Spring Final Review

SPECTROM

Scientific Platform for the Exact Control of Thermally Regulated Optical Mechanisms

Team: Cameron Coupe, Jeff Ellenoff, Jaevyn Faulk, Zach Fellows, Sarah Levine, Eli McKee, Josh Mellin, Tyler Talty, Josh Whipkey, Josh White

Customer: Ball Aerospace & Technologies Corp.

Joe Lopez

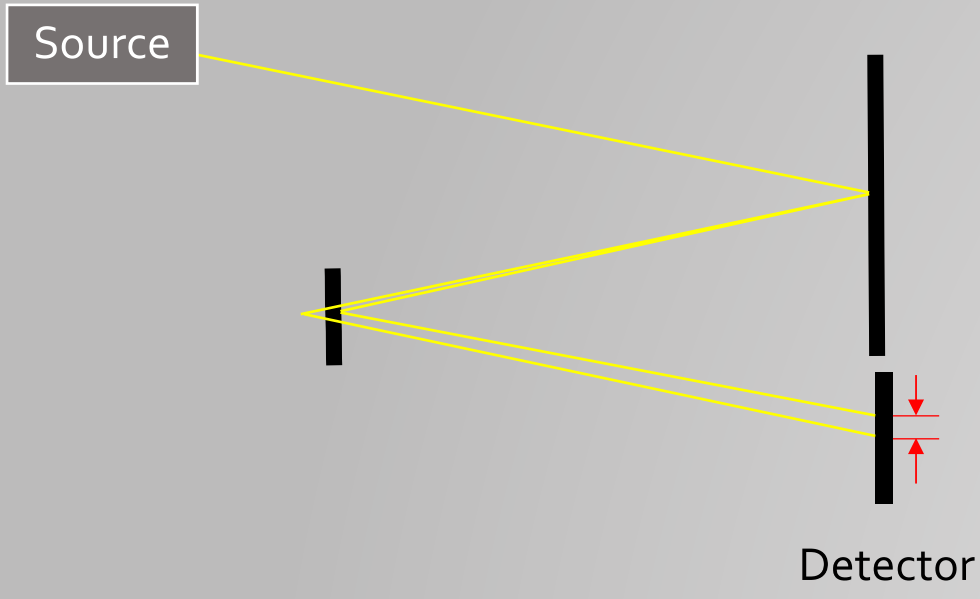
Advisor: Bob Marshall

Agenda:

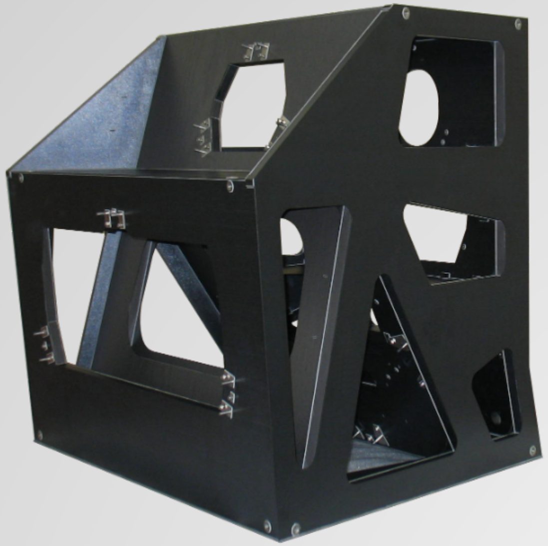
- Project Purpose and Objectives
- Design Description
- Test Overview
- Test Results
- System Engineering
- Project Management

Purpose & Objectives

Project Motivation



- Maintaining precise alignment of spacecraft optical instrumentation often employs costly composite optical bench



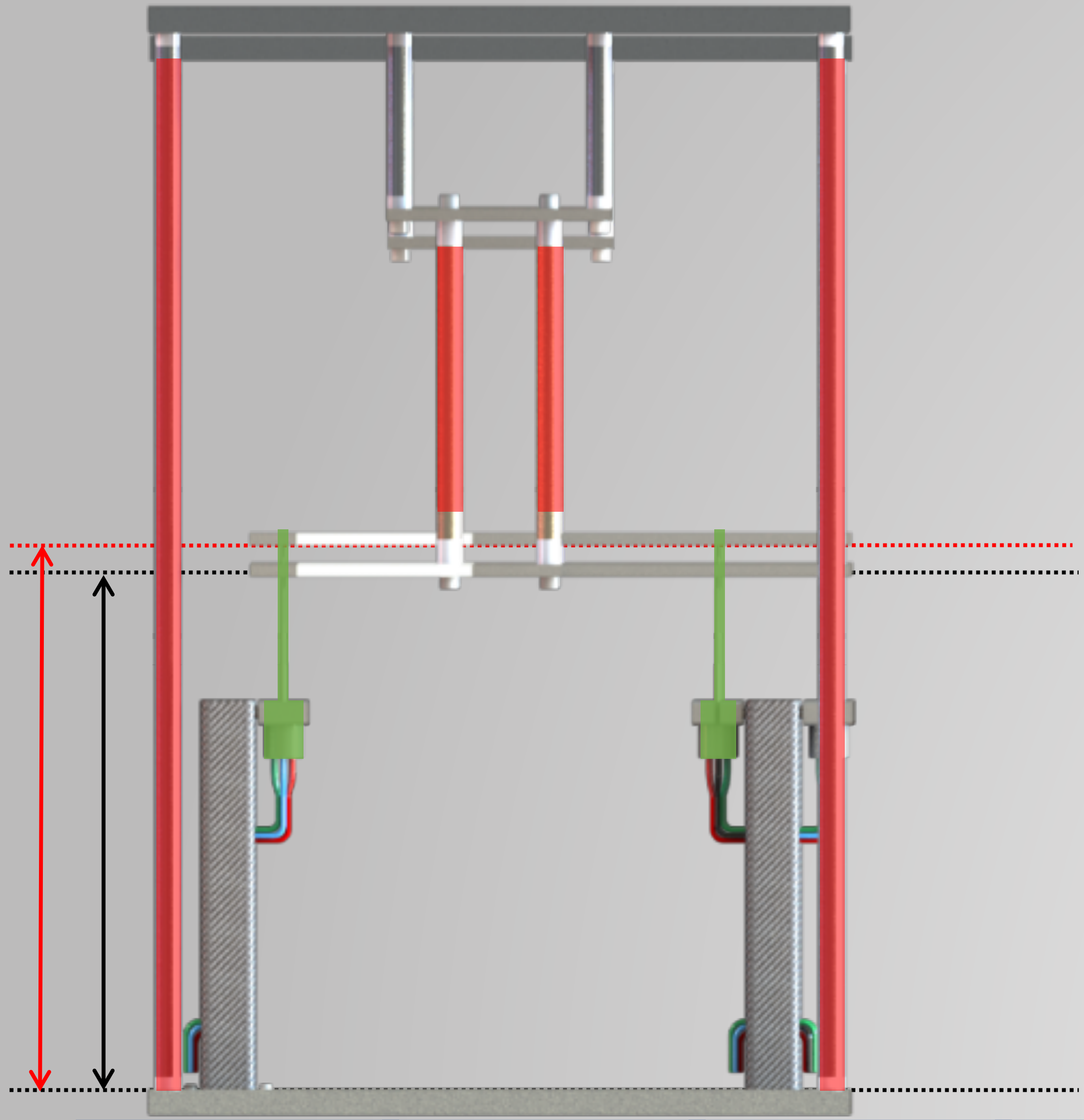
- Reduce cost by using an aluminum bench
- Thermal expansion for active control mechanism

Image: Composites Today[1]

Project Statement

Design, integrate, and verify precision, of an **active control system** that utilizes **thermal expansion** to adjust the **alignment** of spacecraft optical instrumentation. This system will correct for misalignment introduced by thermal expansion of an **aluminum optical bench**.

Concept of Operations



1. The test bed is heated to induce alignment error between two planes.

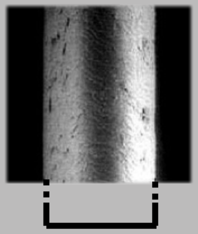
2. Alignment error is measured by the Alignment Measurement System (AMS).

3. Heating is applied to the Alignment Correction System (ACS) to maintain alignment of the two planes.

4. Displacement and temperature data are recorded and stored by the electronics package.

System Requirements

	Characteristic	Requirement	Analysis Prediction	Testing Results
Test Bed	Translation Displacement	> 100 µm in 10K	113 µm	106 µm in 5.6K
	Rotation Displacement	> 50 µradians	169 µradians	> 73 µradians induced
ACS	Translation Correction (Dynamic Test)	95% test ± 2 µm	99%	96% test ± 2 µm
	Rotation Correction (Dynamic Test)	95% test ± 20 µrad	100%	100% test ±15 µrad
	Time Requirement (Static Test)	600 seconds	42 seconds	117 seconds
AMS	Displacement Measurement	± 1.75 µm	± 1.66 µm	± 0.87 µm
	Rotation Measurement	± 15.3 µrad	± 14.42 µrad	± 8.0 µrad
Electronics	Temperature Measurement Accuracy	± 0.2K	± 0.083 K	± 0.13 K RMS error
	Temperature Control	± 0.25K	± 0.195K RMS error	± 0.14 K RMS error



Human Hair
60 µm

Image: NASA[2]

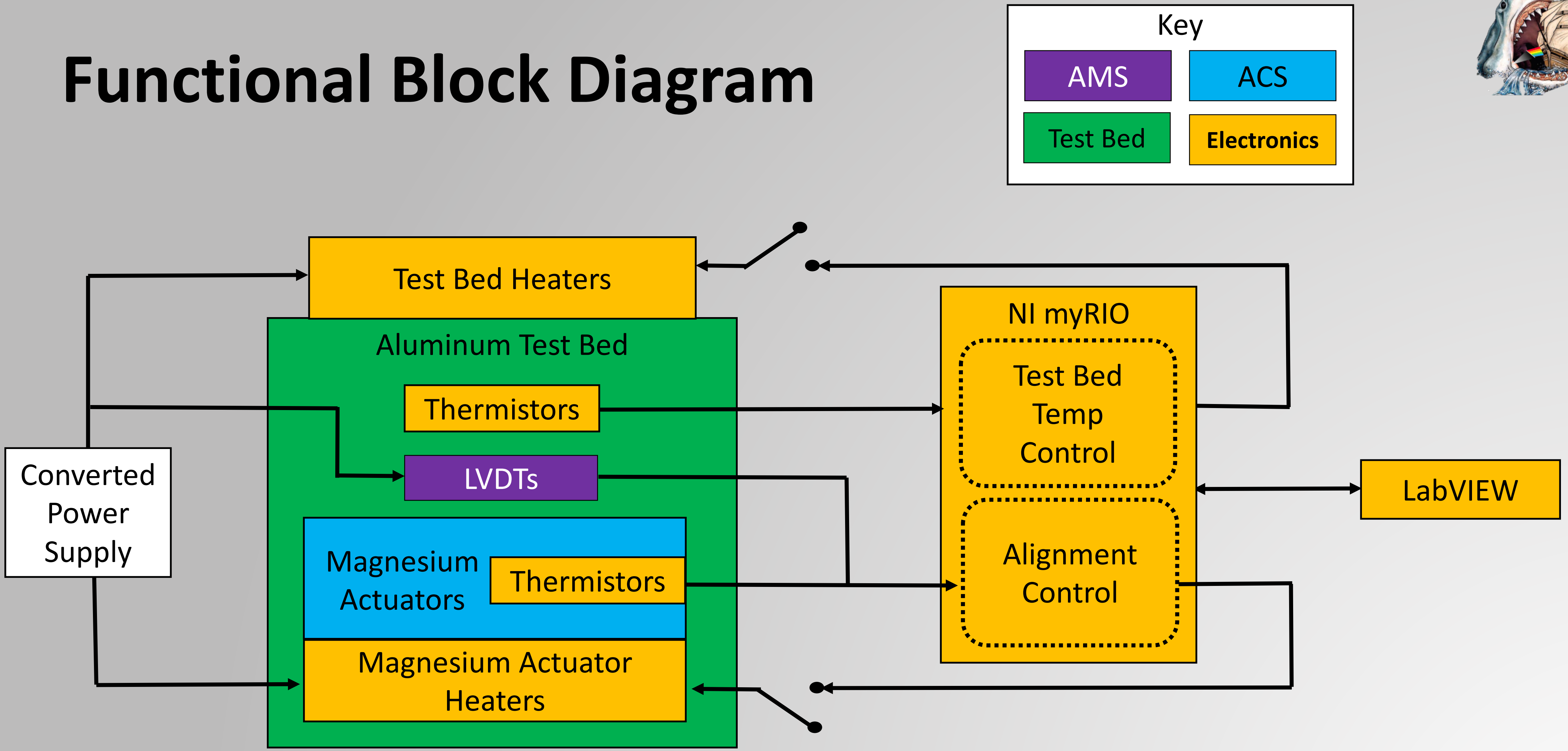
Levels of Success

	Test Demonstration Unit (TDU)	Alignment Correction System (ACS)	Alignment Measurement System (AMS)	Electronics Package
Level 1	• Induce > 100μm of plane alignment translation error over ΔT=10K	• Correct plane alignment to within ±2 μm of original position within 120 seconds	• Measure translation displacement of two planes with 1.75 μm accuracy	• Heater control to enable translation correction within ±2 μm
Level 2	• Induce customer-provided temperature profile to within 0.5 K at all times • Know temperature of actuators to within ±0.2 K at all times	• Maintain plane alignment within ±2μm for 95% of the test bed heating profile		• Active temperature control using thermistor feedback • Record time, position and temperature data for duration of testing
Level 3	• Induce > 50 μm rotational displacement over ΔT of 10 K starting from 296.15 K	• Maintain plane alignment within ±2 μm and ±20 μrad for 95% of the test bed heating profile	• Measure translation and rotation displacements to ±1.75 μm and ±15.3 μrad accuracy	• Record, and display real-time position and temperature data at a rate of at least 1 measurement per second

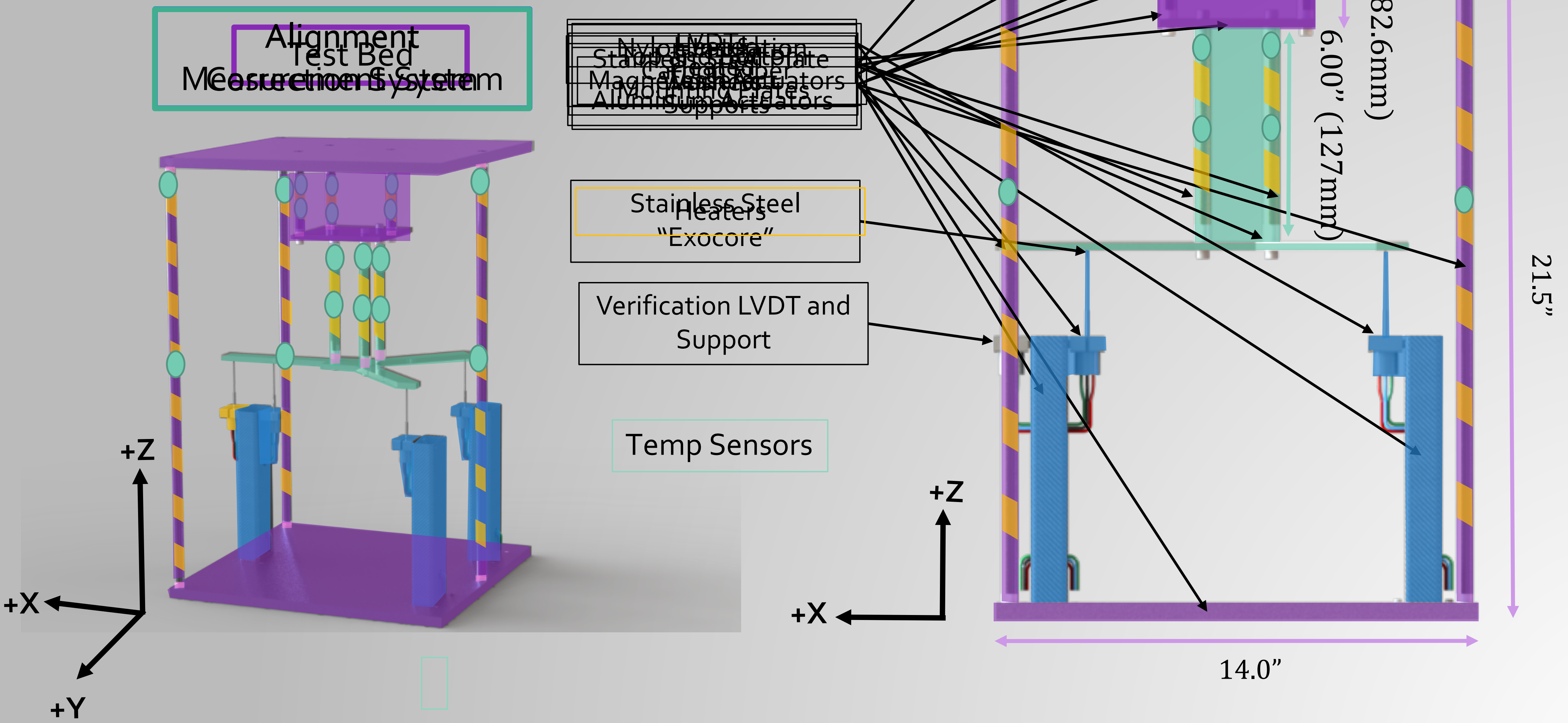
ALL LEVEL 3 SUCCESS CRITERIA MET

Design Overview

Functional Block Diagram



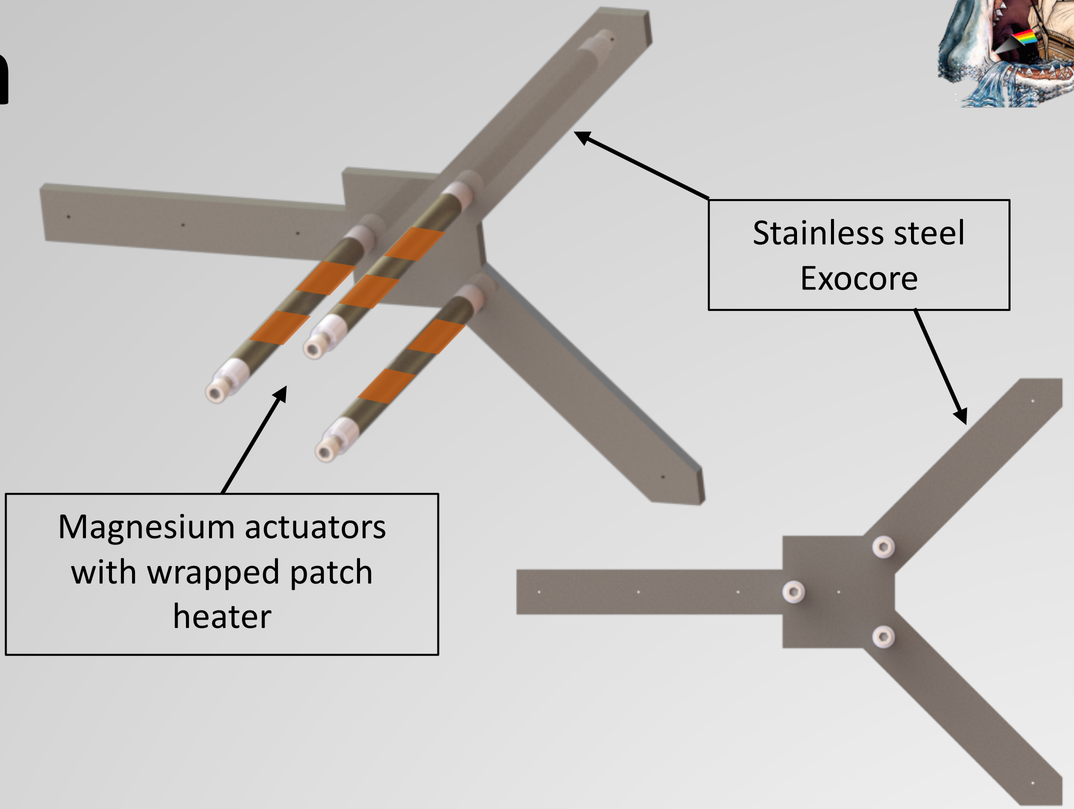
Hardware Design Overview



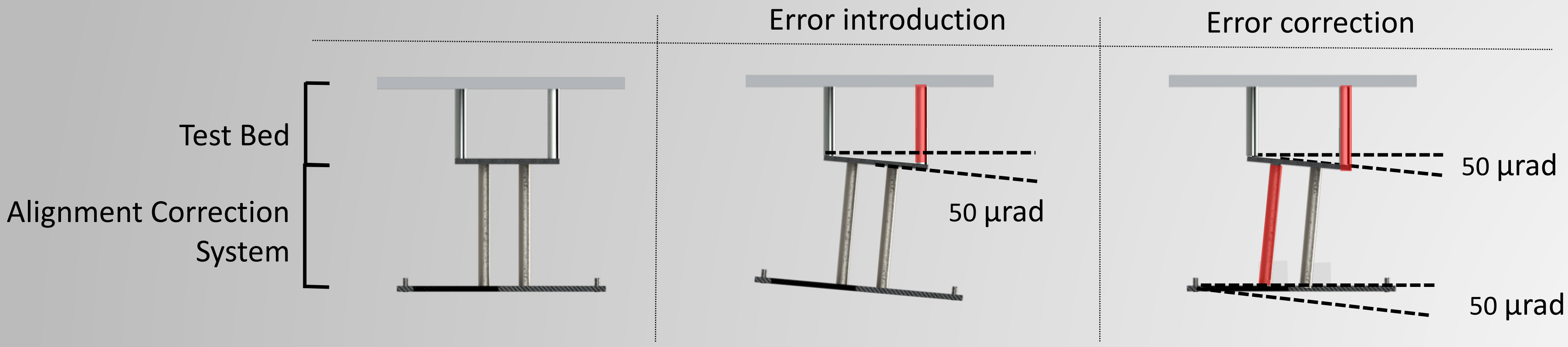
Alignment Correction System

- Control mechanism consists of three, 5” cylindrical heated magnesium actuators attached to stainless steel Y-shaped plate (Exocore)

- Isolated heating of specific rods induces rotation and translation to the Exocore to correct for alignment error
  - Three-axes of corrective capability



CONOPS:

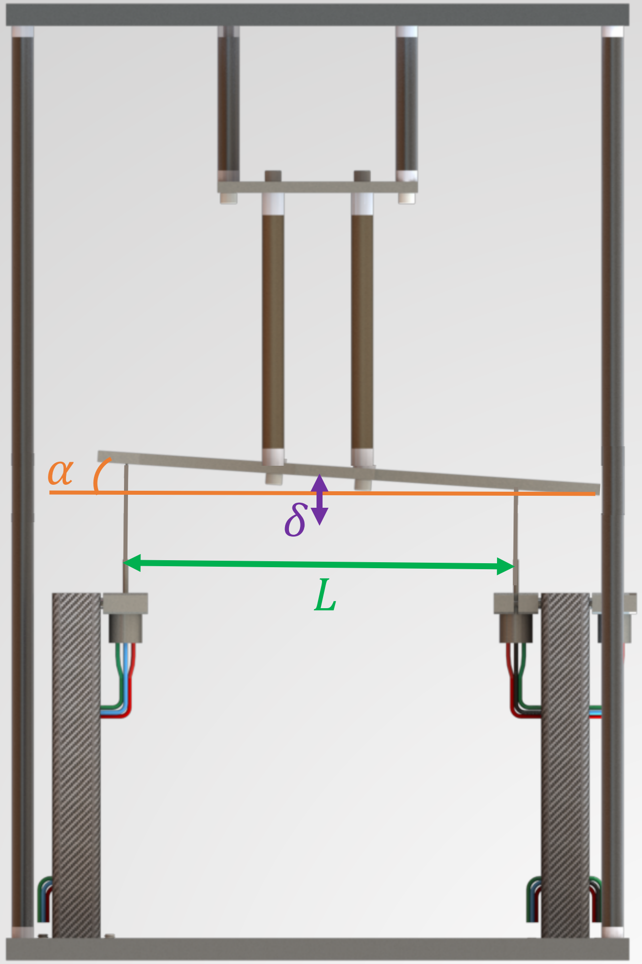


Alignment Measurement System

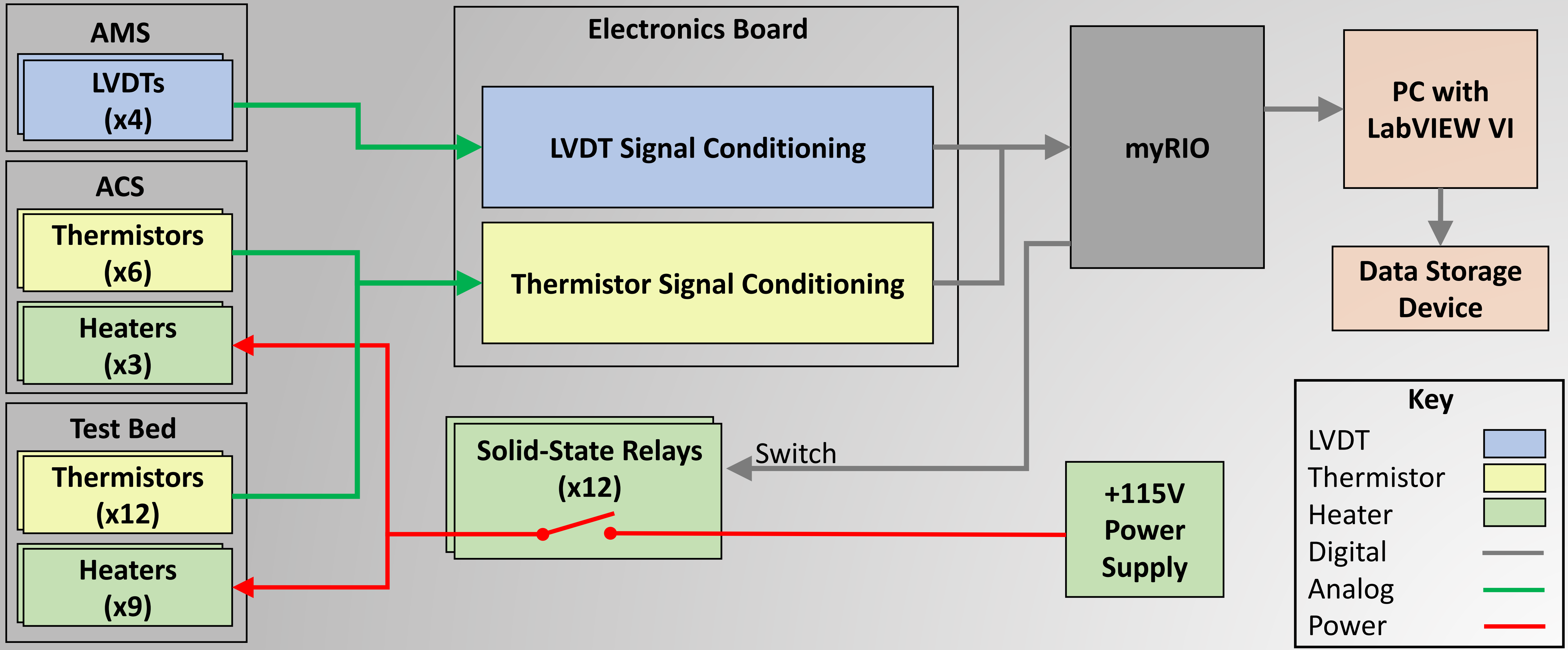
- Plane alignment measured by three primary LVDTs
  - Fourth used for plane orientation verification

- Measured error used to calculate displacement of centroid and two deflection angles

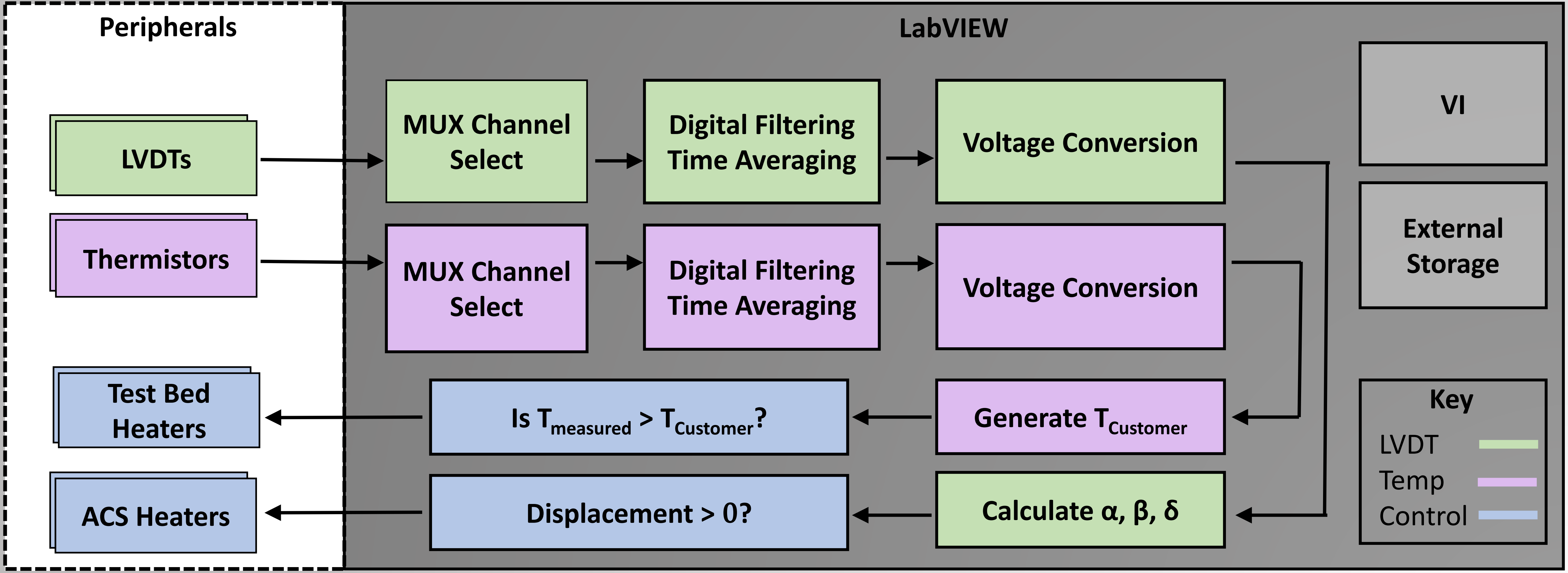
$$\begin{bmatrix} \delta \\ \tan(\alpha) \\ \tan(\beta) \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{4} & \frac{1}{4} \\ -\frac{1}{L} & \frac{1}{2L} & \frac{1}{2L} \\ 0 & -\frac{1}{L} & \frac{1}{L} \end{bmatrix} \cdot \begin{bmatrix} \ell_1 \\ \ell_2 \\ \ell_3 \end{bmatrix}$$



Electronics Design Overview



Software Design Overview



Critical Project Elements

Critical Project Elements	System Solution
Active control of plane alignment using expansion of a high CTE material	Alignment Correction System (ACS)
Accurate measurement of plane alignment in three-axes	Alignment Measurement System (AMS)
Introduction of controlled thermally induced alignment error	Test Bed
Thermal control and measurement of heated elements	Electronics Package

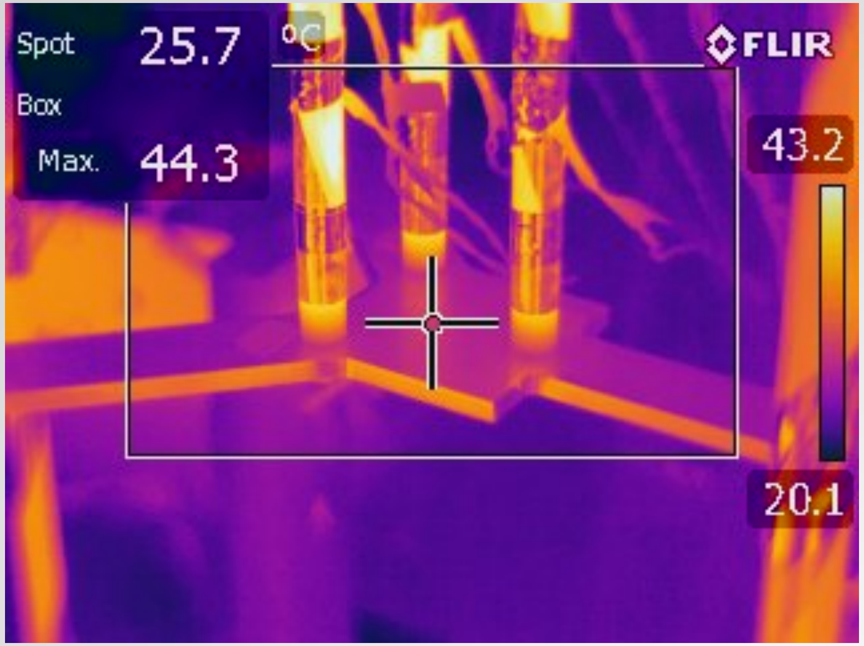
Changes Since TRR

- Thermal Camera used for temperature verification
  - Thermistor calibration
  - Temperature of bench components
- Anti-vibration table not used
  - Not needed to achieve desired results

Testing Overview

Purpose of Testing

- Is a **thermal expansion driven** control system feasible?
  - Validate control and thermal models
  - Establishes feasibility of application for system zeroing and on-orbit correction

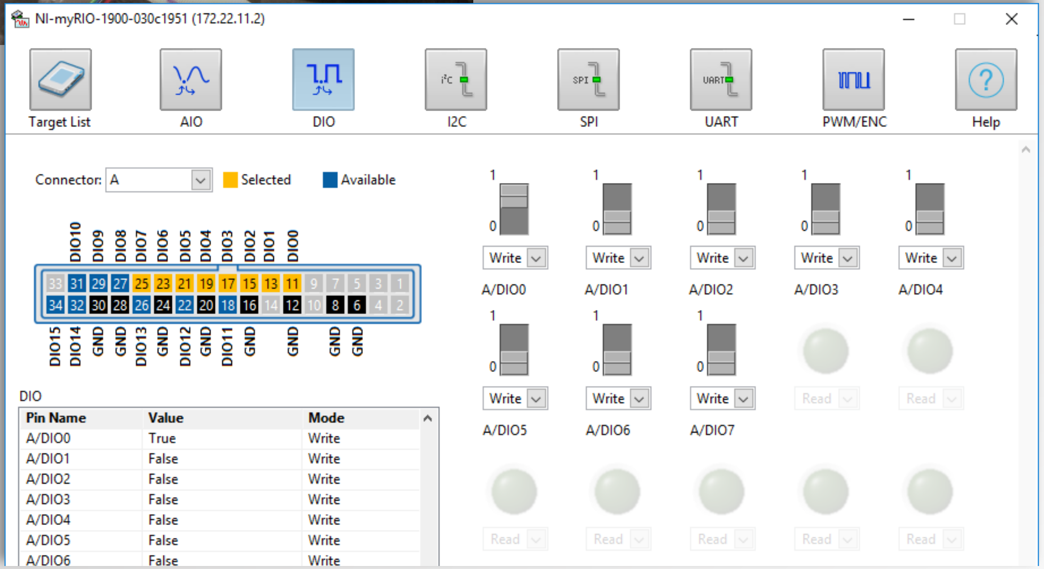


- How **precisely** can the control system maintain "zeroed" plane alignment?
  - Verifies displacement measurement and correction requirements

Electrical Tests

Test	Procedure
Thermistor Calibration	• Submerge thermistor and measure water thermistor temp with thermal camera • Vary R_{sense} in software until readings match camera
LVDT Sensitivity	• Secure LVDT in mill • Lower core known distance • Compare output voltage to expected voltage
Heater Functionality	• Connect heater PCB to myRIO and heaters to PCB • Use the NI IO Monitor to manually switch the digital lines from the myRIO • Confirm heaters turn on

LVDT mill sensitivity testing



Heater Functionality Testing

Software Tests

Purpose:

- Simulate thermistor and LVDT measurement signals
- Verify correct conversion from voltage to temperature/distance

Results:

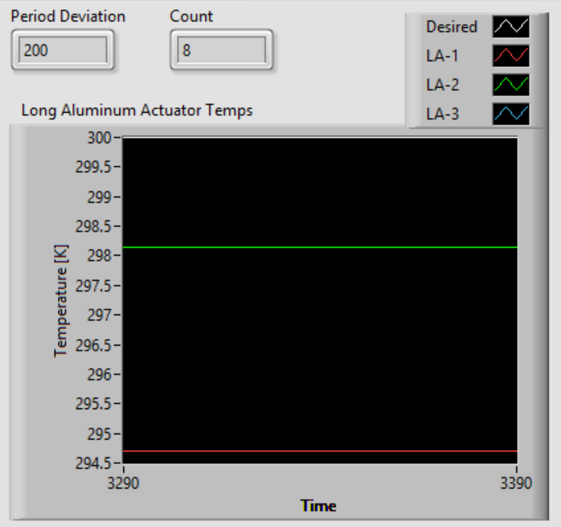
- For known input voltages, output is correct
- Validated all lines and sub VI's between input and output (mostly, see lessons learned)
- Customer temperature profile generated correctly

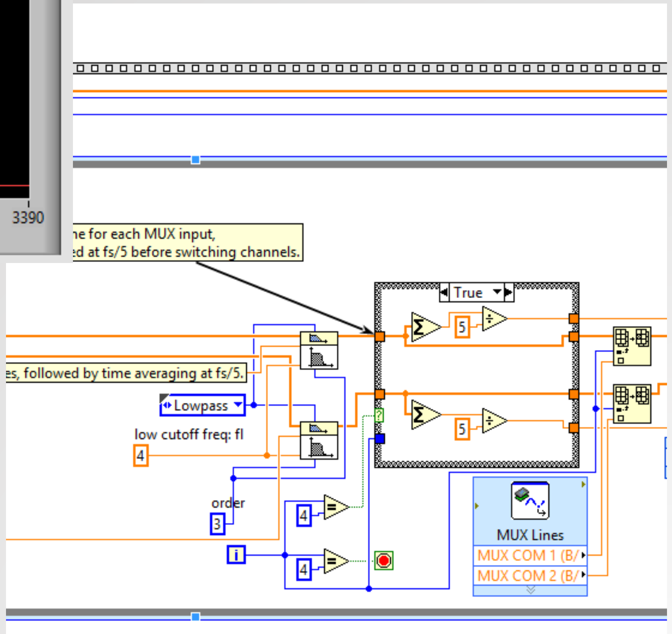
Requirements Traceback:

- Temperature measurement (+/- 0.2K)
- Temperature control (+/- 0.3K)

Lessons Learned:

- Don't replace all variables at the same time. Commonalities make results appear correct, yet variables may be coupled in unseen ways. Replace one at a time.
- Spread LabVIEW VI's out sufficiently. Small working spaces leads to crossed lines, incorrect indexing, etc.





Static Zeroing Test

Purpose:

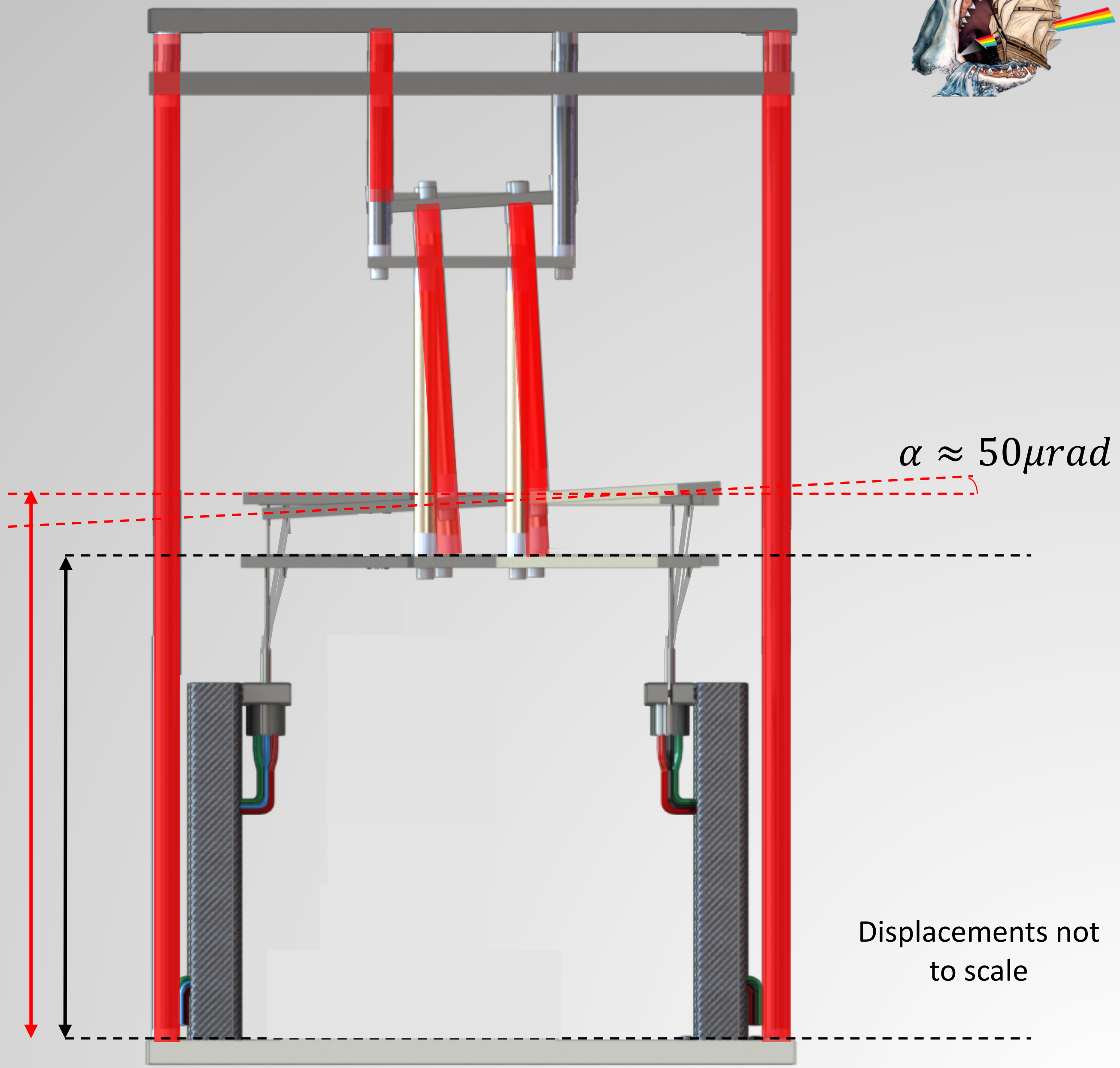
- Simulate initial zeroing of the system alignment upon arrival in orbit

Objectives:

- Correct for induced rotation and translation displacement within time requirements
- Maintain zeroed alignment for duration of test

CONOPS:

1. Heating is applied to the test bed to induce translation and rotation alignment error
2. ACS heaters apply ΔT to correct rotational misalignment
3. ACS heaters apply ΔT to correct for translation errors



Dynamic Test

Purpose:

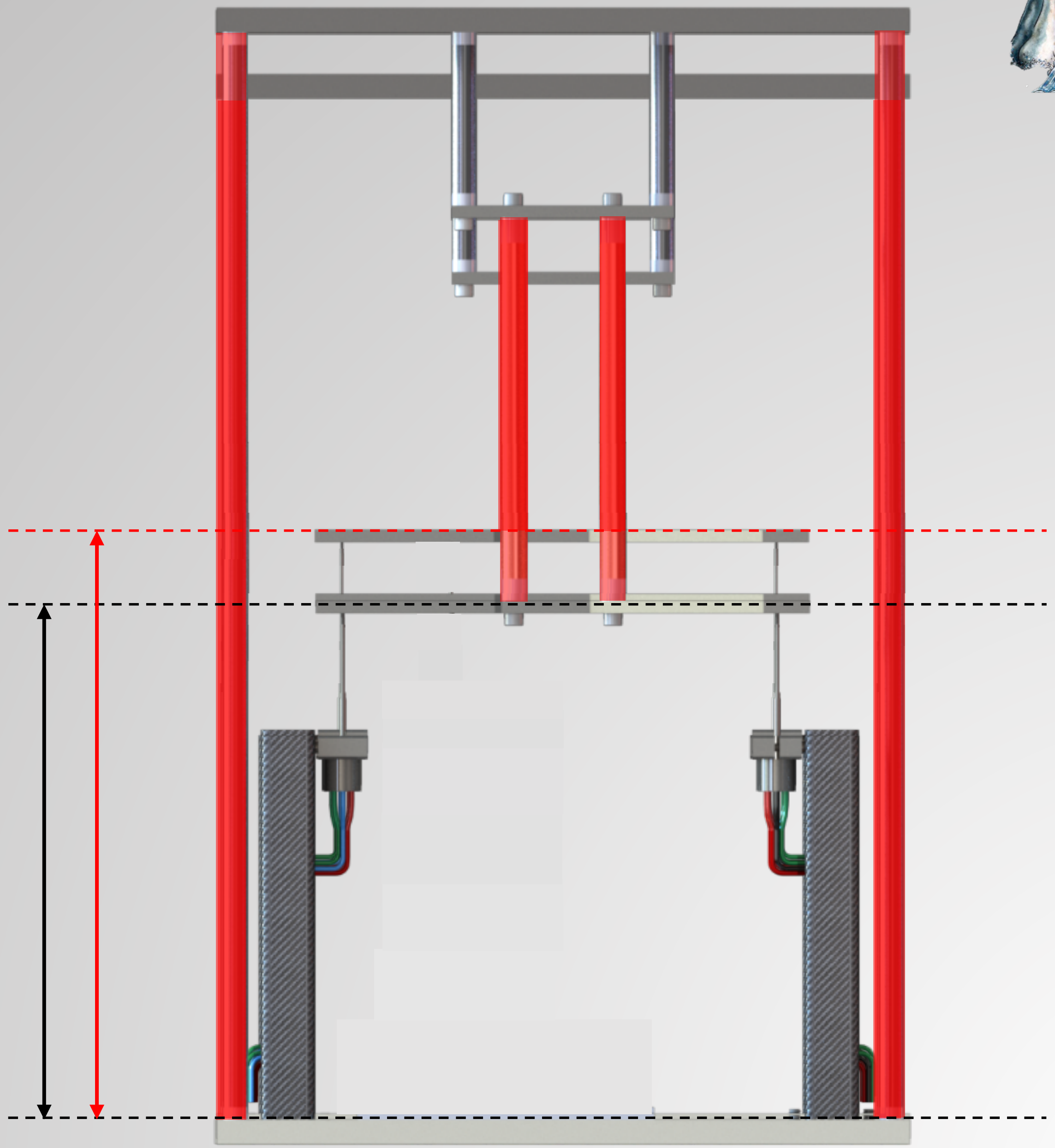
- Validate control system design under simulated on-orbit thermal loading

Objectives:

- Induce customer-provided temperature profile in Test Bed
- Actively correct induced alignment error through duration of profile

CONOPS:

1. Test bed heaters apply ΔT to induce specified temperature profile
2. ACS heaters apply ΔT in order to actively correct for displacement error



Testing Results

Thermistor Calibration

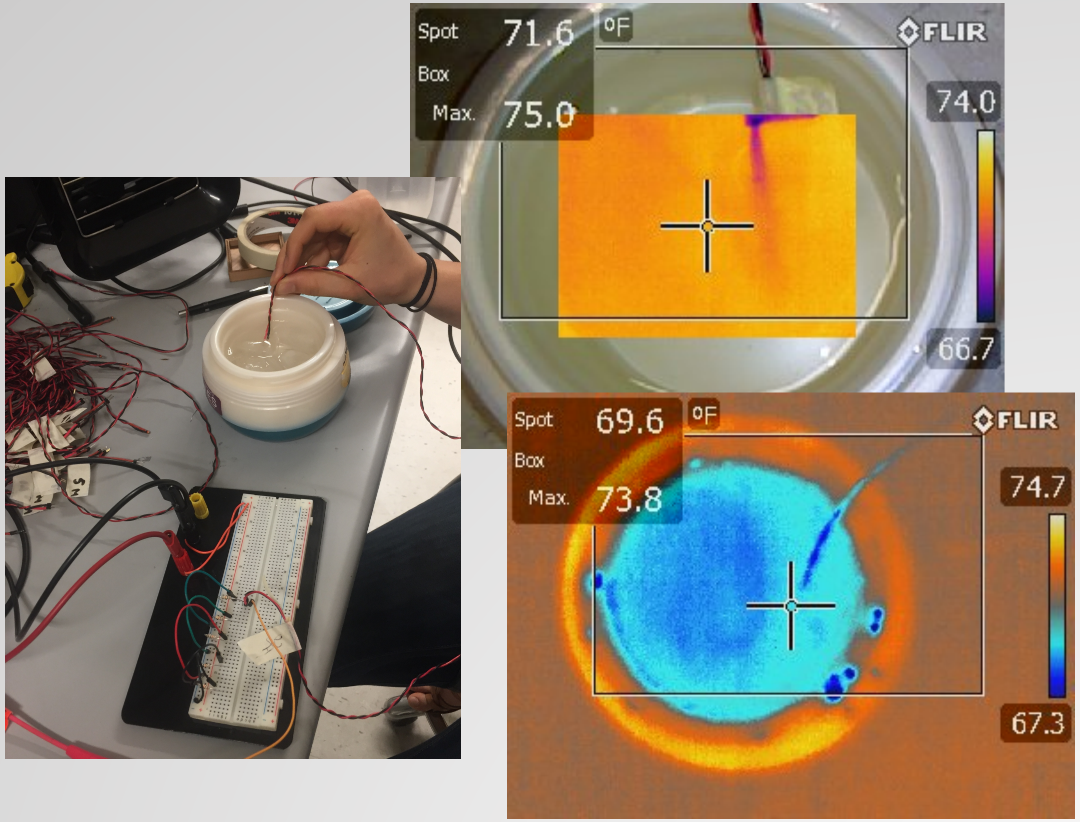
- Thermistors calibrated in room-temperature water using the thermal imager
- Reference resistance adjusted in software until measured output matched camera readout
- Error sources:
  - +/- 0.1K from spec'd camera accuracy
  - +/- 0.08K measured noise
  - +/- 0.08K from thermistor resistivity uncertainty

Required Measurement Accuracy: +/- 0.2K

Final Measured Results: +/- 0.15K

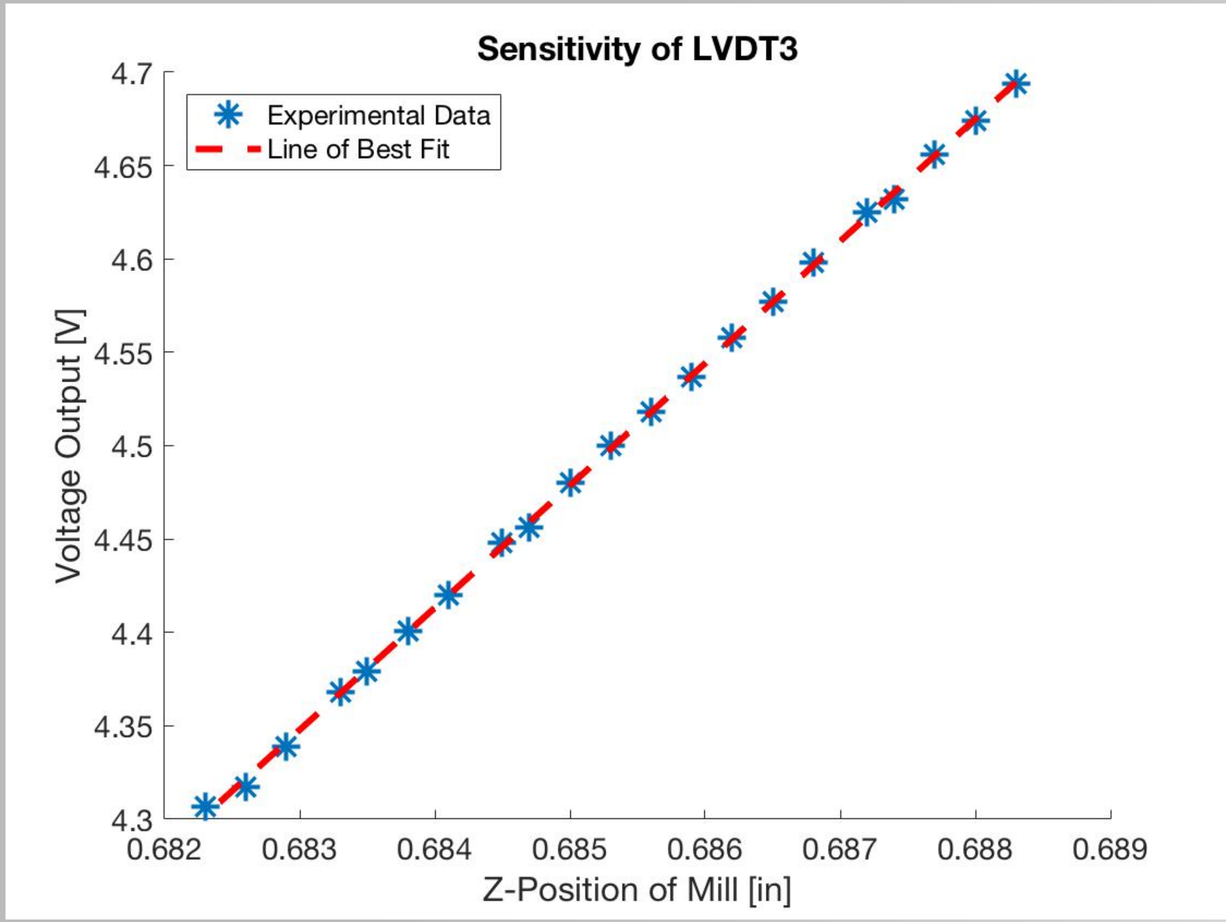
REQUIREMENT VERIFIED

Thermistor calibration test II



Note: Calibrated in Celsius, Fahrenheit pictures only for reference

LVDT Calibration



- Slope of experimental data was 4.3619 V/in
- Manufacturer's claim was a slope of 4.3058 V/in
- Formed a hypothesis test taking the manufacturer's sensitivity as the null
- Set a significance level of 0.05. Found there was not sufficient evidence to reject the null hypothesis

Manufacturer’s maximum uncertainty: ± .576 µm

Measurement Requirement: ± 2µm

SUPPORTS REQUIREMENT

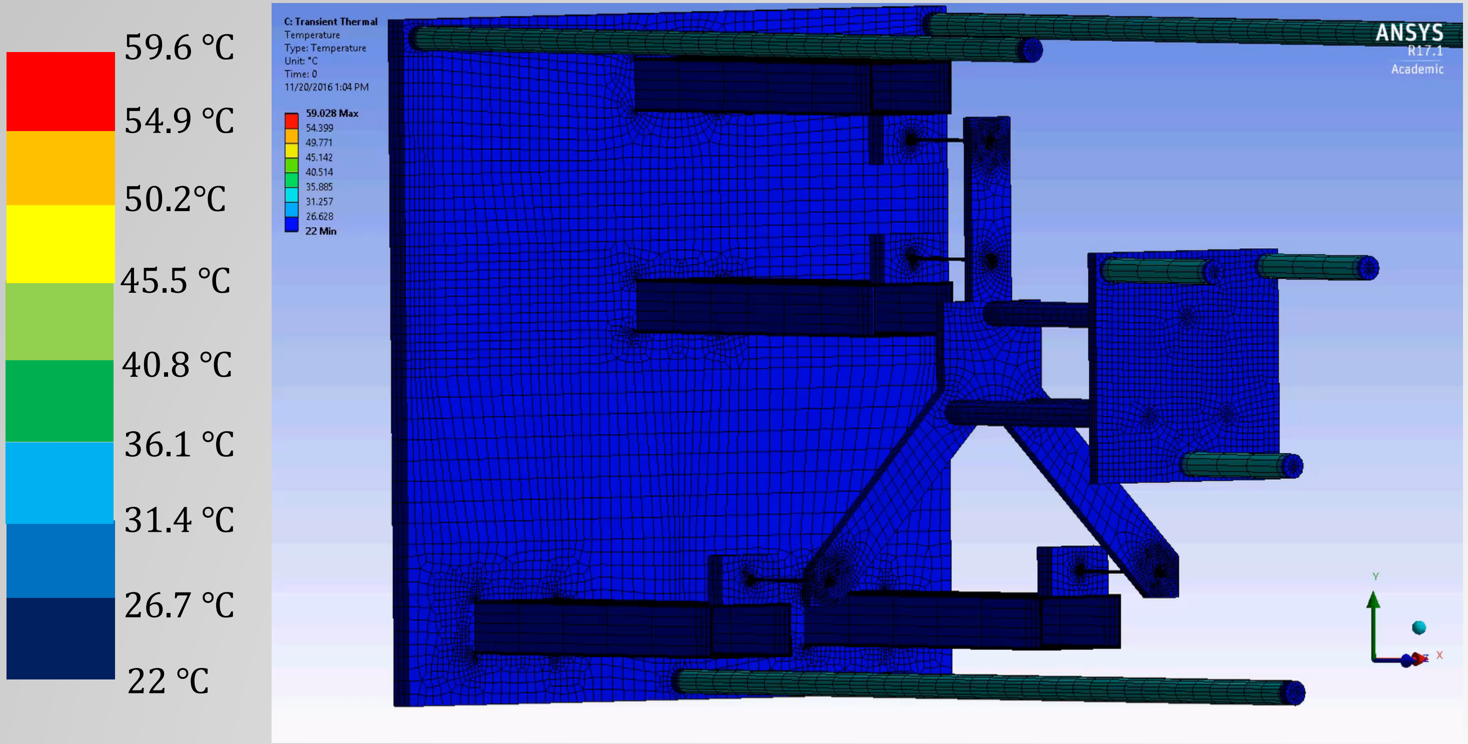
Thermal Modeling

Purpose:

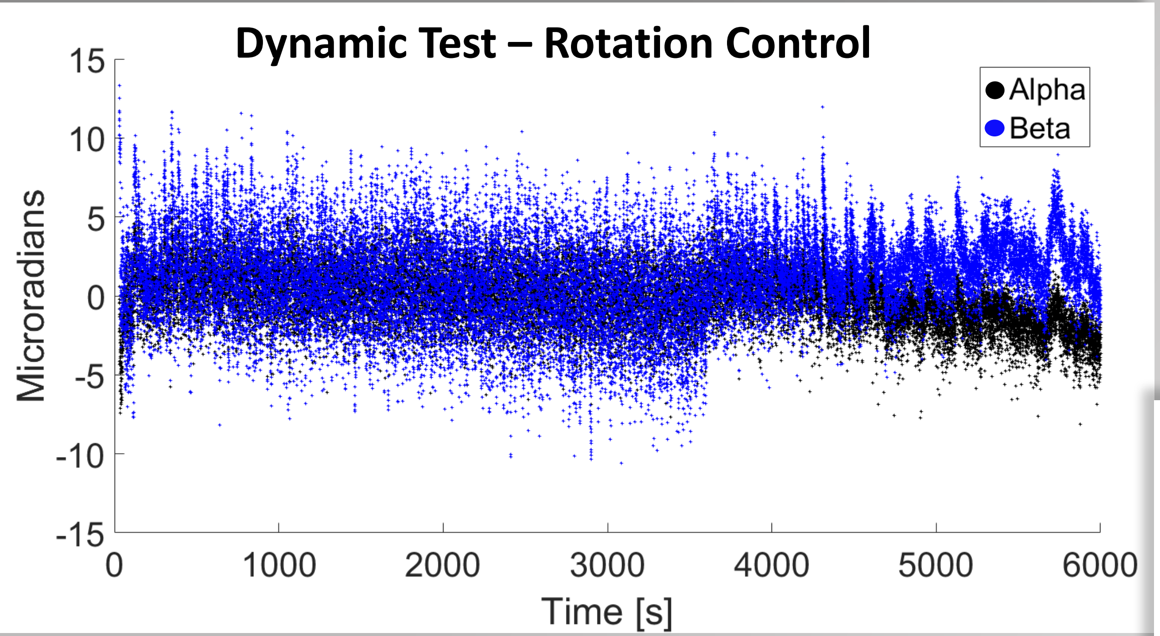
- Quantify measurement error introduced by heat conduction into AMS

Results:

- Error from LVDT heat was a non-issue
  - Power supply to LVDT's produced heat
  - No heat transfer to LVDT's
- Carbon fiber ΔT predicted to within ~ 0.1°C



Dynamic Test: Plane Alignment



Measurement error sources:

- Static noise level captured in data: ± .865 µm
- Worst case LVDT sensitivity uncertainty: ± .576 µm

Total measurement error (quadrature): ± 1.04µm

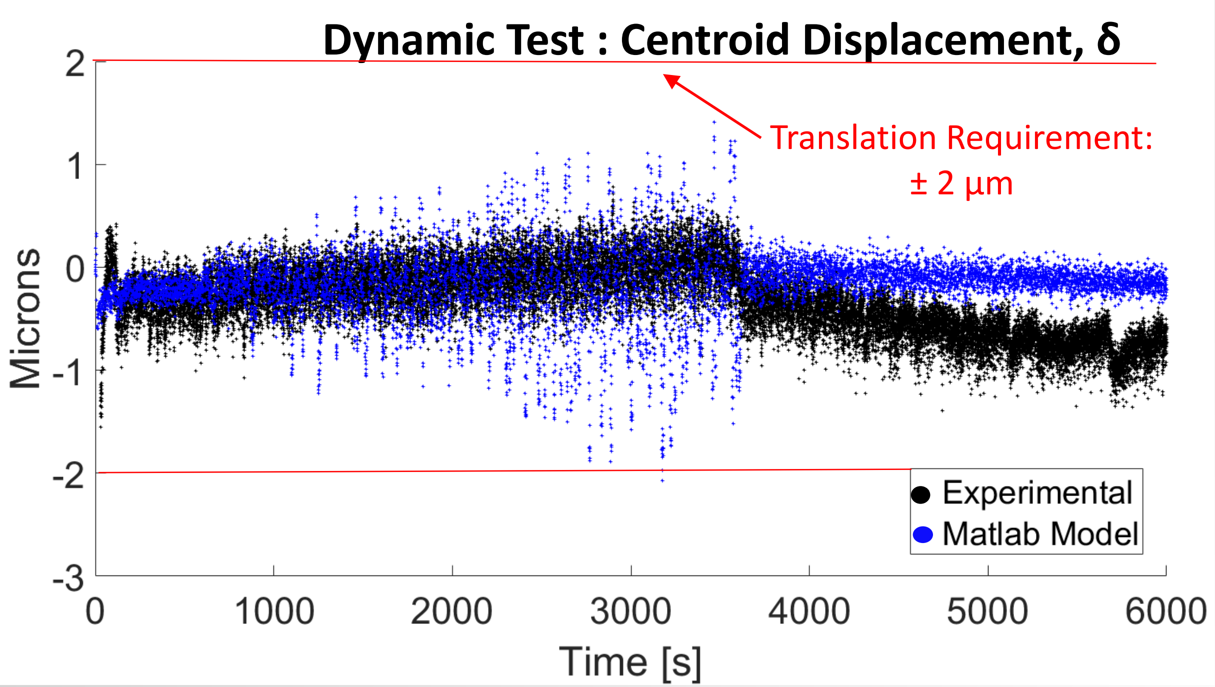
δ displacement control:

Requirement: Within ±2µm for 95% of profile
Test Results: Within ±2µm for 99.59% of profile

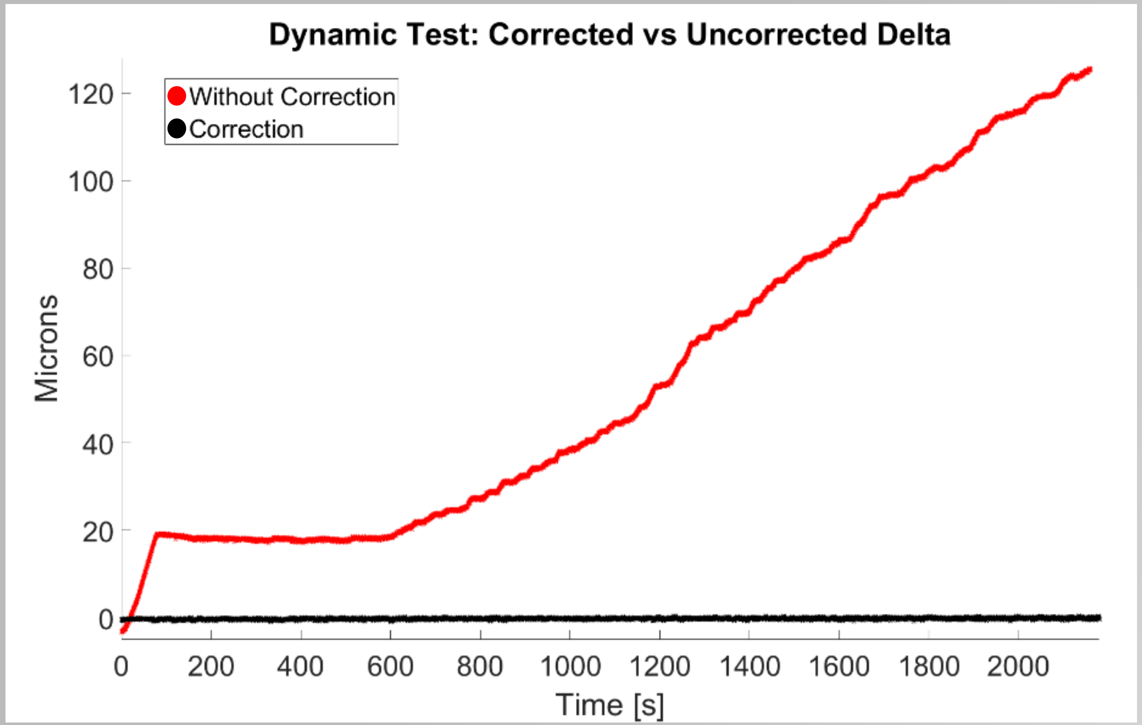
α and β rotation control:

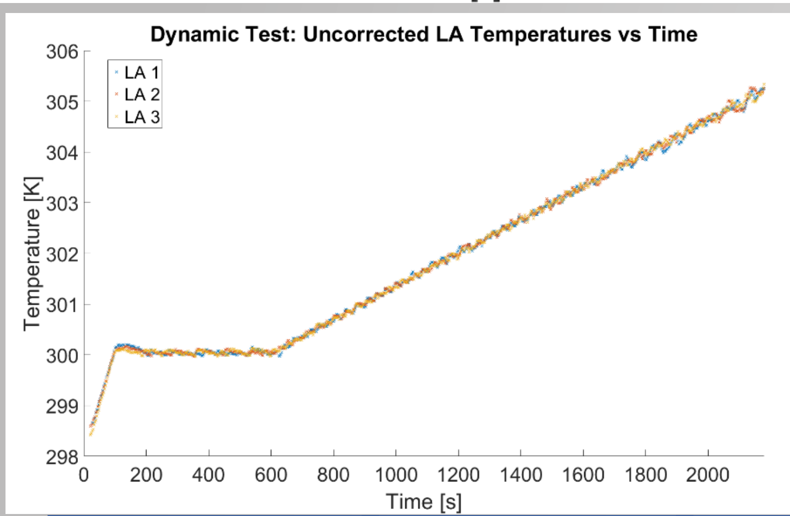
Requirement: Within ±20µrad for 95% of profile
Test Results: Within ±20µrad for 100% of profile

REQUIREMENTS VERIFIED



Dynamic Test With No Control





- Dynamic Test run with no control
  - Verify error introduction and displacement correction requirements
  - Verify correction actually occurring
- Test stopped after centroid had exceeded 100 µm to ensure high voltage not fed into myRIO without correction

Required Test Bed capability: >100 µm error in ΔT ≤ 10K
Required ACS capability: >100 µm corrective capability

Measured: 128.5 µm in ΔT = 6.64K, correction induced

REQUIREMENTS VERIFIED

Thermal Model Results

- Successfully able to induce temperature profile in test bed actuators
- Significantly reduced voltage input to decrease overshoot
  - 115V heaters → 20V, 28V heaters → 15V
- Results:

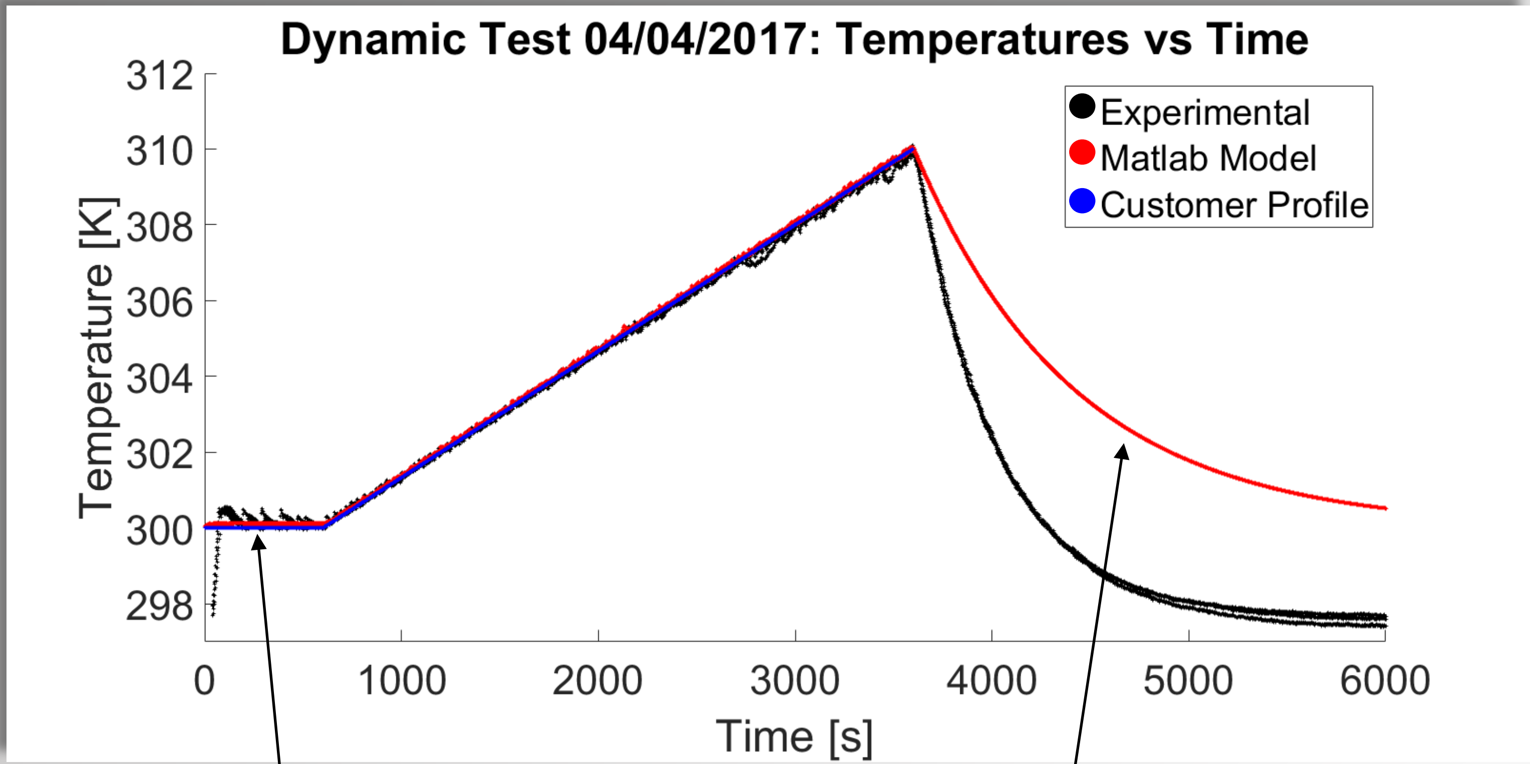
Experimental RMS error: ± 0.14K
MATLAB model RMS error: ± 0.20K

CONTROL MODEL VALIDATED

Required temperature control: ± 0.25K

Final measured control : ± 0.14K

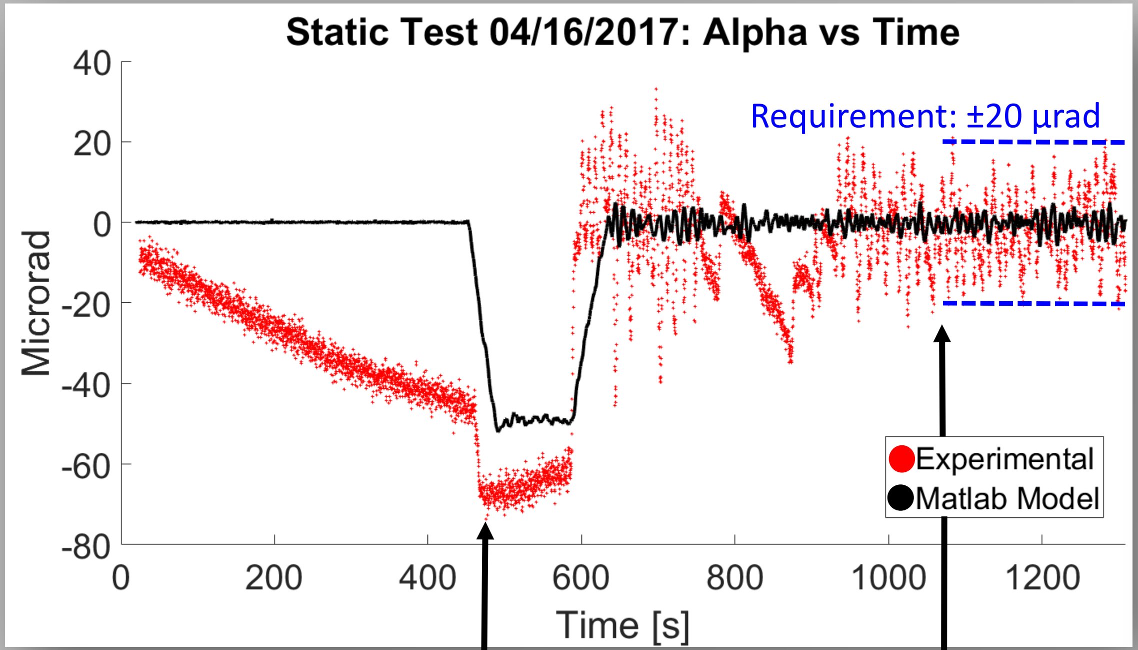
REQUIREMENT VERIFIED

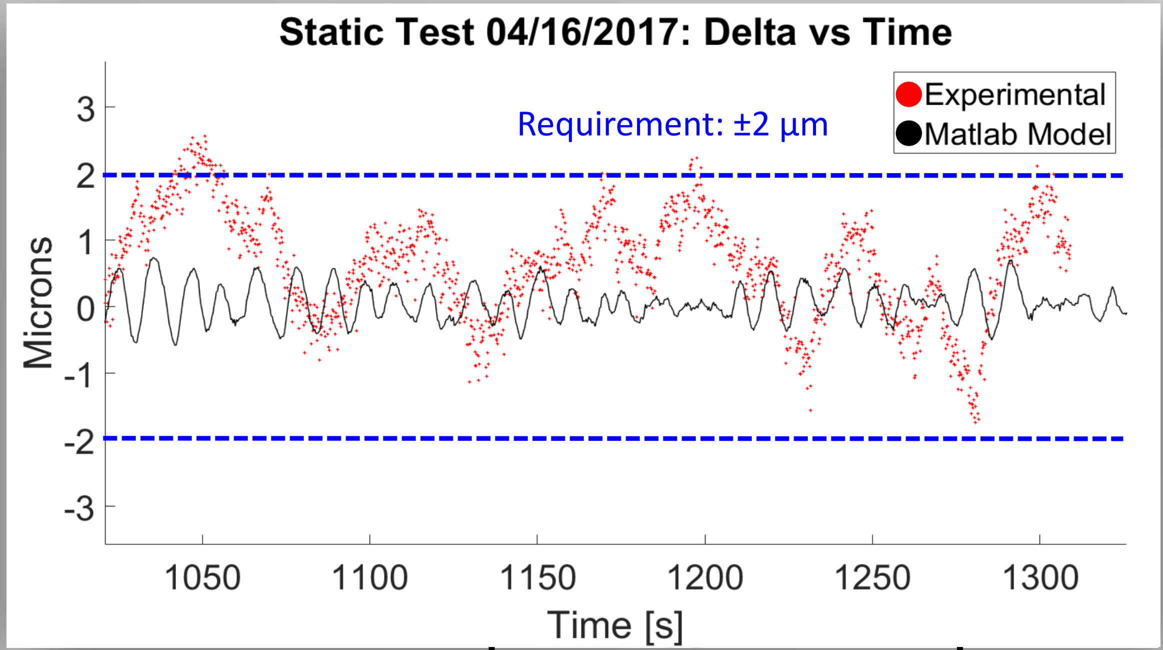


Heater voltage adjusted decrease overshoot

Modeled using worst case convection coefficient

Static Test Results





Correction begins | 600s settling time | Settled

Correction begins | 600s settling time | Settled

α and β rotation control:

Requirement: Restore initial position, ±20 μrad, within 600s

Test Results: α within ±20μrad for 99.35% after 600s

β within ±20μrad for 96.02% after 600s

δ displacement control:

Requirement: Restore initial position, ±2 μm, within 600s

Test Results: δ within ±2μm for 99.43% of time after 600s settling time

Measurement error sources: (Same as dynamic test)

- Total measurement error (quadrature): ± 1.04μm

REQUIREMENT VERIFIED WITH WAIVER

System Requirements

FR1. ACS
- DR1.1 material actuation
- DR1.2 thermal regulation
- DR1.3 Actuation distance and accuracy
- DR1.4 Mounting
- DR1.5 Static Test
- DR1.6 Dynamic Test
- DR1.7 Safety

FR2. Test Bed
- DR2.1 Integrate AMS
- DR2.2 Thermal control
- DR2.3 Temp measurement
- DR2.4 Material
- DR2.5 Displacement Introduction
- DR2.6 Rotation Introduction
- DR2.7 Safety

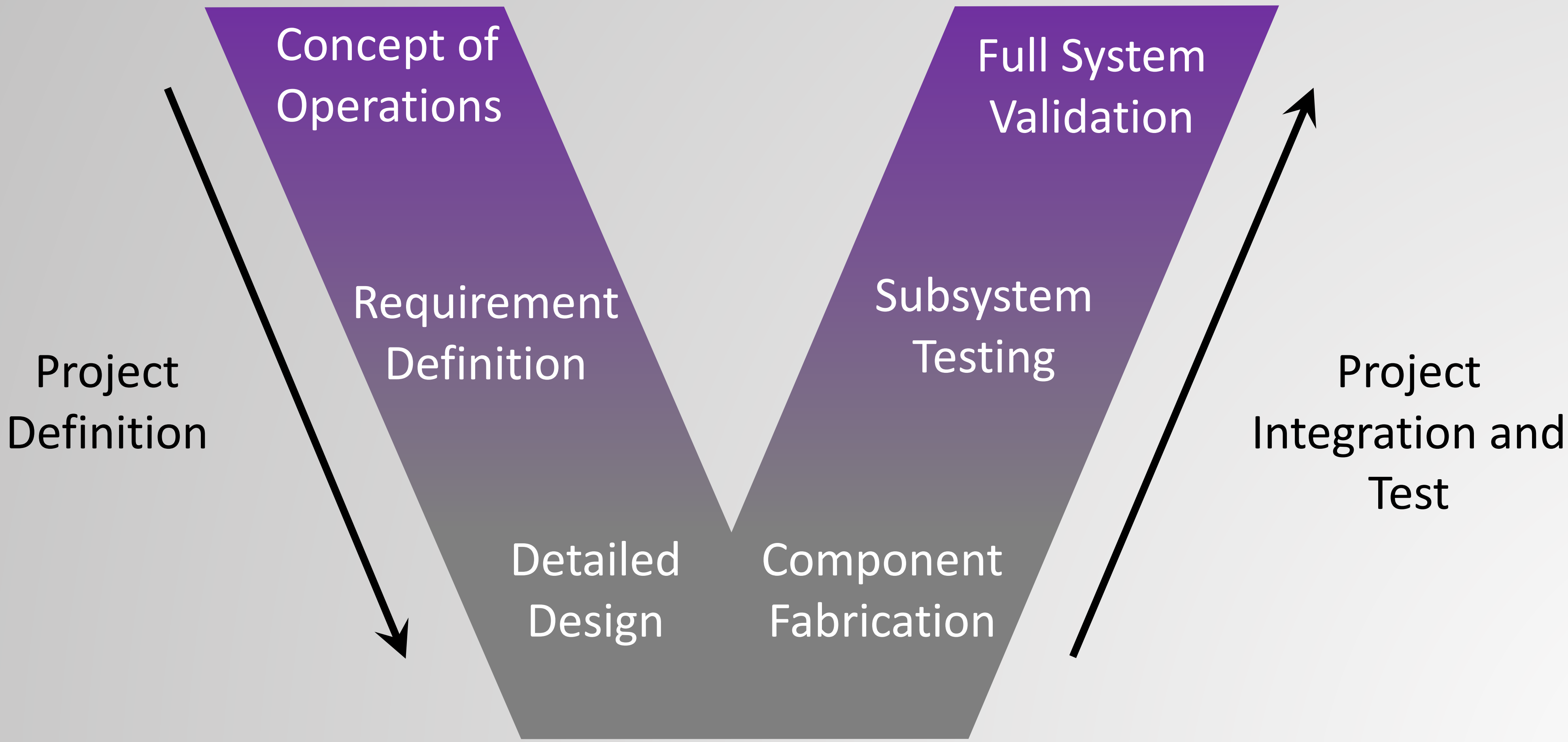
FR3. AMS
- DR3.1 Translation Measurement
- DR3.2 Rotation Measurement

FR4. Electronics
- DR4.1 Active test bed temp control
- DR1.2 Active ACS temp control

Requirement Met (green)
Met with waiver (yellow; DR1.5 Static Test)

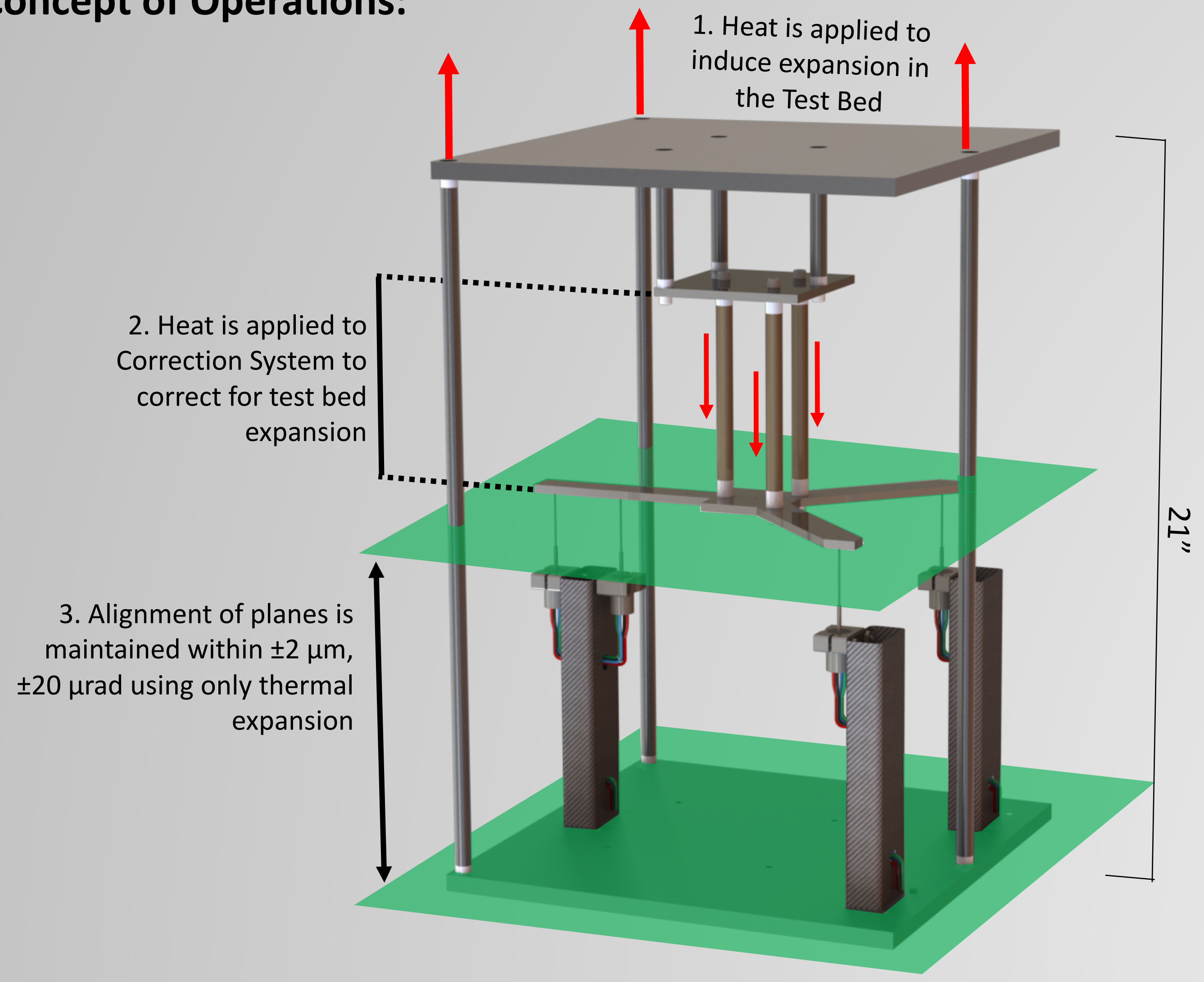
Systems Engineering

Systems Engineering Approach

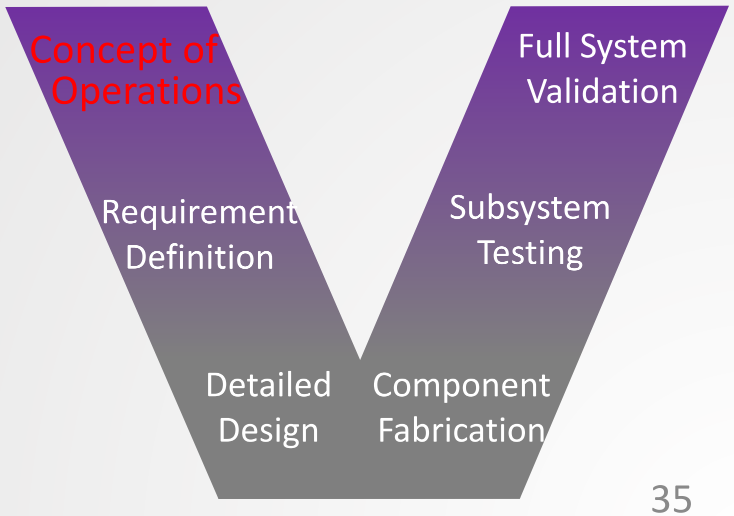


Systems Engineering Approach

Concept of Operations:



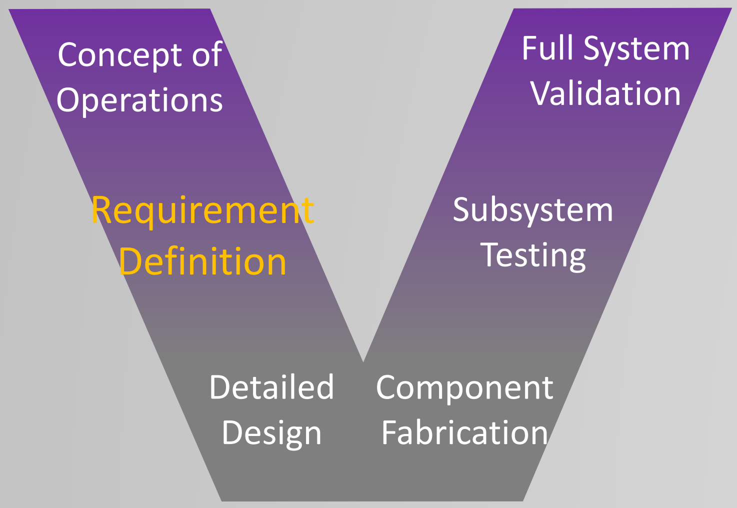
Well defined scope resulted in no changes to CONOPS throughout project



Systems Engineering Approach

Good, early communication with customer lead to no changes in functional requirements during project.

Derived requirements defined early, all changes **driven by modeling or testing data** and negotiated with customer.



FR1. The **Alignment Correction System** (ACS) shall provide sufficient **corrective capabilities** to adjust a flat mirror or representative surface in **one axis of translation and two axes of rotation**, in response to thermally induced alignment errors.

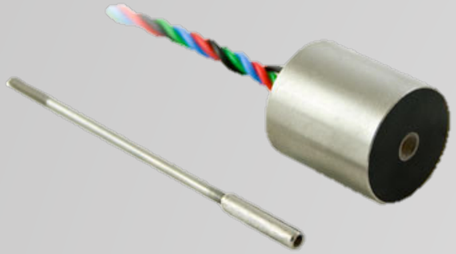
FR2. The **Test Bed** shall introduce **controllable alignment error** to a flat mirror or representative surface, in order to **simulate the thermally induced misalignment** experienced by space-based systems.

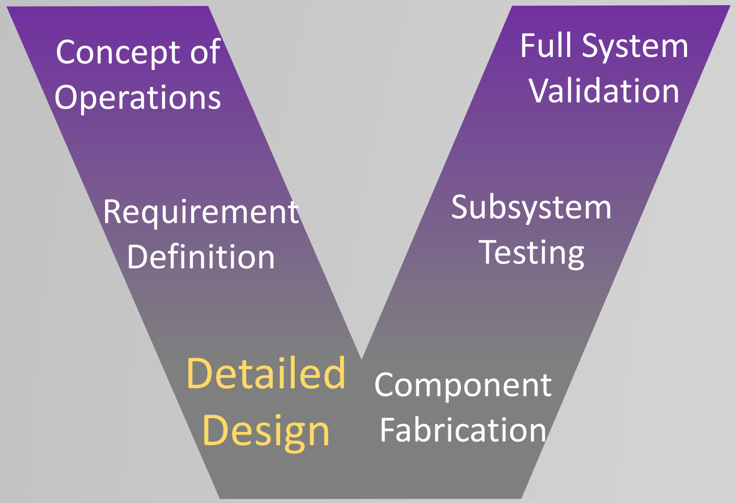
FR3. The **Alignment Measurement System** (AMS) shall **measure thermally induced alignment error** of a flat mirror or representative surface, in order to **provide feedback to the ACS**.

FR4. The **Electronics Package** shall provide **active control** of both the ACS and Test Bed, using **direct measurements of alignment error** and temperature,.

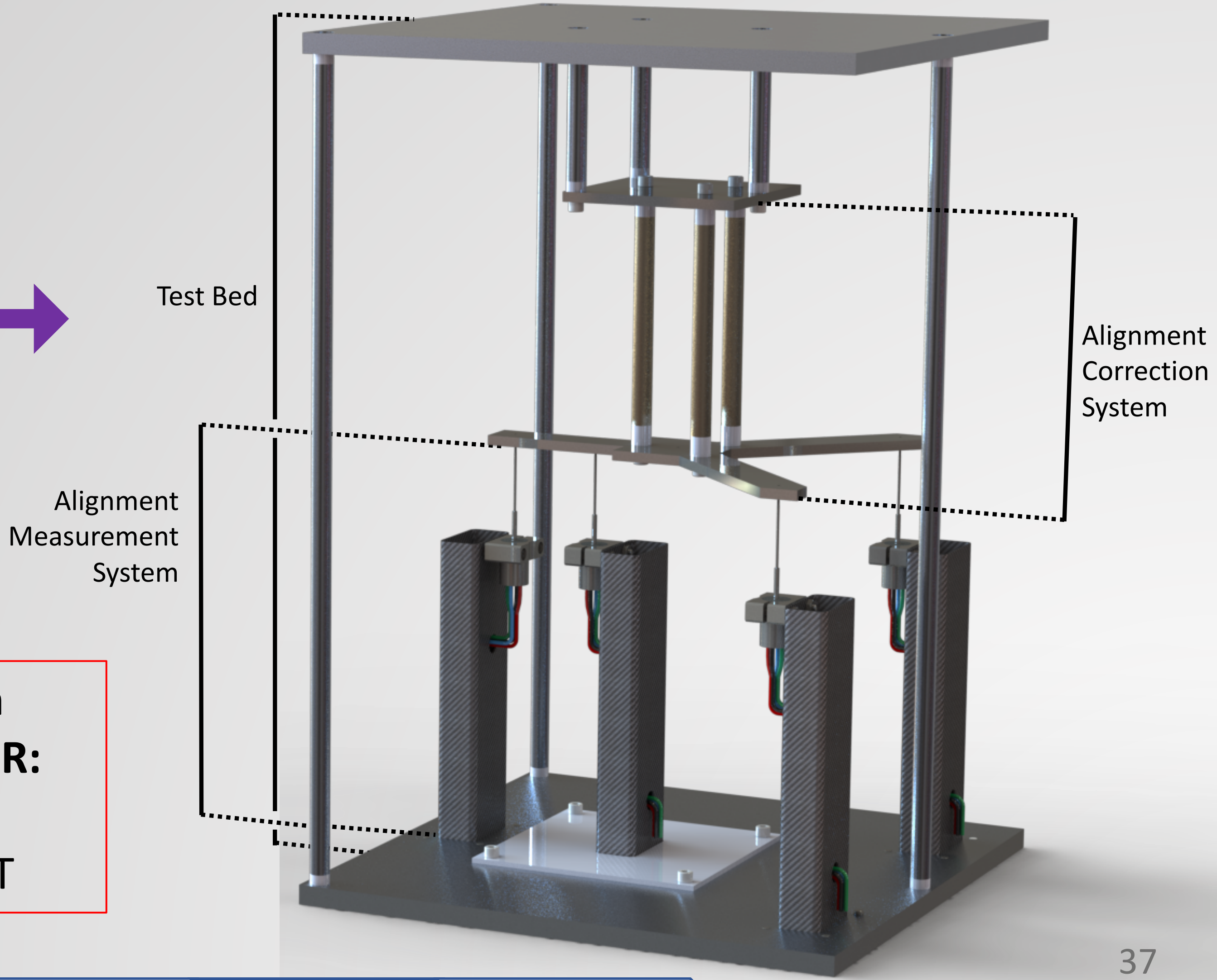
Systems Engineering Approach

Critical trade of the Alignment Measurement System drove overall test unit design





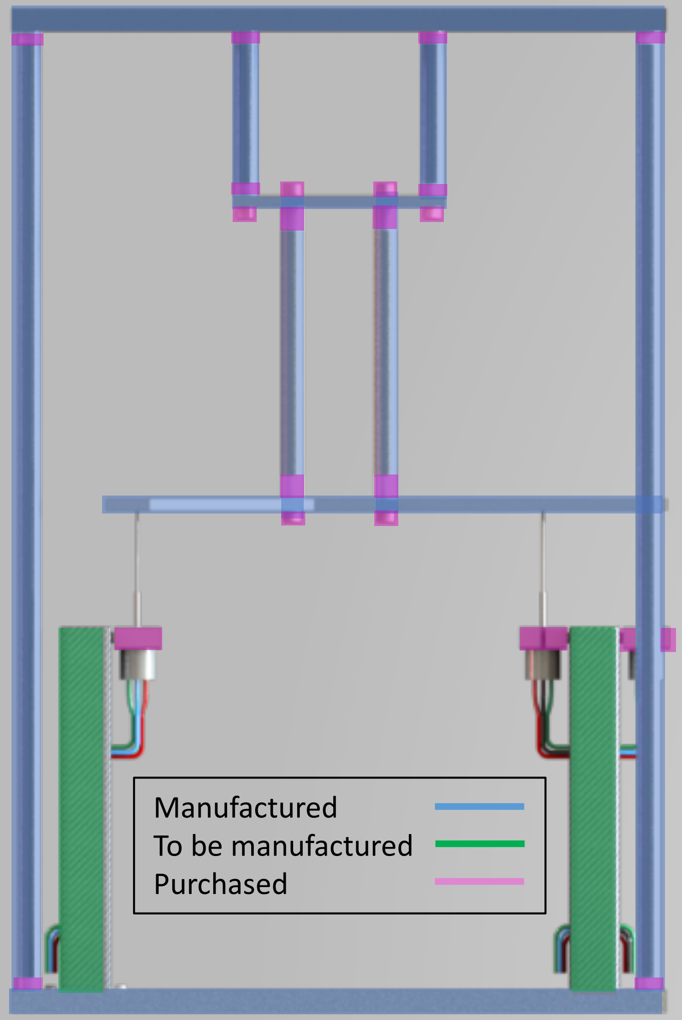
CDR Design:



Minimal design changes since CDR:
Relocation of verification LVDT

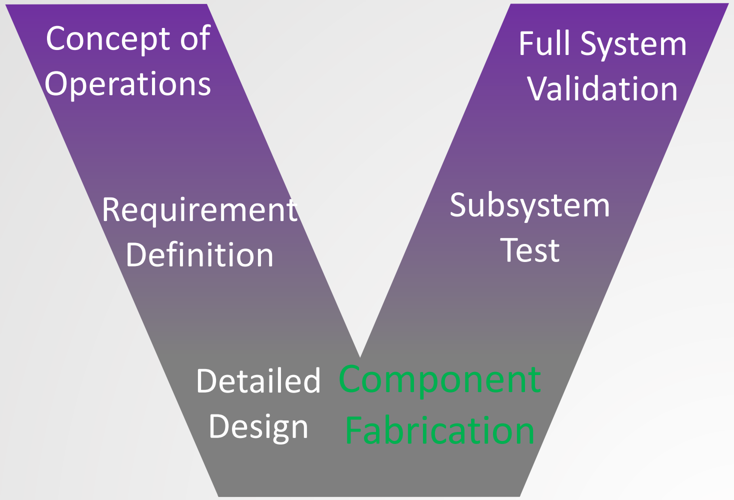
Systems Engineering Approach

MSR Status:



Simple geometry and design allowed for straight-forward manufacturing. (<2 weeks)

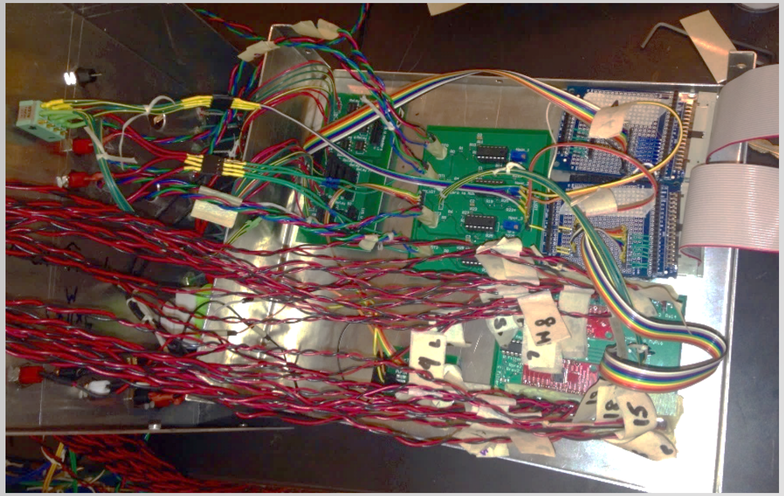
LabVIEW **software written modularly** in subVIs for ease of debugging and integration.



Systems Engineering Approach

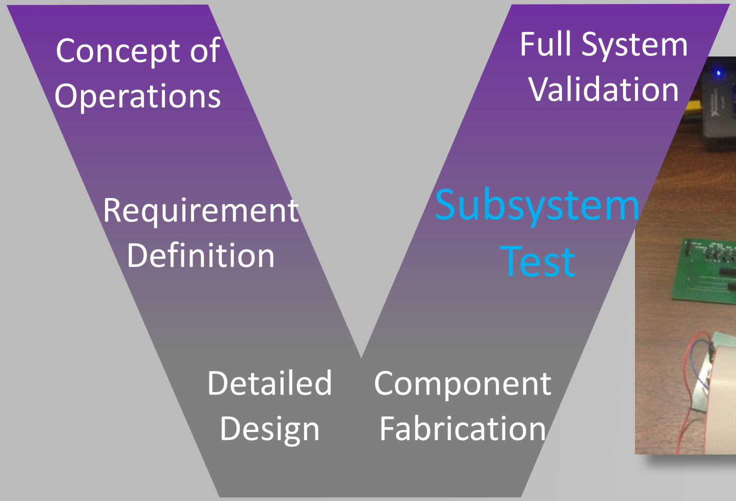
Electronics and software debugging extremely tedious.

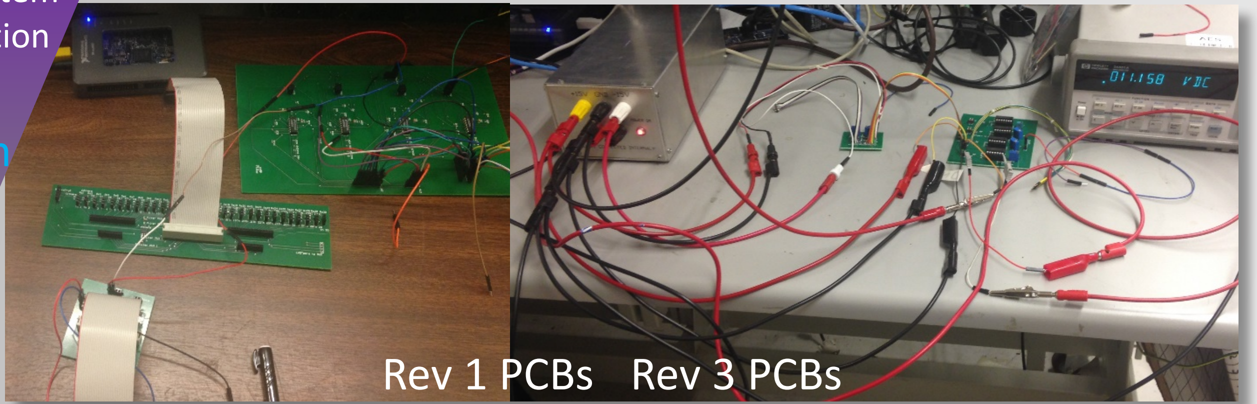
Identified issue: LVDT drift, LVDT sensitivity, inaccurate thermistor calibration, thermistor coupling from Butterworth filter and measurement rate, busted heater relays, circuit design



Electronics package sensor integration

LVDT mill sensitivity testing





Rev 1 PCBs Rev 3 PCBs

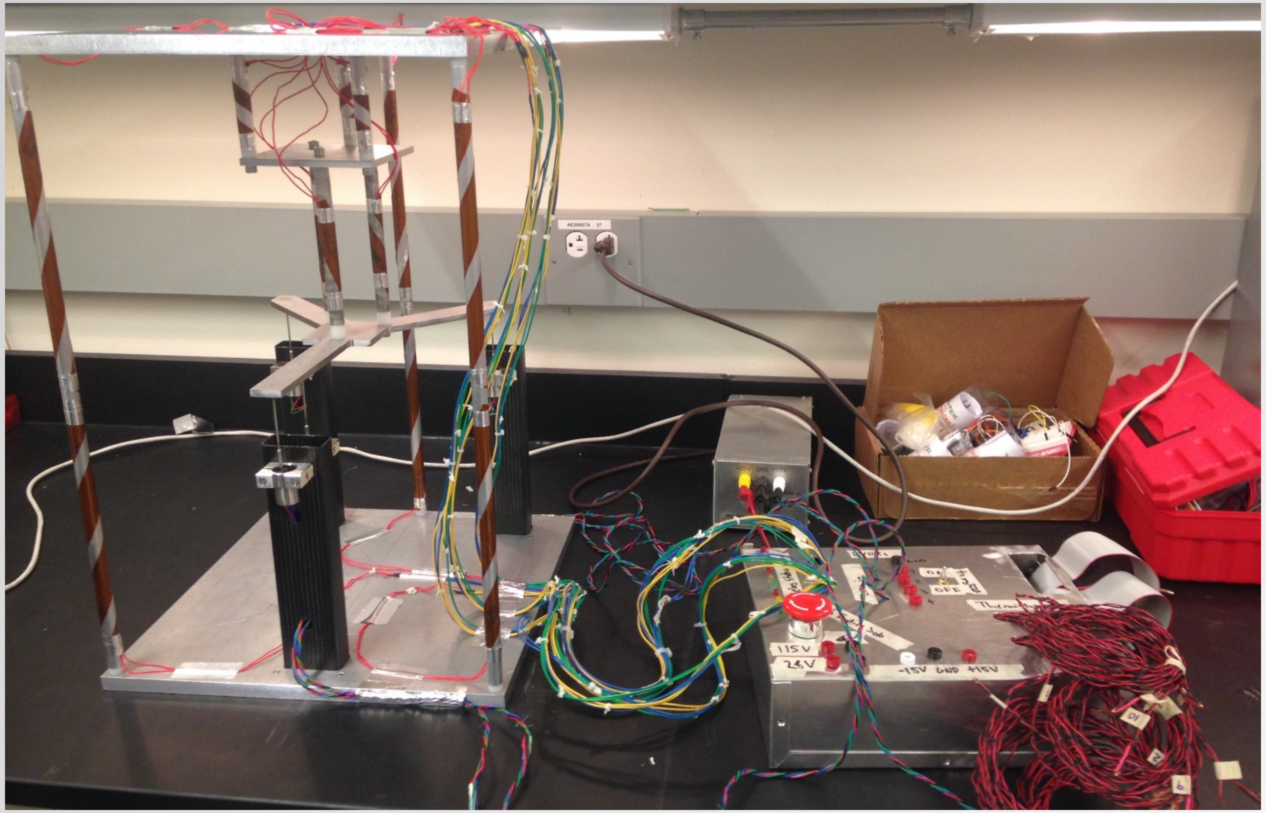
PCB debugging and testing

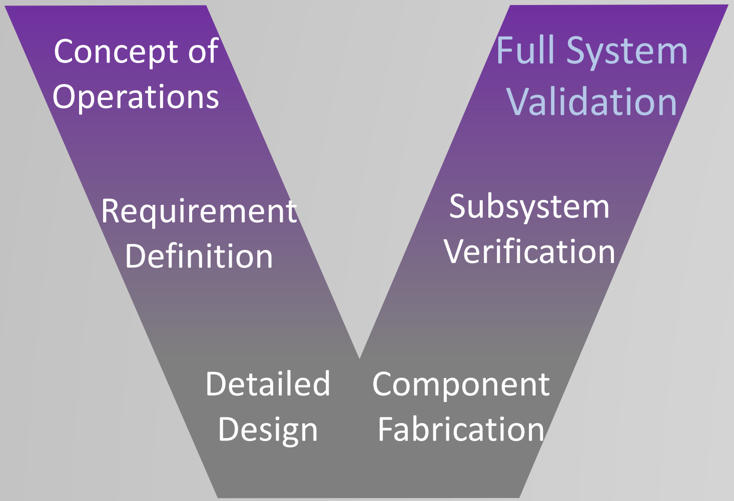
Purpose | Design | Testing Overview | Testing Results | System Engineering | Project Management

Systems Engineering Approach

Integrated Static Zeroing and Dynamic Tests used to validate design.

Identified issues: non-fastened actuators, static test software implementation errors, decreased power supply to heaters





Full **verification matrix constructed and delivered** to client for requirement sign-off

CDR Risks

Severity

Probability	1	2	3	4	5
5			8	6	2, 3
4				3 1, 5, 7, 10	
3		1		9	
2			2, 6 4	5, 7	
1		4	8, 10	9	

2, 3. Thermal environment expands LVDT cores
- Never accounted for heating of LVDT core caused from power supply
- Solution: Allowed to heat until equilibrium reached
  - DC bias

5. Inaccurate Thermal Model Prediction
- Incorrectly modeled based on power supply

7. Inability to accurately control thermal expansion
- Solution: Significantly decrease power supply to heaters

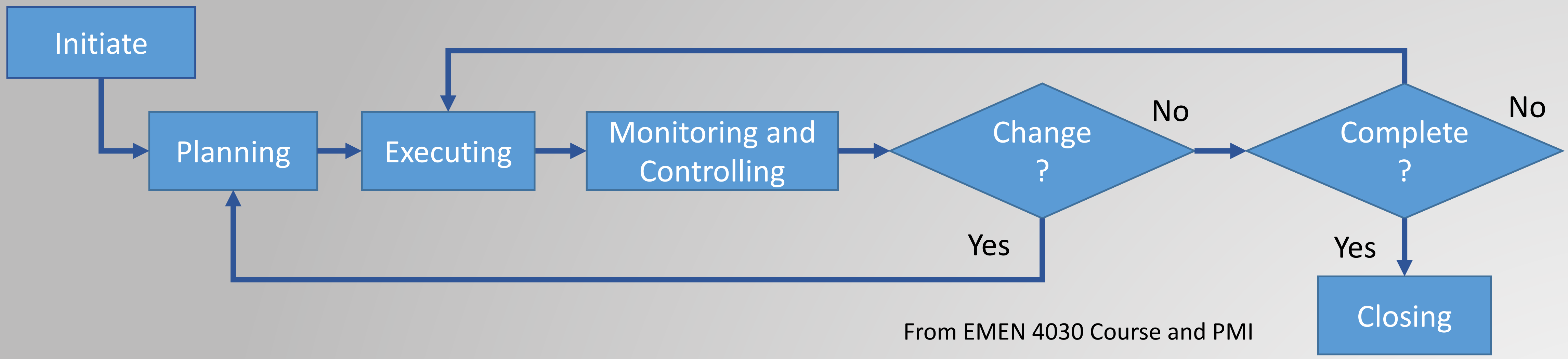
6. Failure to resolve 1µm of displacement due to LVDT SNR
- SNR not the issue, amplification circuitry largest risk
- Solution: extensive sensitivity analysis and gain tuning

Systems Lessons Learned

- Pays to be resourceful in looking for alternative ways to validate results
  - Thermal camera identified heating issue with LVDT cores, enabled better calibration of thermistors
- Software simulation testing is only good to a point
  - More bugs discovered with real data input than otherwise
    - Point-wise Butterworth filtering indexing induced cross-coupling of thermistor feeds
    - Only identified with full set-up
- Test early and often
  - Early testing of components can save significant re-work when issues are identified

Project Management

Project Management Process



From EMEN 4030 Course and PMI

- Plan, Do, Check, Decide (Act)
- The iterative nature makes communication crucial
- The iterative nature causes unforeseen schedule changes

Organizational Structure

- **SPECTROM** — Project
  - Ball Aerospace (Customer) — Dr. Joe Lopez
  - Advisor — Dr. Bob Marshall
  - Project Manager — Cameron Coupe
  - Systems Engineer — Sarah Levine
  - Financial Officer — Tyler Talty
    - Design and Test Lead — Jeffrey Ellenoff
    - Thermal and Safety Lead — Zach Fellows
    - Electrical Lead — Jaevyn Faulk
    - AMS Lead — Josh Mellin
    - Manufacturing Lead — Eli McKee
    - Integration and Software Lead — Josh White
    - Controls Lead — Josh Whipkey

Lessons Learned

Successes:

- Diversity of team strengths
  - Strengths in manufacturing, electronics and software
- Strong planning from fall semester
  - Clear project requirements
  - Minimized design changes
- Ample margin in schedule (3x planned hours worked!)
- Weekly updates and action items
  - Specific individual tasks
  - Clear deadlines

Lessons Learned:

- Clear project definition is key to early success
- Communication needs to be constant
- Schedule needs constant adjustments
- Test early and often
- Need to separate work from personal life

Budget

- Final budget compared to CDR

Category:	CDR:	Final:	Difference:
Testing for CDR	$395	$395	$0
Materials	$829	$1047	+$218
Electronics	$379	$784	+$405
Heaters	$725	$544	-$181
Sensors	$1644	$1319	-$325
Printing	$0	$109	+$109
Total:	**$3972**	**$4198**	**+$226**

$802 under budget

- Sensors were obtained at a discount
- Replacing electronics increased final cost
- Did not account for printing in initial budget

Industry Cost

Assumptions:

- Entry level salary of $65,000 for 2080 Hrs/Year ($31.25 per Hr)
- 200% overhead

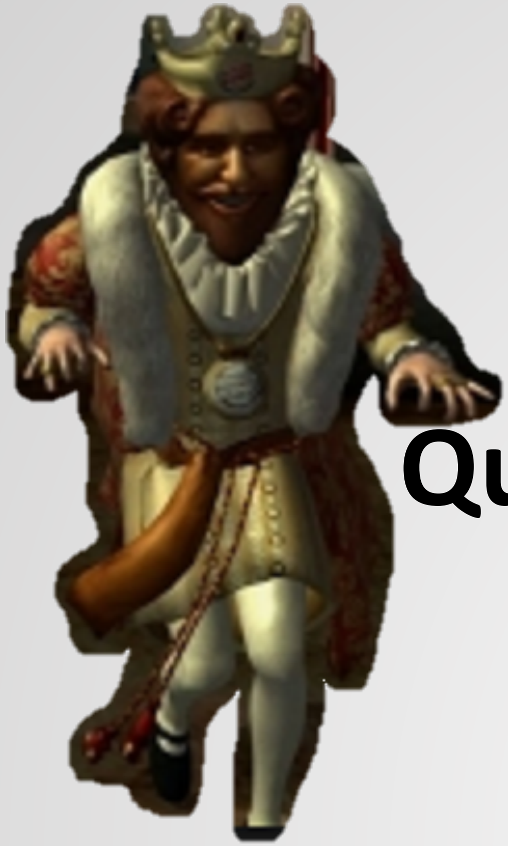
Average Team Hrs/Week	170 Hrs
Total Hours	4,594 Hrs
Equivalent Labor Cost	$143,563
Overhead Cost	$287,125
Materials Cost	$4,189
Total Industry Cost	**$434,885**

Conclusions

- Team successfully designed and demonstrated an active control system that uses thermal expansion as the control mechanism

- Difficult to interface with LVDTs, and to achieve required measurement resolution
  - Recommend future applications use an alternative measurement system
  - Non-contact measurement such as interferometer, good but more expensive

- Application of thermal expansion-driven control system for micron-precision correction is a feasible design solution



Questions?

References

[1]Composites Today: https://www.compositestoday.com/2013/02/advanced-composites-on-the-ldcm-satellite-mission/

[2]NASA: https://www.giss.nasa.gov/research/briefs/hansen_10/

[3]MATLAB, Matrix Laboratory, Software Package, Ver. 9.0, Mathworks, 2016.

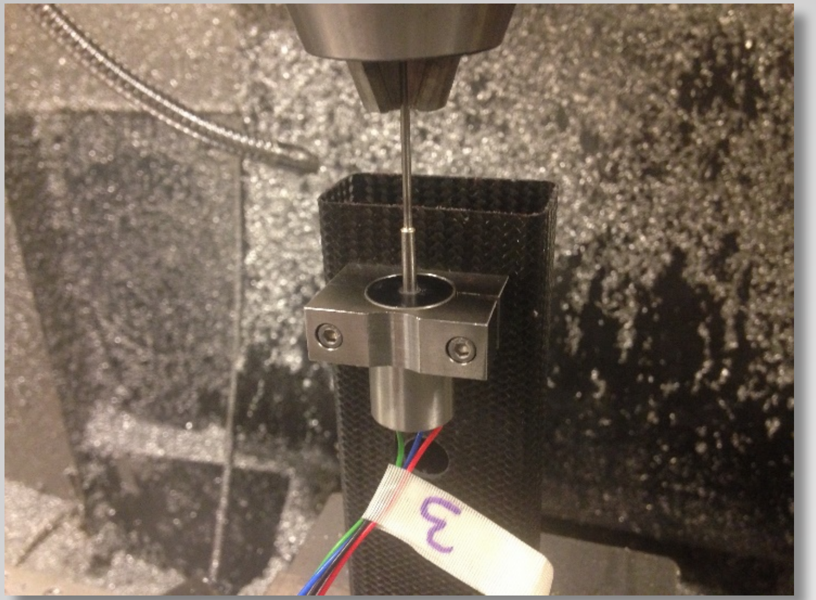
[4]LabVIEW, Laboratory Virtual Instrument Engineering Workbench, Software Package, Ver.15.0f2, National Instruments, Austin, TX, 2016.

Backups

Electrical Tests

Test	Procedure	Results	Requirements Trace-back	Lessons Learned
Thermistor Calibration	• Look at thermistor temp with thermal camera • Vary R_{sense} in software until readings match camera	• Thermistor temp readings achieved within ± 0.2 Kelvin	• ± 0.2 Kelvin temperature measurement accuracy	• Getting higher quality thermistors will save a lot of work on calibration in the end
LVDT Sensitivity	• Secure LVDT in mill • Lower core known distance • Compare output voltage to expected voltage	• Verified manufacturer stated sensitivity with a 99.5% confidence interval	• Displacement/Rotation measurement accuracy (± 1.75 μm, ± 15.3 μrad) • Displacement/Rotation control (± 2 μm, ± 20 μrad)	• LVDTs have an inherent warm up time which causes voltage drift over its duration
Heater Functionality	• Connect heater PCB to myRIO and heaters to PCB • Use the NI IO Monitor to manually switch the digital lines from the myRIO • Confirm heaters turn on	• Confirmed heaters can be controlled using myRIO	• ± 0.3 K temperature control	• Accurate temperature control can be achieved better using voltages below the manufacturer stated operating voltages

LVDT Sensitivity



Purpose:

- Verify linearity of LVDT signal in full range and working range
- Verify manufacturer stated sensitivity

Motivation:

- Original testing showed LVDT sensitivity varying test to test

Preliminary Results:

- Mill has uncertainty with 0.0001” increment adjustment
- Full LVDT Range shows constant, linear sensitivity

Remaining Work:

Establish confidence in working range sensitivity

Equipment	Test Procedure	Facilities
• LVDT (x4) • LVDT PCB Rev 3 • Mill • Voltmeter • Power Supply	1. Secure LVDT in mill 2. Lower core known distance 3. Compare output voltage to expected voltage	ASEN Machine Shop

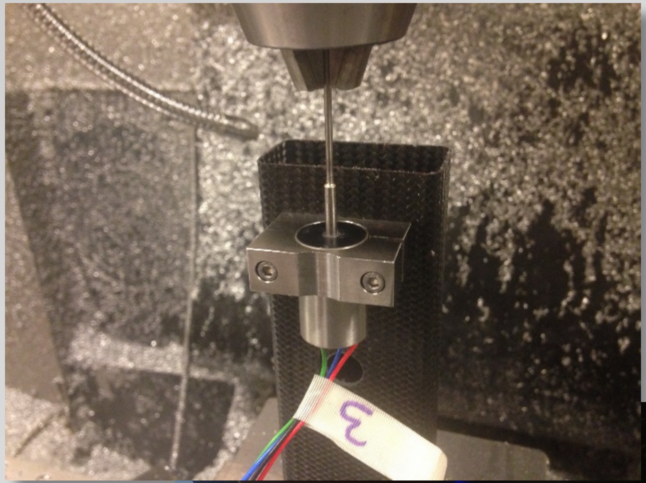
Risk Mitigation:

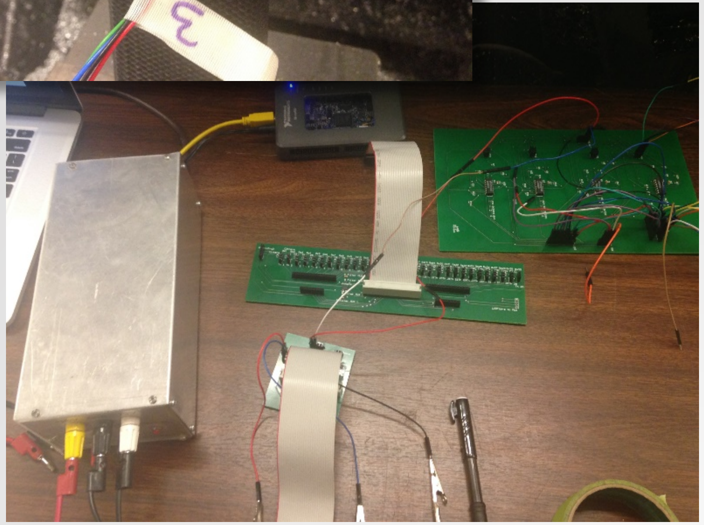
Inaccurate displacement measurements

Requirement Trace Back:

- Displacement/Rotation measurement accuracy (±1.75 μm, ±15.3 μrad)
- Control Precision (±2 μm, ±20μrad)

LVDT-PCB Interface Testing





Purpose:

- Verify measurement accuracy of LVDTs over working range of 300μm
- Validate circuit design:
  LVDT output gains expand 25,00 μm/ 12.8V working range to 300 μm / 5V range
- Establish confidence in manufacturer spec'd sensitivity

Risk Mitigation:

- Inaccurate LVDT measurement
- Signal Noise

Requirement Trace back:

- Displacement/Rotation measurement accuracy (±2 μm, ±20 μrad)

Equipment	Test Procedure	Facilities
• LVDT (x4) • Mill • Power Supply • myRIO • LabVIEW • Voltmeter • LVDT PCB	1. Mount LVDT housing to support, secure in mill vice 2. Secure core in mill chuck 3. Align LVDT core and housing 4. Record mill +Z displacement at 0V 5. Lower LVDT core by 0.001" increments, recording voltage output pre and post conditioning	ASEN Machine Shop

Thermistor PCB-Interface Testing

Purpose:

- Verify myRIO/MUX compatibility and Rev1 PCB design

Results:

- Updated signal filtering
- Discovered important software bugs to fix
- Verified PCB

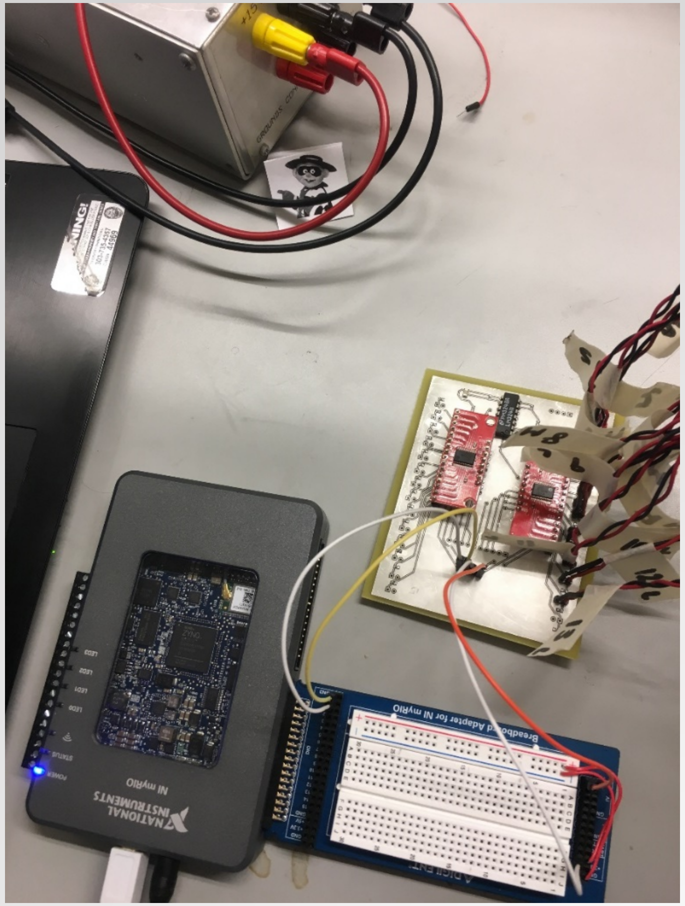
Risk Mitigation:

- Signal noise
- Loss of heater control

Requirement Trace Back:

- Temperature Knowledge
- Control Precision

Equipment	Test Procedure
• Thermistors • Therm PCB Rev1 • Voltmeter • myRIO • LabVIEW	1. Manually select each channel using myRIO I/O manager 2. Measure thermistor voltage drop before and after MUX 3. Confirm rapid voltage change before and after MUX upon applying heat to specific thermistor



Thermistor Calibration Test

Purpose: Determine Sense Resistance for thermistor accuracy calibration

Results:

- 28 thermistor values recorded
- All values within expected range

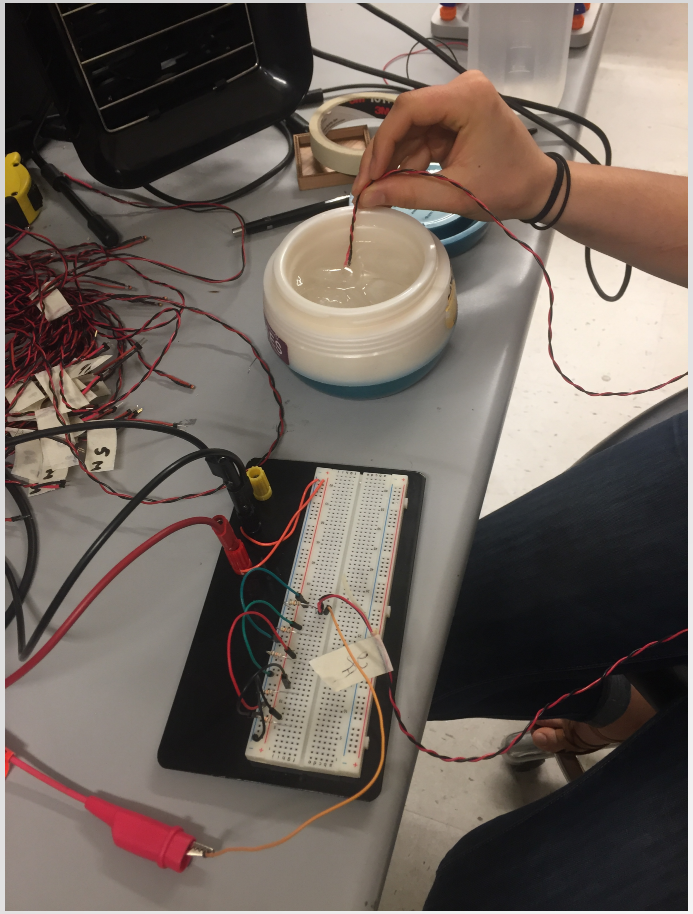
Equipment	Test Procedure	Facilities
• Thermistors (x28) • DI Water • Ohm meter	1. Place thermistor in ice bath 2. Record Resistance	• Bobby's Lab

Risk Mitigation:

Inaccurate temperature measurement

Requirement Trace Back:

- Temperature accuracy requirement



Heater myRIO-Interface Testing

Purpose:

Verify heater control using SS Relays

Results:

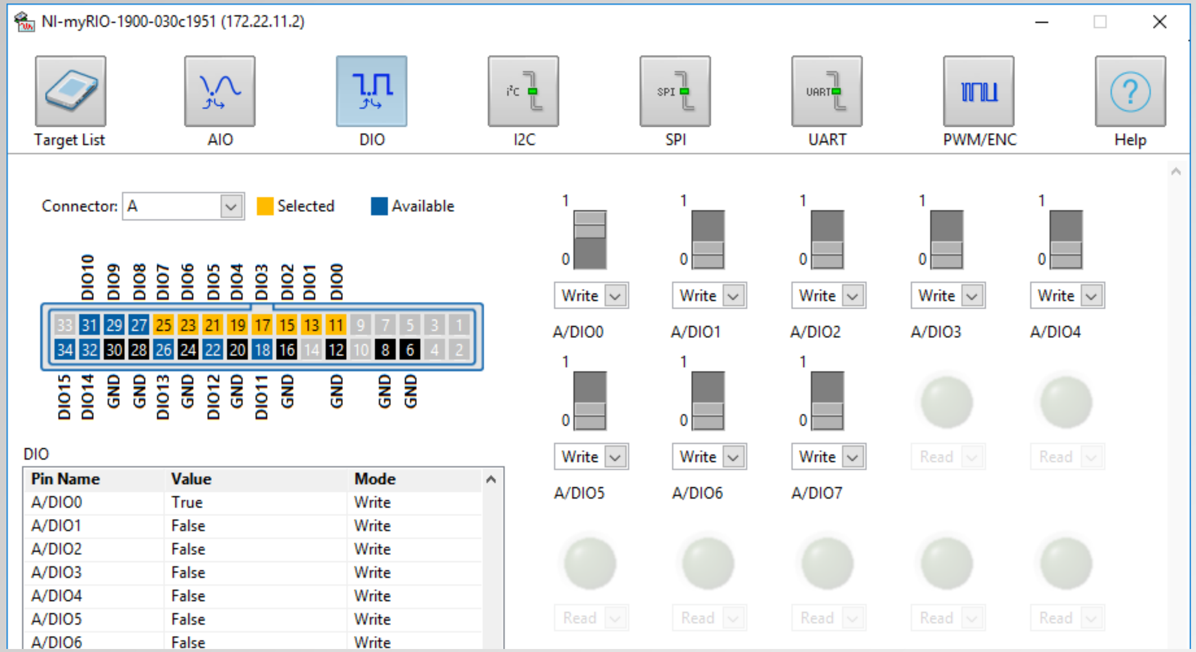
- Circuit design of PCB validated
- Control of 12 heaters achieved

Risk Mitigated:

Loss of heater control

Requirement Trace Back:

ACS control



Equipment	Test Procedure	Facilities
• Heaters (x12) • Heater PCB • myRIO • LabVIEW	• Used myRIO DIO to manually turn on heaters • Verified heater control	• Senior Design Room

Budget Backup

Al rods	43.98
Mg rods	38.44
Test Heater	55
Demo Board	155.49
16bit ADC	
Bread Board	54.75
LTC Chip	34.85
Breakout Boards	46.31
Printing FFR	3.99
Plates and Shims	527.67

PCB1	33
PCB 2	33
Surface Mount Resistors	46.61
Surface Mount Resistors2	31.1
PCB round 2	115.4
Shipping for last LVDT Mount	11.59
Female Headers	15
Reorder of Surface Mount	71.65
PCB 3	43
MUX	24.9
Therms	17.7

LVDTs and Mounts	1261.67
Relays	86.57
MUX/ therms	27.67
Carbon Fiber Rods	144.45
Heaters	544.36
Screws	155.32
Epoxy	63.45
Extender cable MyRio	24.74
Plugs and end mills	114.28
New Relays	224.44
End Mill and Nylon Screws	41.95

Requirements: FR1

FR1: The Alignment Correction System (ACS) shall provide corrective capabilities to adjust a flat mirror or representative surface in two axes of rotation and one axis of translation, in response to thermally induced alignment errors.

DR1.1 The ACS shall utilize thermal expansion of a material as the actuation mechanism.

Motivation: Customer requirement. Purpose of project is to prove feasibility of thermal material control.

Verification: Inspection- Material will be visually inspected, and thermal specifications recorded.

DR1.2 The ACS shall provide thermal regulation of the high CTE adjustment mechanisms.

Motivation: Temperature regulation is required to utilize the expansion properties of the high CTE adjustment materials as the control mechanism.

Verification: Inspection

DR1.3 The high CTE mechanism shall actuate a linear distance of up to $+100\ \mu m$, with an accuracy of $\pm 2\ \mu m$.

Motivation: In order to correct for the displacement error introduced to the mirror, the ACS must accommodate up to 100 microns of expansion, in order to provide sufficient translation and rotation corrective capabilities.

Verification: Analysis and Test

DR1.3.1 After settling, the ACS shall be able to maintain the average steady state temperature of the high CTE adjustment mechanisms, to within $\pm 0.3K$ of the commanded temperature.

Motivation: For the correction system to introduce adjustments on a micron scale, the applied heating must be controllable to the specified tolerance.

Verification: Analysis and Test

Requirements: FR1

DR1.4 The ACS shall accommodate mounting of a flat mirror or representative surface.

Motivation: The high CTE mechanism(s) must be sized to induce sufficient alignment adjustment to correct errors introduced to the mirror, as well as structurally support the selected mirror.

Verification: Inspection

DR1.5 The ACS shall be able to return to the mirror to its initial position (± 2 μm,± 20 μradians) within 600 seconds, after the mirror is exposed to a 50 μm translation displacement, and a 50 μradian rotation displacement.

Motivation: Customer Requirement. Verification of material driven adjustment system.

Verification: Analysis of design and test of the following scenario:

1) The test bed is at ambient temperature with the mirror zeroed.
2) With the ACS inactive, a 50 micron translation displacement is induced to the optical element via thermal expansion of the test bed.
3) With the ACS inactive, a 50 μradian rotation displacement is induced to the optical element in two axes via thermal expansion of the test bed.
4) The ACS is activated to correct for error with the test bed held at constant temperature ($\pm$ 0.2 K).

DR1.6 The ACS shall be able to maintain mirror alignment to within ± 2 μm and ± 20 μradians for 95% of temperature profile execution described in DR2.2.2

Motivation: The high CTE mechanism(s) mussized to induce t be sufficient alignment adjustment to correct errors introduced to the mirror, as well as structurally support the selected mirror.

Verification: Inspection and Analysis

Requirements: FR1

DR1.7 A physical safety barrier shall be included with the ACS.

Motivation: Safety consideration to ensure personnel and equipment safety during testing operations.

Verification: Inspection of test bed to ensure safety barrier is in place.

DR1.7.1 Any components of the ACS that are heated above 320K shall be inaccessible during operations.

Motivation: Customer Requirement. Safety requirement to ensure personnel are not accidentally burned by heated components.

Verification: Analysis of thermal design and inspection of test set-up.

Requirements: FR2

FR2: The test bed shall introduce controllable alignment error to a flat mirror or representative surface, in order to simulate the thermally induced misalignment experienced by space-based systems.

DR2.1 The test bed shall integrate the Alignment Measurement System (AMS).

Motivation: The test bed is intended to emulate a spacecraft optical bench, and must be designed to accommodate and house the optical alignment measurement system.

Verification: Inspection of test bed design and fabrication.

DR2.2 The test bed shall provide thermal regulation of individual control members.

Motivation: Control members are defined as all thermally controlled structural elements of the test bed, heated to induce three axes of skew to the flat mirror or representative surface. Heat must be applied to individual control elements to induce thermal expansion in a specified direction.

Verification: Analysis and test

DR2.2.1 After settling, the test bed shall be able to maintain the average temperature across a control member, to within ± 0.3 Kelvin of the commanded temperature.

Motivation: Validation of DR1.3 and FR1

Verification: Analysis and Test

Requirements: FR2

Time [min]	Temperature [k]
0	300
5	300
10	300
15	301
20	302
25	303
30	304
35	305
40	306
45	307
50	308
55	309
60	310
65	Remove heat
70	Remove heat
75	Remove heat
80	Remove heat
85	Remove heat
90	Remove heat
95	Remove heat
100	Remove heat

DR2.2.2 The test bench shall be capable of inducing the temperature profile in all translation control members, with a maximum error of ± 0.3K at any time during the profile execution.

Motivation: Customer requirement. Derived as a representative timing requirement for on-orbit adjustments.

Verification: Test

DR2.2.2.1 The test bed shall be able to increase the average temperature across a specified control member 1K in less than 120 seconds.

Motivation: Validation of DR2.2.2

Verification: Test

Requirements: FR2

DR2.3 The temperature of the test bench structural elements shall be known to within 0.2K for the operating range of temperatures.

Motivation: Customer Requirement. In order to induce controlled deformation on a micron level, sufficient temperature resolution is required to feed back for control.

Verification: Analysis and Test

DR2.3.1 The test bed shall accommodate mounting of temperature sensors for measurement of thermally controlled structural elements.

Motivation: Temperature knowledge describing the state of the heated elements is necessary for implementing thermally regulated control. Mounting surface and location must be designed to ensure necessary sensors can be mounted.

Verification: Inspection and Analysis

DR2.4 Thermally controlled structural elements of the test bed, excluding fasteners, shall be constructed from at least 95% by weight aluminum.

Motivation: Customer Requirement. Aluminum selected based on low cost and ease of manufacturing. Weight percentage selected to encompass common aluminum alloys.

Verification: Analysis

Requirements: FR2

DR2.5 The test bed shall be capable of inducing at least 100 μm of single axis translation displacement to a mirror or representative surface, when a 10K temperature increase is applied to the control members, from a starting temperature of 296 K.

Motivation: Customer requirement. Displacement requirement selected to allow for measurable translation displacement within the system.

Verification: Analysis and Test

DR2.6 The test bed shall be capable of inducing more than 50 μradians of rotation displacement in two separate axes to the mirror or representative surface.

Motivation: Customer Requirement.

Verification: Analysis and Test

DR2.7 A physical safety barrier shall be included with the test bed.

Motivation: Safety consideration to ensure personnel and equipment safety during testing operations.

Verification: Inspection of test bed to ensure safety barrier is in place.

DR2.7.1 Any control member of the test bed heated above 320K shall be inaccessible during operations.

Motivation: Customer requirement. Safety requirement to prevent possible human contact.

Verification: Analysis of thermal design and inspection of test set-up.

Requirements: FR2

DR2.8 The test bench shall maintain structural integrity while supporting all integrated hardware within the expected temperature operating range.

Motivation: The structure must retain its shape if loaded at elevated temperatures to ensure creep is not introduced by the mounted components, affecting measurement accuracy.

Verification: Structural Analysis

Requirements: FR3

FR3: The Alignment Measurement System (AMS) shall measure thermally induced alignment error of a flat mirror or representative surface, in order to provide feedback to the ACS.

DR3.1 The AMS shall measure translation error introduced to the mirror or representative surface with an accuracy of $\pm$ 1.75 µm.

Motivation: Customer requirement. Precision representative of requirement for space-based optical systems.

Verification: Analysis and Test

DR3.2 The AMS shall be capable of measuring rotation error with an accuracy of $\pm$ 15.3 µrads.

Motivation: Customer requirement. Rotation resolution selected to ensure consistent order of magnitude with DR3.1, assuming a range of standard mirror sizes.

Verification: Analysis and Test

Requirements: FR4

FR4: The electronics package shall provide active control of both the ACS and test bed, using direct measurement of alignment error and temperature.

DR4.1 The electronics package shall enable active temperature control of the test bed control members to within 0.3K, over a 10K temperature range.

Motivation: Validation of DR2.2 and DR2.4
Verification: Analysis and Test

DR4.1.1 The electronics package shall incorporate an active feedback loop using sensor data from the test bed hardware

Motivation: Active feedback loop is necessary to control temperature of test bed in real time.
Verification: Inspection and Test

DR4.1.1.1 The electronics package must interface with sensors and heaters on the test bed.

Motivation: Interface with input and output data sources is necessary for successful implementation of the feedback loop.
Verification: Inspection and Test

Requirements: FR4

DR4.2 The electronics package shall enable active temperature control of the ACS high CTE actuators to within 0.3K over a temperature range large enough to induce 100 µm of thermal expansion.

Motivation: Validation of DR1.5-6
Verification: Analysis and Test

DR4.2.1 The electronics package shall incorporate an active feedback loop using sensor data from the AMS, as well as temperature sensors on the ACS and test bed hardware.

Motivation: Active feedback loop is necessary to control temperature of ACS in real time.
Verification: Analysis and Test

DR4.2.1.1 The electronics package shall interface with sensors and heaters from the ACS and measurement sensors from the test bed.

Motivation: Data flow in both directions is necessary for actively controlling alignment of the ACS.
Verification: Inspection of system architecture, and test

DR4.3 The electronics package shall save a data file containing temperature data and alignment error in three axes for the duration of testing.

Motivation: Post processing of data is necessary for validating design of ACS.
Verification: Inspection