  - Power flux not absorbed by solar panels is incident on outer walls of bay

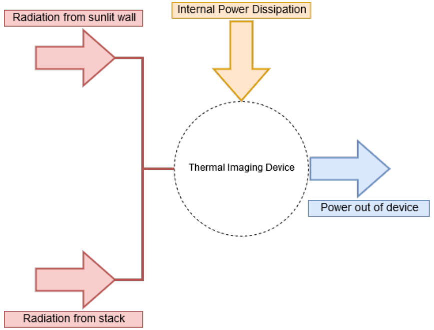
Incident Thermal Model Feasibility

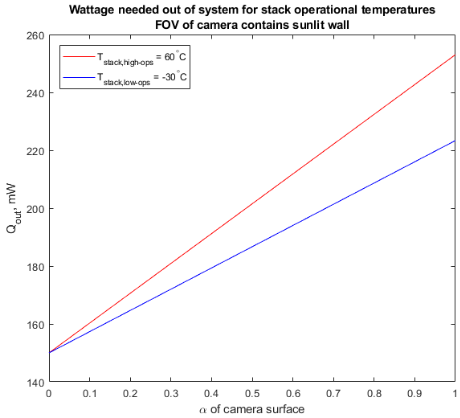
Deep space wall in FOV:





Sunlit wall in FOV:





Incident Thermal Model Feasibility

- Maximum Power needed to be rejected from camera:
  - 253 mW
    - From sunlit wall in FOV and stack at high operating temperature
- For the sunlit wall in FOV, camera can be in contact with outer walls
  - If all heat rejected is through conduction and thus radiation to deep space:
    - **0.058 mK is needed as a thermal gradient across the plate**
- For the deep space wall in FOV:
  - 191 mW is maximum power to be rejected
    - **10mm Copper cube will require at least 0.5 K thermal gradient across cube**

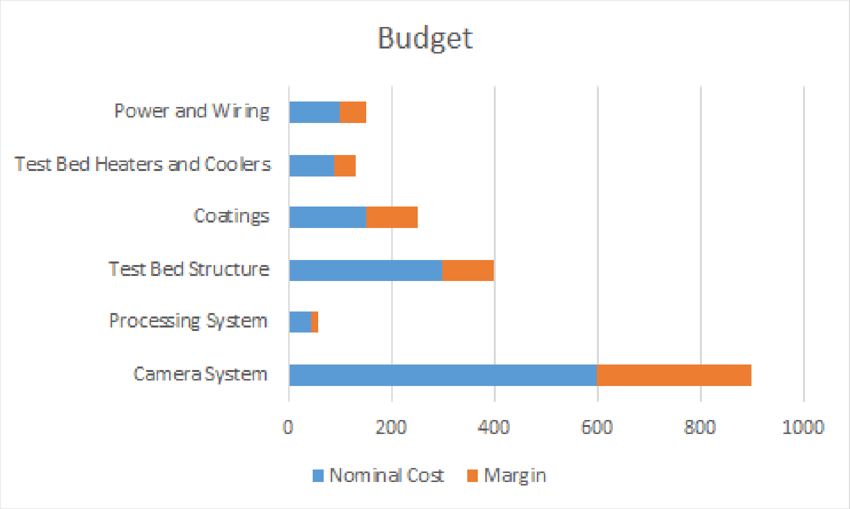
Therefore the operational heat rejection requirements for the camera are: **Feasible**

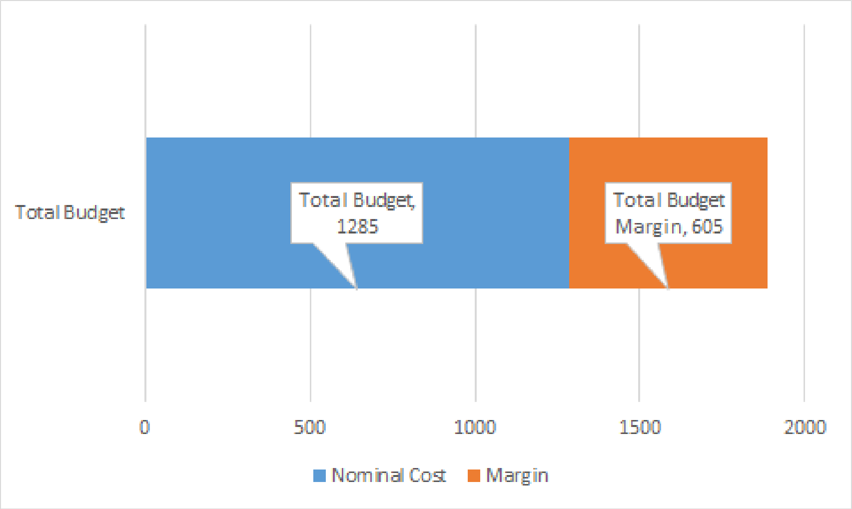
Design Summary
&
Future Strategy

Critical Project Elements

Critical Project Element	Solution
Camera Layout	Two cameras covers a full side of the stack
Processor	A Microcontroller can run the required software at the desired frequency.
Image Processing	Python and OpenCV can stitch and process images
Thermal Model	Camera will be limited by factory sensitivity and incident power can be rejected

Budget



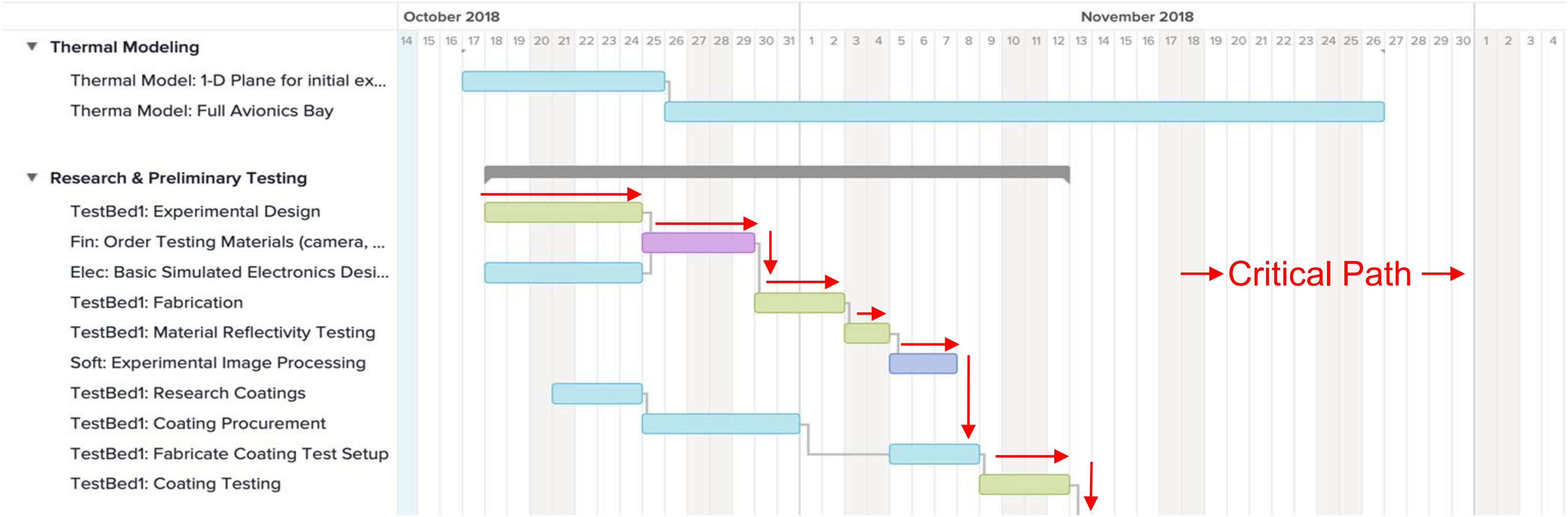


Remaining Budget = $3110

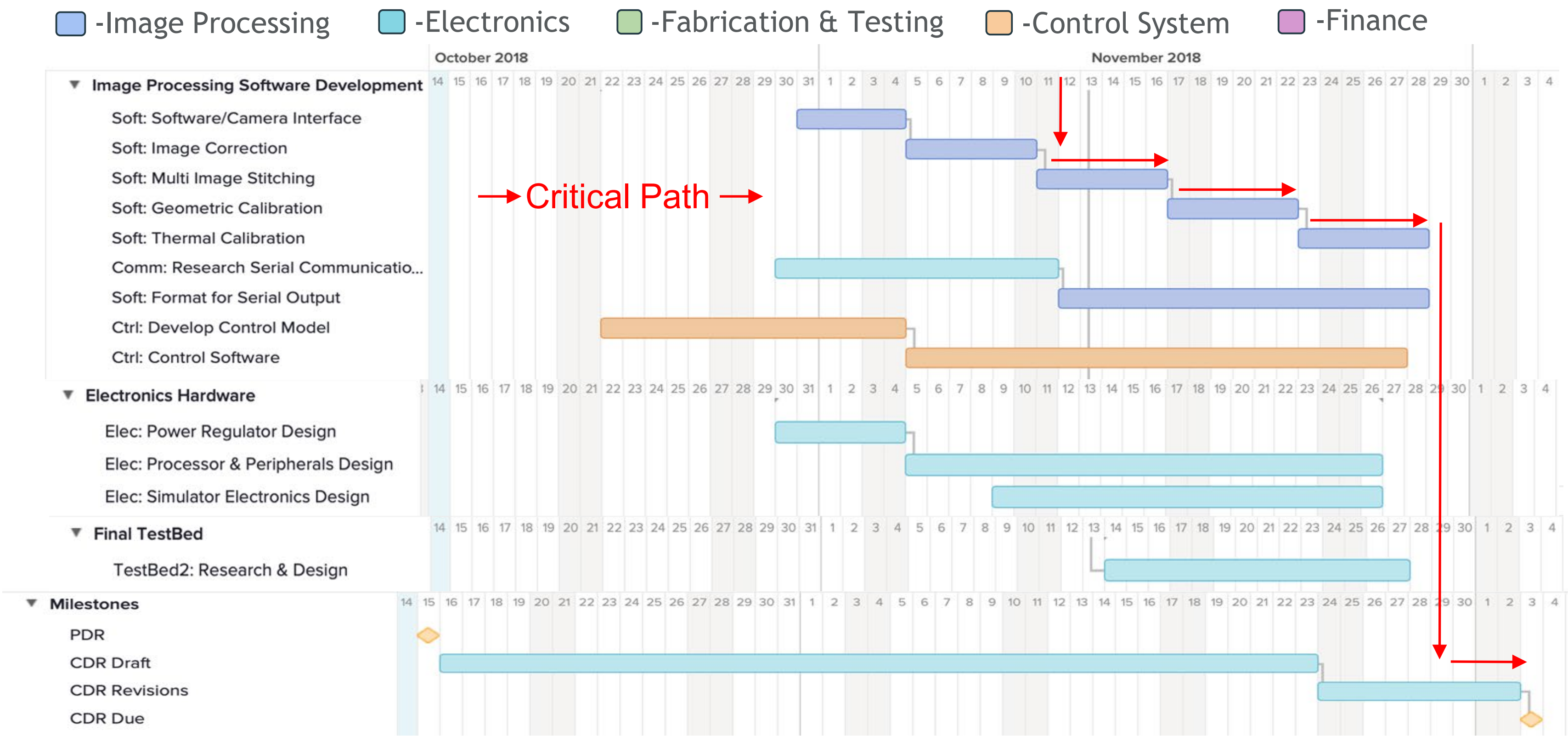
Feasible

Gantt Chart & Critical Path

-Image Processing -Electronics -Fabrication & Testing -Control System -Finance



Gantt Chart & Critical Path



Moving Forward

- Communications
  - RS232 or GA provided CAN support
  - D-type connectors suggested by GA
- Thermal Control
  - Methods to manage heat of the OTheRS system components
    - Cameras & system electronics
- Thermal Modeling
  - Cannot accurately model system without knowing thermal imaging device location(s)
  - 2D node based vs. 3D fully developed
    - Increasing level of model complexity → Better model fidelity & image processing validation
  - Highest level achievable depends on difficulty in implementing reflection characteristics
    - Note: Data to GA must tell them whether this system is suitable as is or if they will need to coat the satellite bus/avionics stack, or consider other design options
- TestBed
  - Start testing soon for reflectivity data
  - Start thinking about setup for mock electronics on board

Questions?

References

- https://opencv-python-tutroals.readthedocs.io/en/latest/py_tutorials/py_calib3d/py_calibration/py_calibration.html
- http://u88.n24.queensu.ca/exiftool/forum/index.php?topic=4898.msg23972#msg23972
- https://opencv-python-tutroals.readthedocs.io/en/latest/py_tutorials/py_imgproc/py_geometric_transformations/py_geometric_transformations.html
- https://docs.opencv.org/3.1.0/d5/daf/tutorial_py_histogram_equalization.html
- https://www.pyimagesearch.com/2016/01/11/opencv-panorama-stitching/
- https://docs.opencv.org/3.4/d4/d73/tutorial_py_contours_begin.html
- https://www.sparkfun.com/products/14654
- https://www.azahner.com/resources/relative-cost-metals
- https://agmetalminer.com/metal-prices/

Backup Slide Deck

Backup Slide Deck

TestBed

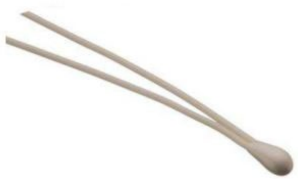
TestBed Requirement Flow Down

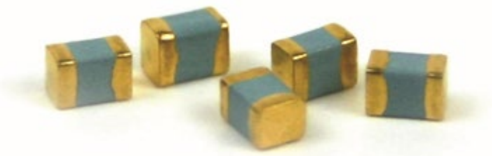
DR-TEST 1	The outer dimensions of the test bed shall be 261.3mm x 515mm x 547mm.
DR-TEST 1.1	The outer dimensions of the stack in the test bed shall 246.3mm x 290mm x 318mm.
DR-TEST 1.1.1	The stack surface material shall be 5mm thick.
DR-TEST 2	The stack shall replicate the thermal operating range of electronics contained in the stack, as defined in FR 1.
DR-TEST 3	OTheRS shall not be mounted to the outer walls or stack of the test bed.

TestBed: Thermistors

Thermistors:

- GA30K5A1IA 30K NTC series thermistors
  - $4.33 from DigiKey
  - $6.15 from Mouser Electronics ($3.05 if more than 10)





TestBed: Materials

Regarding price, consider:

- Life-time
- Fluctuation (with global demand)
  - Aluminum is the third most abundant element, making its price more stable.

Metal pricing (as of 10/10/18):

- Aluminum: $1.76/lb
- Carbon Steel: $0.40/lb
- Nickel Alloy: $15.31/lb
- Stainless Steel: $1.49/lb
- Titanium: $25.62/lb

Buying aluminum (companies):

- Aluminum Supply Denver
- Online Metals
- McMaster Carr
- Misumi

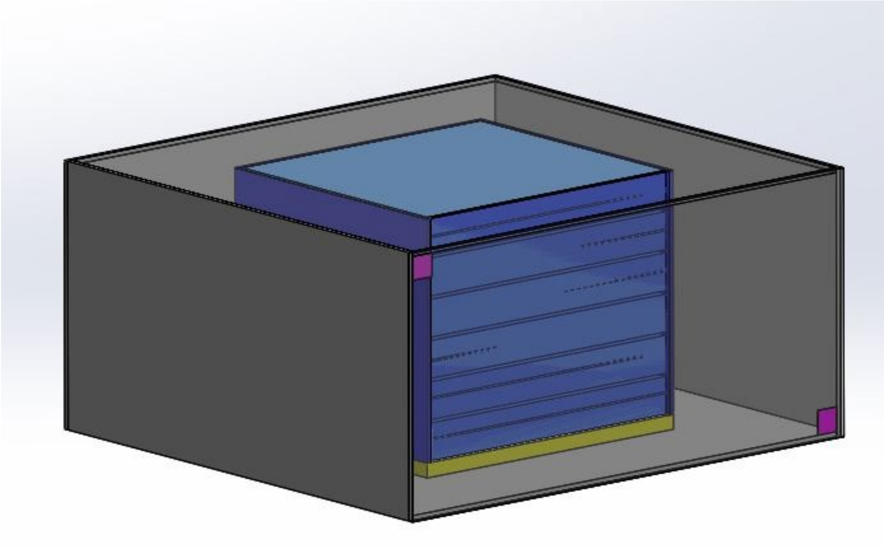
Coatings

Coatings	Emissivity
Lacquer: Matte Black	0.97
Cerablak HTP	>0.97
Electrical Tape	0.96
White Out Fluid	0.95-0.96
Thermographic Spray Paint	0.97

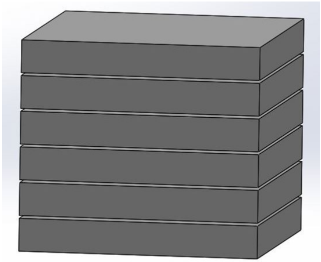
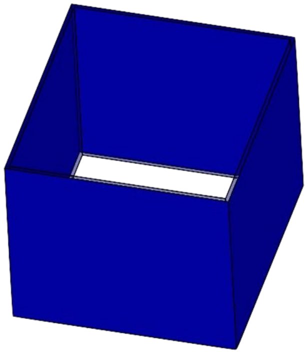
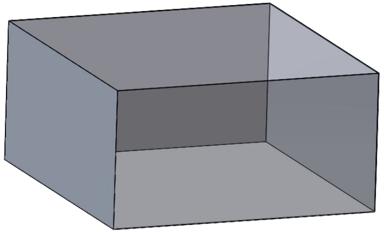
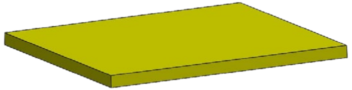
*Bare aluminum has an emissivity of ~0.4

TestBed Mock-Up

- Avionics Bay
- Stack Shell
- Trays
- Offset Plate



TestBed Component Dimensions

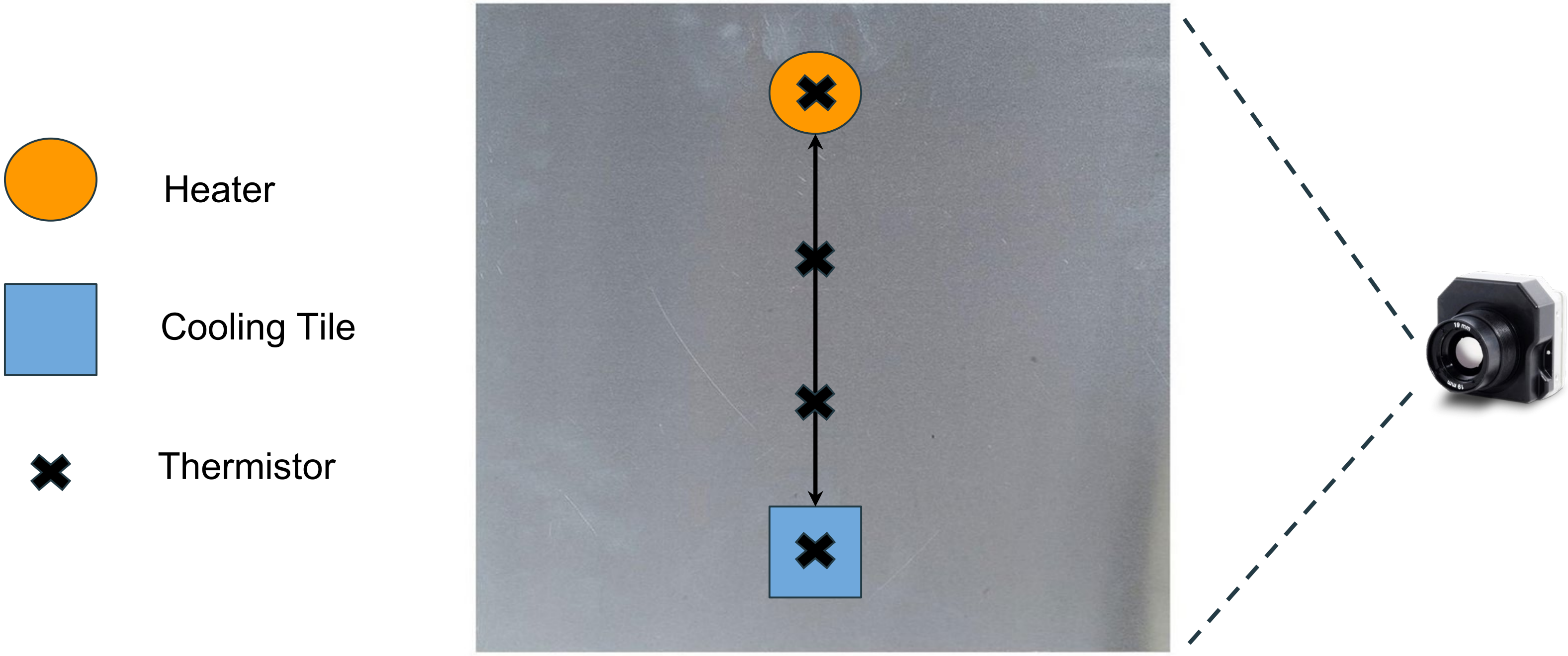
Trays	Stack Shell	Avionics Bay	Offset Plate
			
246.3 x 280 x 308 mm	246.3 x 290 x 318 mm	261.3 x 515 x 547 mm	15 x 290 x 318 mm

Wall Thicknesses = 5mm

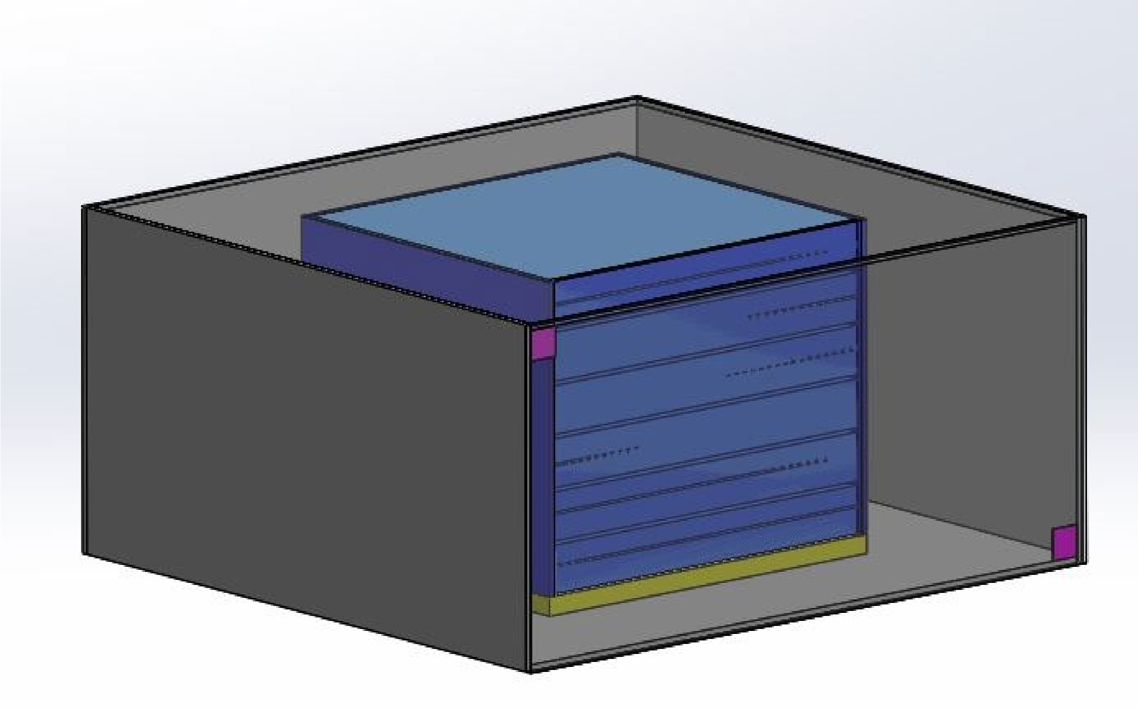
TestBed Feasibility: Key Parameters

- Time
  - Multiple iterations
  - Levels of testbed development facilitate final design
    - Learn what will & will not work in the final design, saving time
- Manufacturing
  - Test bed allowing for a variety of configurations
    - Non-reflective coatings
    - Flexibility of camera placement
    - Extensive wiring of thermistors
  - Simultaneous comparison of non-contact and contact thermal data
- Testing
  - Need thermal data soon to validate thermal model & provide reflectivity impact/feasibility
  - Ambient & thermal chamber environments
- Flexibility of design
  - Ability to mount a variety of heaters & coolers to account for electronics, sun-loads, and deep space ambient

TestBed Feasibility: Development - Level 1



TestBed Feasibility: Development - Level 2



TestBed Preliminary Design

1. Heat aluminum “stack” wall w/ power resistors and measure temperature w/ thermistors
2. Measure the plate temperature w/ FLIR(s) from our determined mounting point(s).
    a. Key to this step will be to ensure that there are no heat sources reflecting onto the plate
3. Add a uniformly heated plate 111.0mm away from stack in such a way that its temperature profile will reflect back into the stack
    a. Compare thermistor truth data to measured data. May need to account for radiative heat transfer
    b. If necessary, retest with sticky notes to mimic original GA test to provide additional baseline data
4. If reflectivity issue is confirmed, retest with coatings on stack and compare the results
    a. Goal is to determine the maximum allowable reflectivity to achieve “accurate” temperature measurements
5. Test coatings and confirm measurements with truth data from surface mounted readings to reach tolerable error

Backup Slide Deck

Processing

Proof for processing speed requirement

- Image processing (IP) time range:
  - Longest IP step: ORB stitching - 0.6 seconds
  - Adaptive thresholding IP step: 0.003 seconds
- Change in temperature range:
  - 1 degree change between 330.85 and 618.15 seconds

Proof for processing speed requirement

- Camera Temperature Range: 263 K to 338 K
- Stack Temperature Range: 243 K to 333 K
- Thermal Conductivity of Al 2014A-T6: 150 W/m/K
- Emissivity of Anodized Al(Chromic Acid Processed): 0.55
- Lumped System Analysis:

$$Bi = \frac{h\, L_c}{\kappa} \quad where \;\; L_c = L_{plate} \;\; and \;\; h_{rad} = \; \varepsilon\, \sigma\, (T_1^2 + T_2^2)(T_1 + T_2)$$

- h_{rad} will range between 2.0232 and 4.7109 W/m²/K
- Bi will range between 0.00006744 and 0.000157
  - Lumped System applies: Bi ≤ 0.01 in both cases

Proof for processing speed requirement

- Using Lumped system analysis a time constant can be defined
- Density of Al 2014A-T6: 3000 kg/m^3
- Specific heat of Al 2014A-T6: 870 J/kg/K
- τ ranges between 0.000155 and 0.000361 s^{-1} (see below eqn.)
- For a change in stack surface temperature of 1 Kelvin the resulting equation will give the time for the change to take place

$$\frac{T(t) - T_\infty}{T_i - T_\infty} = e^{-\tau * t} \;\; so \;\; t = -\frac{1}{\tau}\ln\left(\frac{T(t) - T_\infty}{T_i - T_\infty}\right) \; and \; \tau = \frac{h\,A_s}{\rho\,V\,c_p} = \frac{h}{\rho\,L_{plate}\,c_p}$$

- A range of times dependent on the the initial temperature of both the stack surface and the camera
  - Time for 1 Kelvin change is between 330 and 618 seconds

Image Processing Overview

Camera subsystem captures thermal image(s)

→

Image Processing Software Stack

- **Bash scripting**
- **OpenCV Python**
- **Precompiled C/C++ codes**

→

Extract temp. data of data clusters and send to Controls subsystem

Image Processing Overview

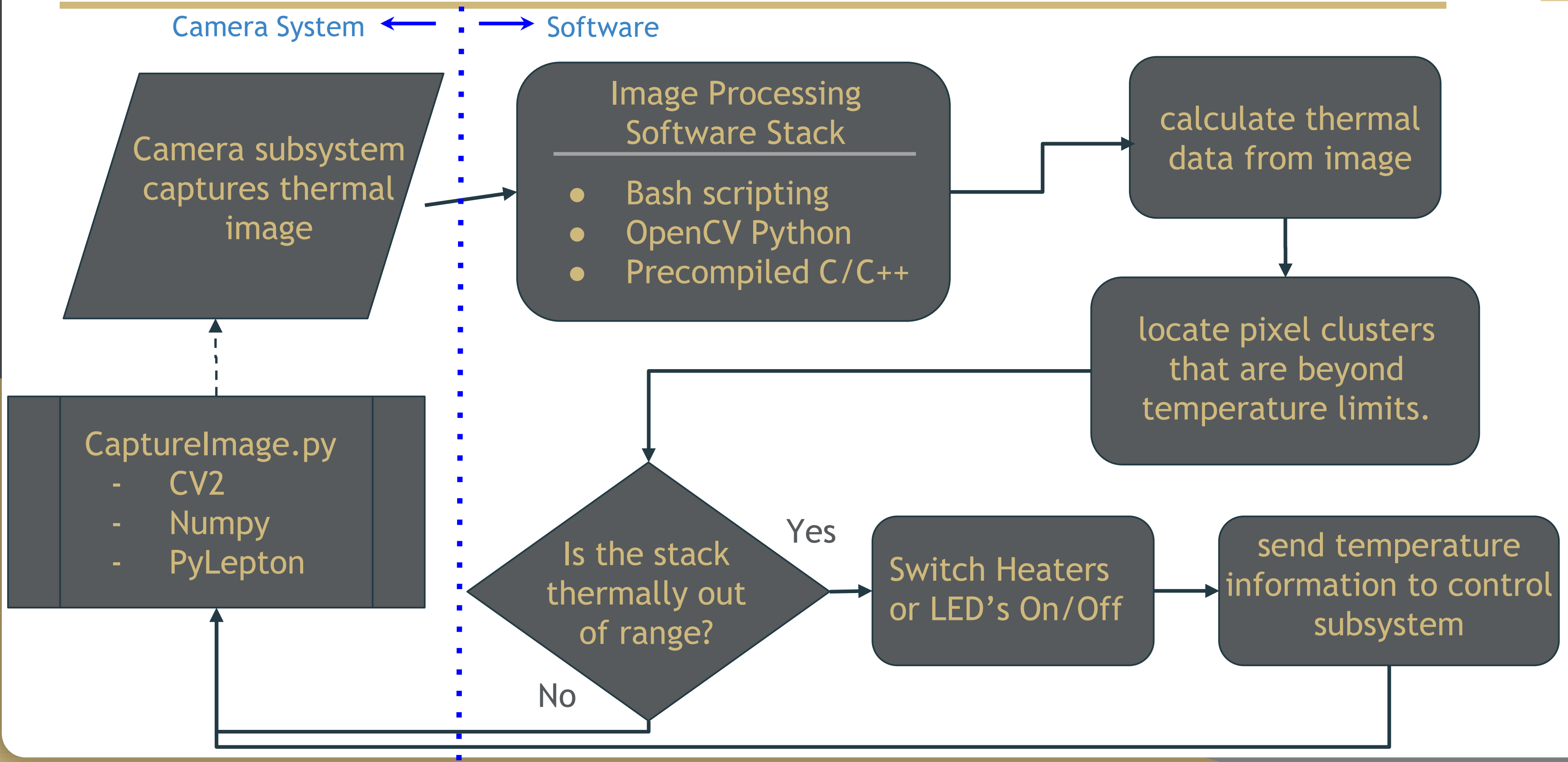
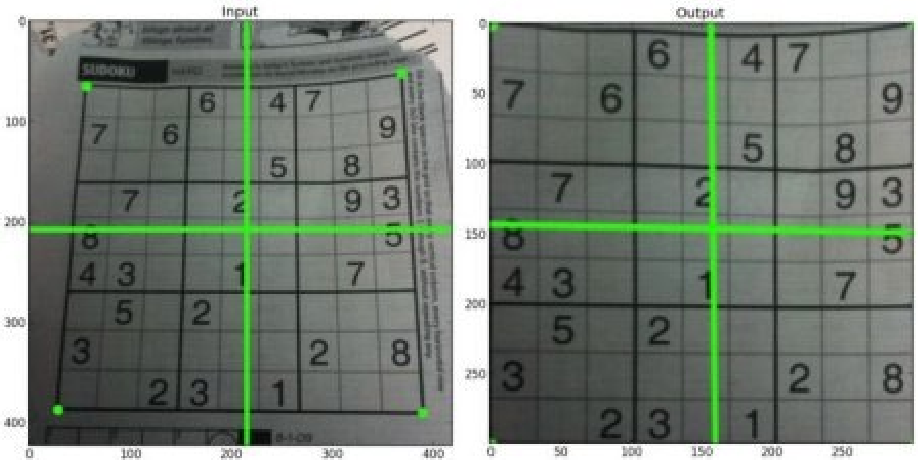


Image Processing Tools Available

OpenCV: Image Processing

- **Image Sharpening**
- **Contours**
- **Noise Removal**
- **Image Thresholding (Ohr's)**
- Canny Edge Detection



OpenCV: Computer Vision

- **Geometric calibration**
  - **Fix imaging distortions**
- Object Detection - Haar Cascades
- Machine Learning - K-Means Clustering

Additional software tools:

- **Exiftool - Metadata extraction**
- **C/C++ precompiled OpenCV code**
- **Numpy library**
- **Matplotlib library**
- Scikit-learn library

Image Processing - Extracting Temp. Data

Thermal Image Capture

80 px

60 px

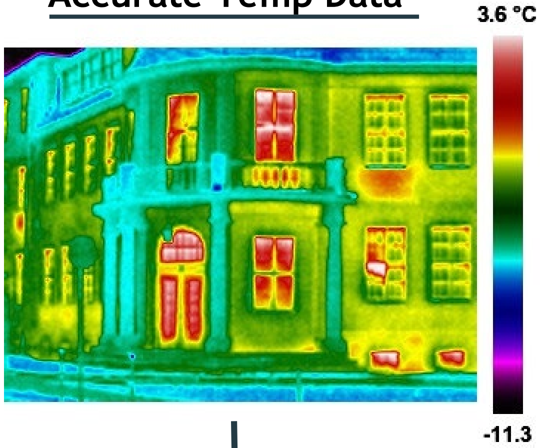
Extract Metadata

Humidity Data
Pixel Location 1x1: Planck Constants A, B, C, D, ...
Pixel Location 1x2: Planck Constants A, B, C, D, …
…………………………………….
…………………………………….
Pixel Location 80x60: Planck Constants A, B, C, D, ...

Exiftool Software Command Line

Planck's Law Calculations

Accurate Temp Data



Export

Image Processing - Planck's Law Calculations

- FLIR uses its own calibration method to calculate temp. threshold for a given image
  - 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.

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

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

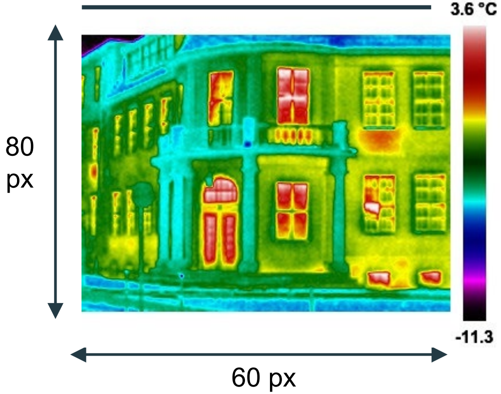
$$T_{obj} = \frac{B}{ln(\frac{R1}{R2(RAW_{obj}+O)} + F)}$$

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**

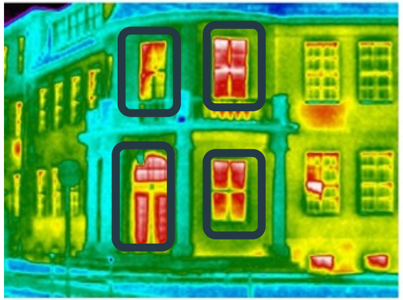
Image Processing - Computer Vision

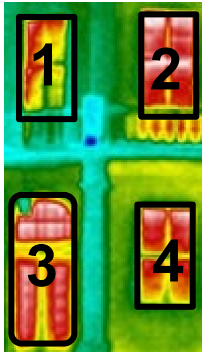
Input: Thermal Image



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

OpenCV Contour Approximations





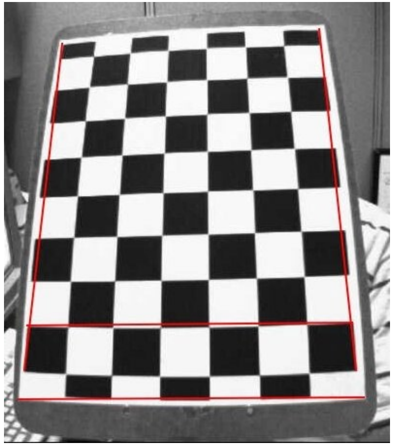
Export

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

Image Processing - Geometric Calibration

- Geometric calibration is imperative due to 2 different image distortions
  - Radial Distortion - Straight lines appear curved
  - Tangential Distortion - Some areas look nearer than actual

1



2

Radial Distortion

$$x_{corrected} = x(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)$$
$$y_{corrected} = y(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)$$

Distortion Coefficients: k1, k2, p1, p2, k3

Tangential Distortion

$$x_{corrected} = x + [2p_1 xy + p_2(r^2 + 2x^2)]$$
$$y_{corrected} = y + [p_1(r^2 + 2y^2) + 2p_2 xy]$$

3

$$camera\ matrix = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}$$

Focal length: fx, fy
Optical centers: cx, cy

Image Processing - Extracting Temp. Data

Input: Thermal Image

80 pixels

60 pixels

Exiftool Software

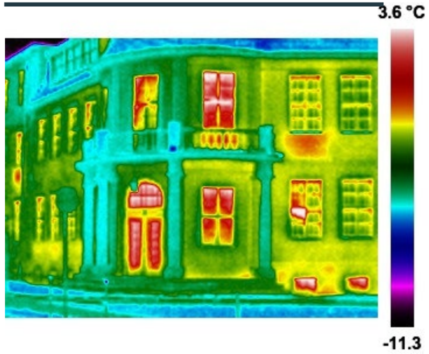
Extract (hidden) metadata

Extract Metadata

Humidity Data
Pixel Location 1x1: Planck Constants A, B, C, D, …
Pixel Location 1x2: Planck Constants A, B, C, D, …
…………………………………
…………………………………
Pixel Location 80x60: Planck Constants A, B, C, D, …

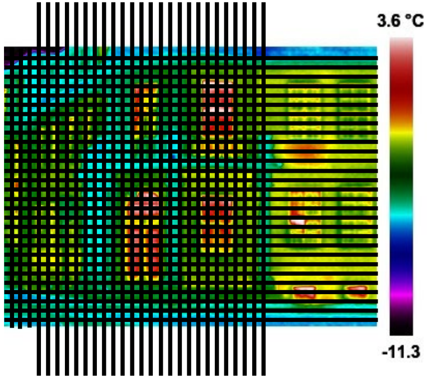
Planck's Law Calculations.py

Accurate Temp. Data



Relevant thermal data at each pixel location in the grid, use to calculate temperature

Perform parallel processing to break up image, calculate temp at each pixel location in ½ of the time (2 images - 4 cores on the Rasp Pi)



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

Backup Slide Deck

Thermal Model

Thermal Model Motivation

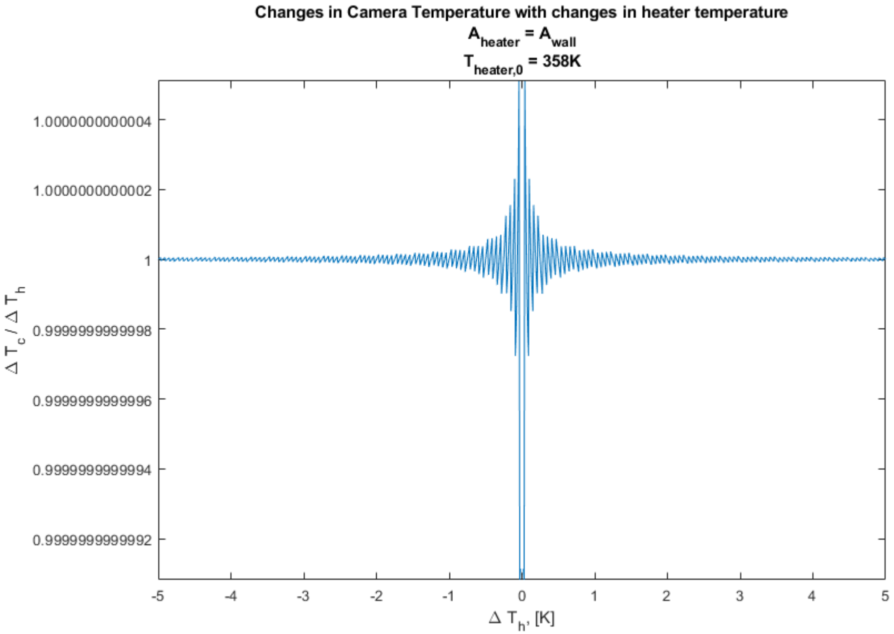
- Check how much radiation will be incident on our thermal imaging device(s)
  - Can this power be dissipated or rejected from the system
- Check sensitivity of camera to changes in heater temperature
- Give additional data to thermal calibration method
  - Possible sources of error to account for in calibration technique used
    - Reflectivity for black body calibration technique
- Allow for testing of various thermal properties from surface coatings for camera or stack
  - Absorptivity
  - Emissivity

Planar Thermal Model Solution Method

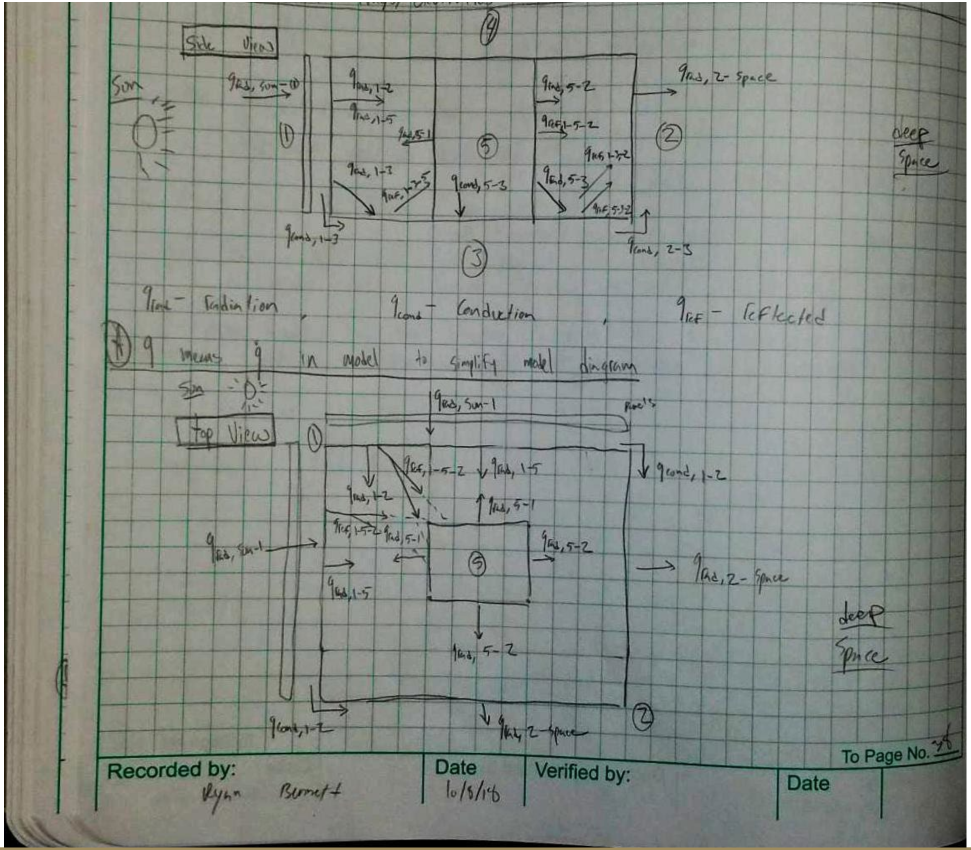
1. Solve for thermal radiation resistance ($R_{rad,2}$) with known quantities
2. Find heat transfer rate with $R_{rad,2}$ and change in temperature between outer wall of stack (T2) and camera
3. Solve for inner wall temperature with conduction and assumption that heat transfer rate is conserved
4. Solve for heater temperature using expanded form of Qdot = $\Delta T/R$ with $R_{rad,1}$ and change in temperature between heater and inner wall
5. Introduce changes in heater temperature and look for changes in camera temperature
    a. Assume that Qdot and total thermal resistance do not change
6. Graph and check for feasibility.

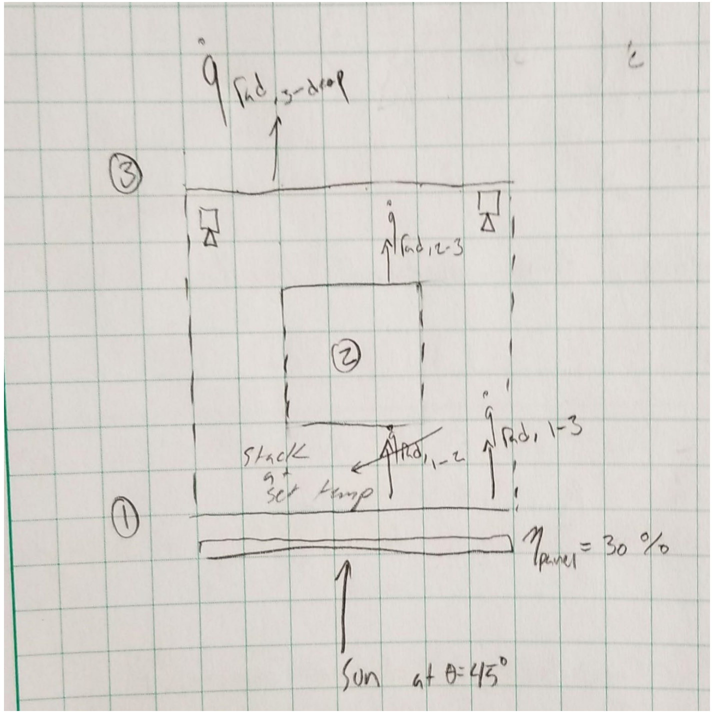
Planar Thermal Model Results

- At this heater temperature, the instantaneous changes in will be approximately constant to the changes in the camera



Incident Thermal Model Baseline

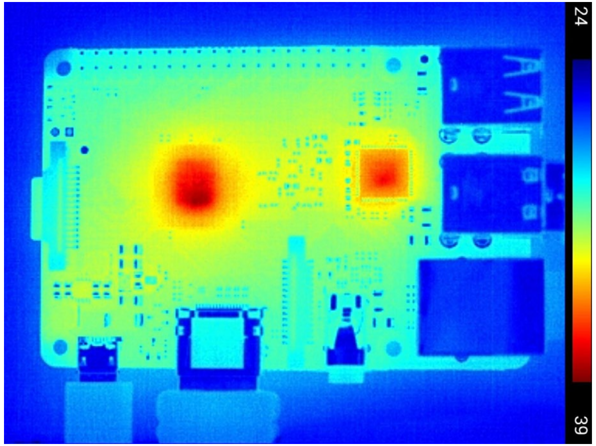




Incident Thermal Model Assumptions

- Solar panels absorb 30% of radiation
- Sun is directly pointed at corner of spacecraft
  - Viewing angle to each panel is constant
- Camera temperature is assumed to be constant when at thermal equilibrium
- 2D model, top and base plate are neglected
- Stack and bay are squares
  - Using average values for calculations
- Sunlight walls and deep space walls are respectively lumped as a single node
- Outer wall temperature on sun facing side is 531 K
  - Solar radiation is 1366 W/m^2 in LEO but only 676 W/m^2 is on the outer wall

Thermal Simulator: The Stack



Typical Microcontroller
(Temperature in Celsius)

- The exact contents of the stack are proprietary
- The contents of the stack are circuits on a PCB and can be assumed to be running at the same temperature as a microcontroller.

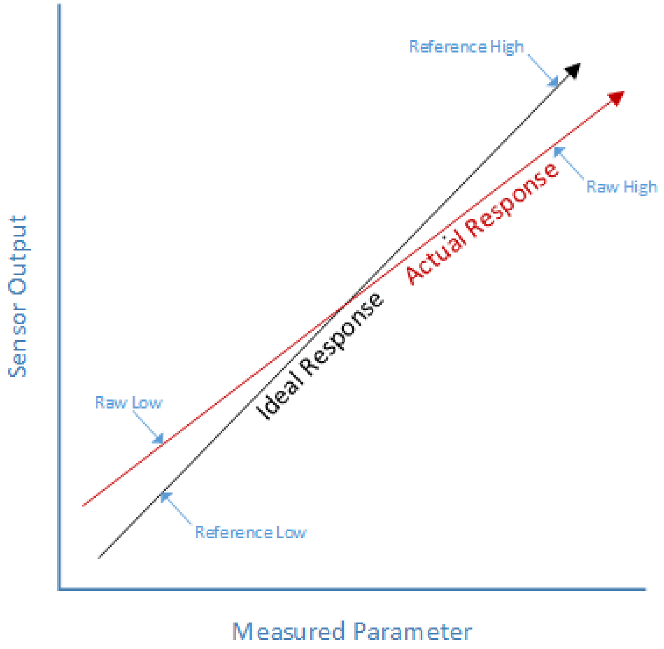
Thermal Simulator: The Stack

- Power resistors can be utilized to replicate these PCB temperatures in the test bed
- The power resistors can also be spaced in such a way as to calculate how close the PCB objects can be and still be resolved separately by the camera.
- Ceramic Heaters can also be used to simulate thermal loads

Backup Slide Deck

Calibration

Camera Calibration: Methodology (1/2)



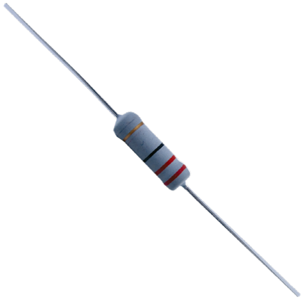
Two-point calibration is able to correct both slope and offset errors.

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: Point Determination (2/2)



The **Power Resistor** is assumed to emit as a blackbody. Supplying specific quantities of power heats it to a well known temperature to be used in calibration.

Thermistor to be used as a measurement device for the purpose of calibration

The **optimal thermal calibration** point determination is 1 thermistor and 1 black body radiator

Backup Slide Deck

Camera Setup

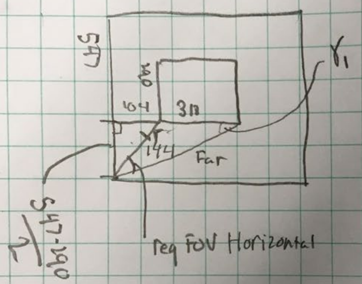
Camera Setup Calculations

48 Project No. ______ TITLE ______

Book No. ______

From Page No. ____

Horizontal Calculations



$$Far = \sqrt{\left(\frac{547-290}{2}\right)^2 + (318+104)^2}$$

$$\rightarrow \frac{\frac{547-290}{2}}{\sin \gamma_1} = \frac{Far}{\sin 90}$$

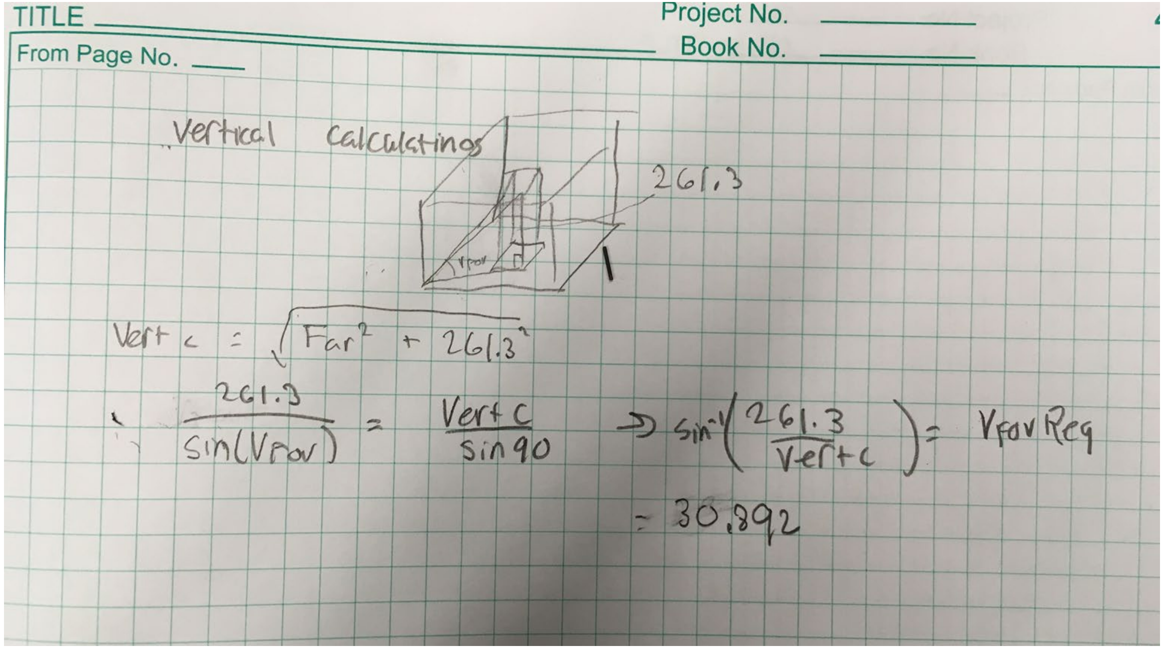
$$\gamma_1 = \sin^{-1}\left(\frac{\frac{547-290}{2}}{Far}\right)$$

$$\frac{318}{\sin(FOV_{Hreq})} = \frac{144}{\sin \gamma_1}$$

$$FOV_{req} = \sin^{-1}\left(\frac{318 \sin \gamma_1}{144}\right)$$

$$= 29.9762$$

Camera Setup Calculations



TITLE

From Page No.

Project No.

Book No.

Vertical Calculatinos

261.3

$$\text{Vert}_c = \sqrt{\text{Far}^2 + 261.3^2}$$

$$\frac{261.3}{\sin(V_{FOV})} = \frac{\text{Vert } c}{\sin 90} \Rightarrow \sin^{-1}\left(\frac{261.3}{\text{Vert } c}\right) = V_{FOV}\,\text{Req}$$

$$= 30.892$$

Camera Setup Calculations

$$\frac{51.5 \text{ deg}}{80 \text{ pix}} = .6438 \frac{\text{deg}}{\text{pix}}$$

$$\frac{318 \text{ mm}}{29.97 \text{ deg}} = 10.6106 \frac{\text{mm}}{\text{deg}}$$

$$10.6106 \frac{\text{mm}}{\text{deg}} * .6438 \frac{\text{deg}}{\text{pix}} = 6.8306 \frac{\text{mm}}{\text{pix}}$$

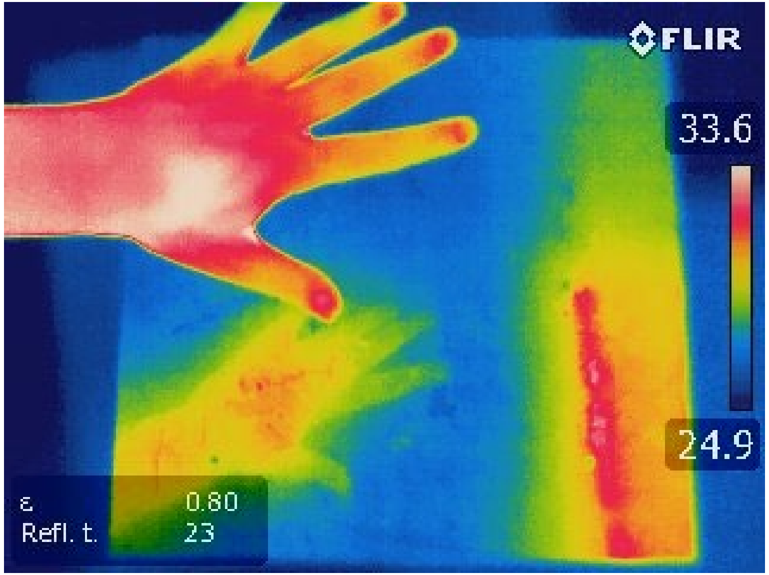
Backup Slide Deck

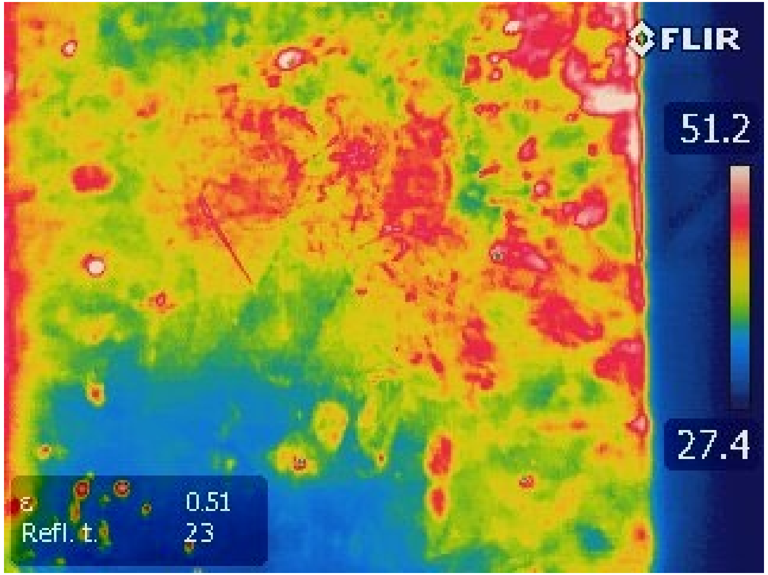
Miscellaneous

Thermal Controls and Feedback

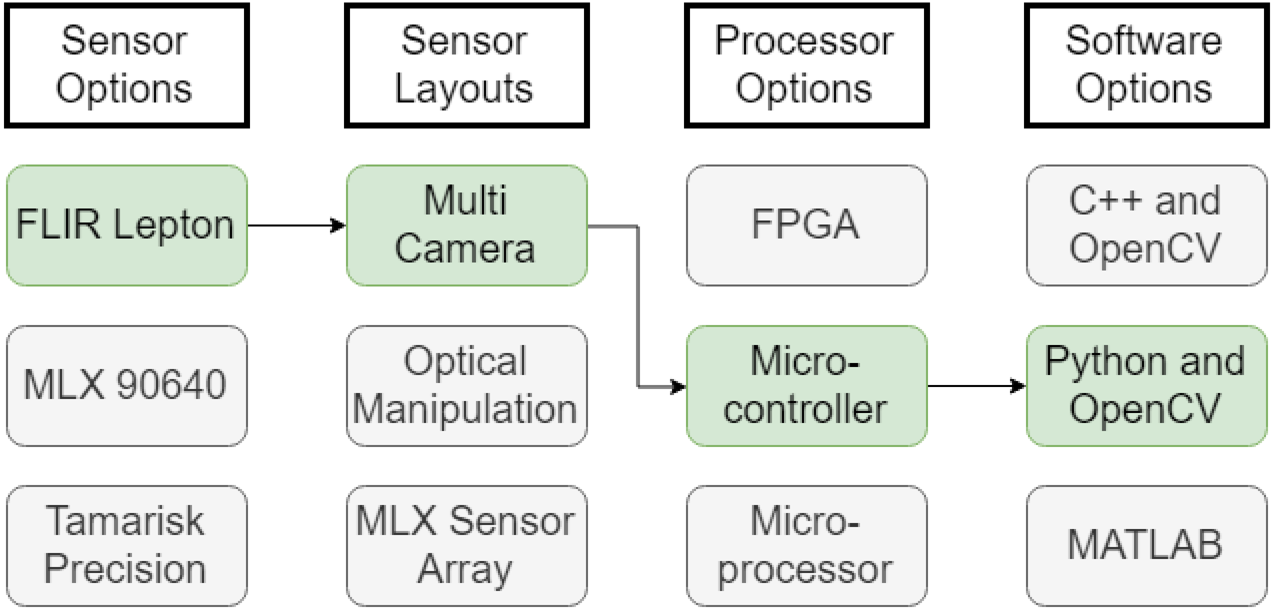
- Mostly **out of scope**.
- We are focusing on proving the **feasibility of the sensor.**
- Many unknowns exist with regard to the thermal properties of the stack and surrounding environment. Studying these and **producing a good system would take lots of time**.
- Advanced **thermal models and thermal control systems already exist** and exceed what we could produce in fidelity and accuracy.
- Data from the sensor can be fed into existing control systems

More Sample Thermal Images

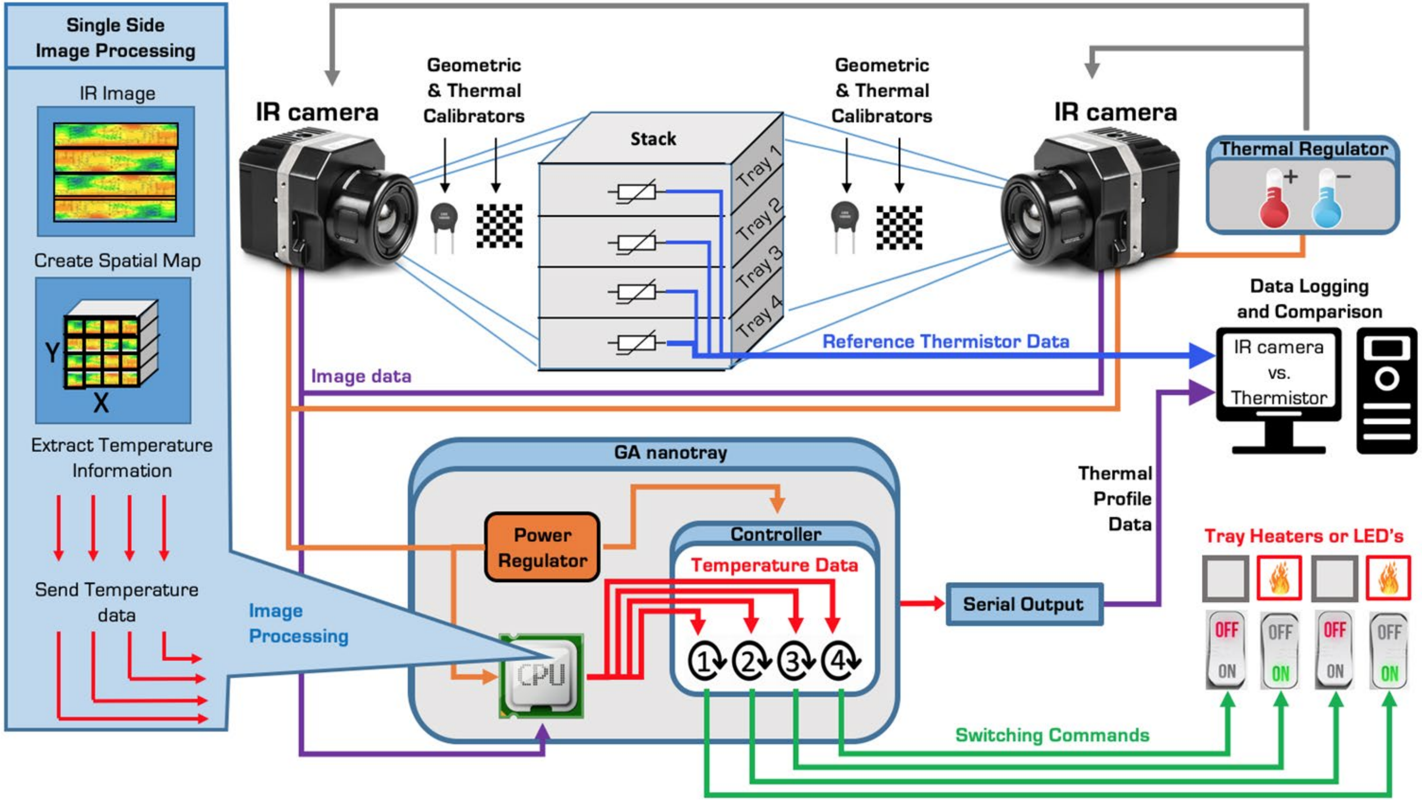




Design Options Considered



Detailed CONOPS



FLIR Lepton

Cost	$300.00
Resolution	80 pixels x 60 pixels
FOV	Horizontal: 51°, Vertical: 39° Diagonal: 63.5°
Thermal Sensitivity	0.05℃
Wavelength Range	8-14 microns
Thermal Sensing Range	-10℃ to +120℃
Operating Temperature Range	-10℃ to +80℃