Preliminary Design Review

SPECTROM

Scientific Platform for the Exact Control of Thermally Regulated Optical Equipment

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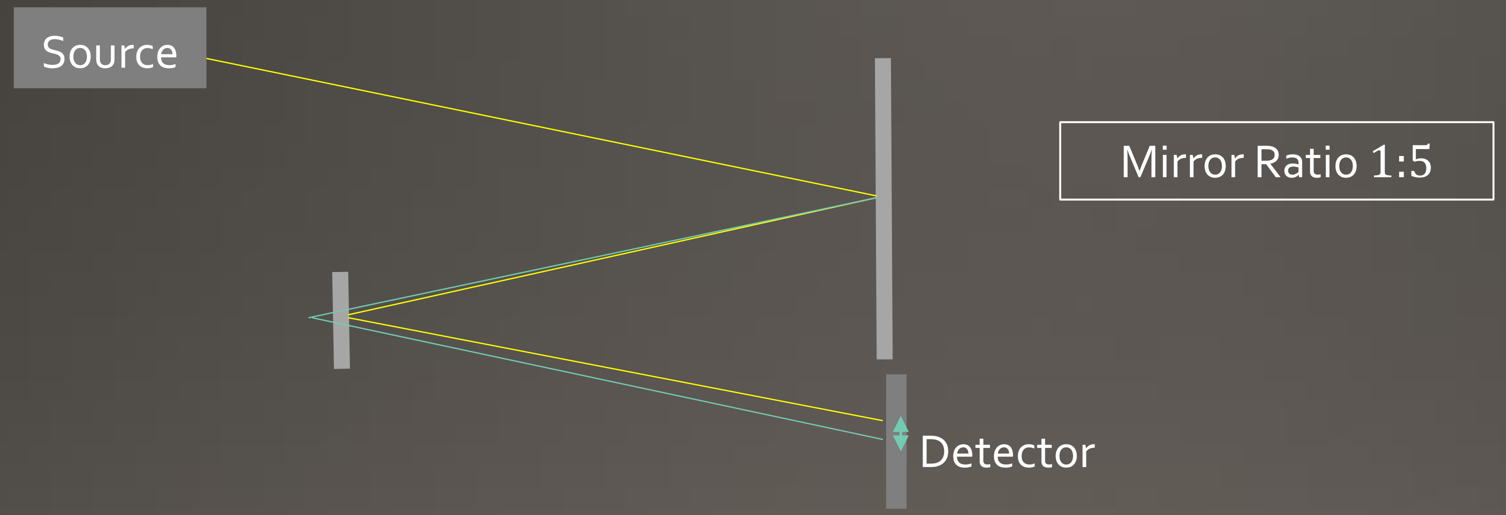
Project Statement

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**.

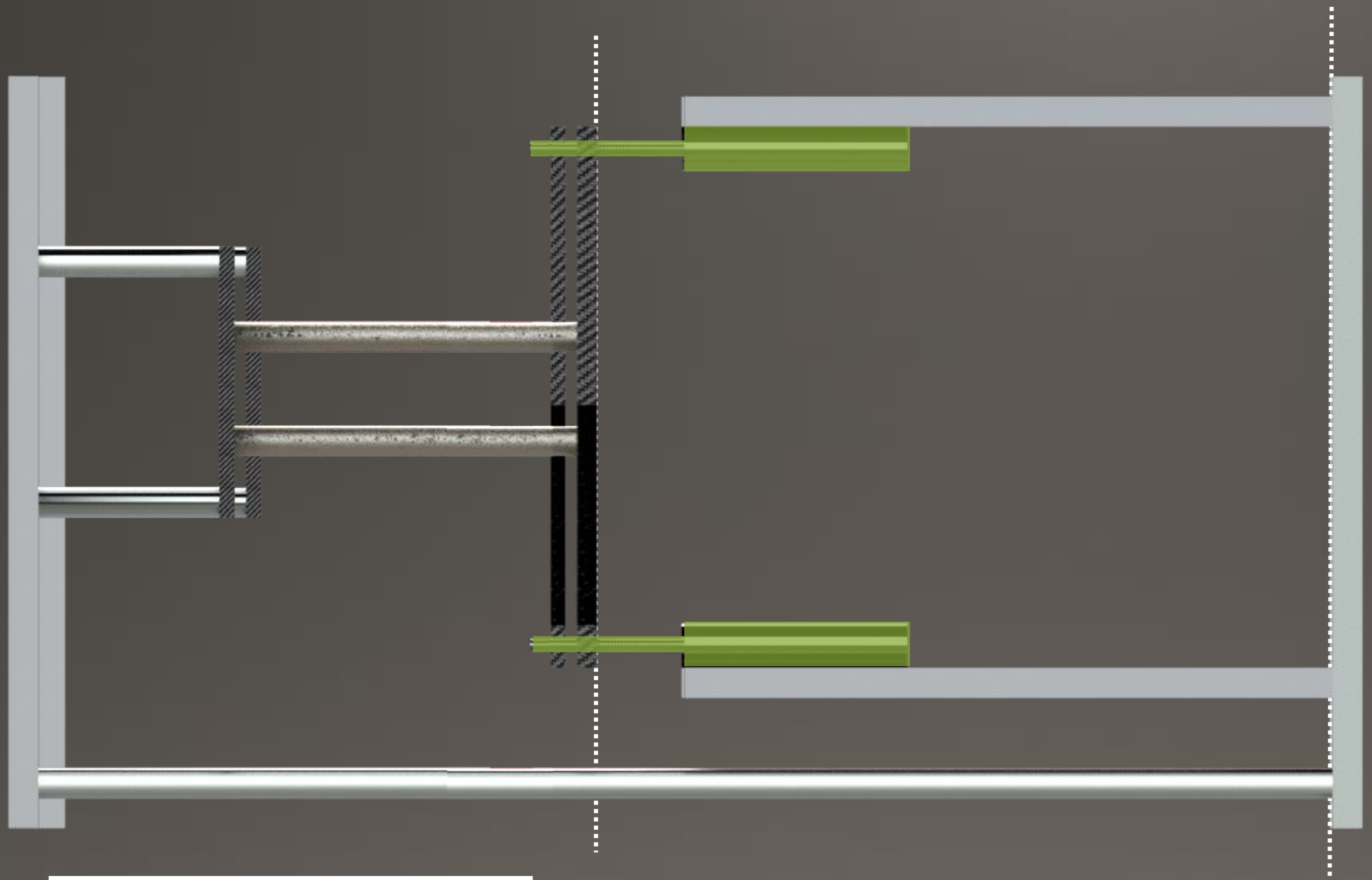
Project Motivation

- Maintaining placement of optical instrumentation



- Reduce cost of optic bench by using aluminum frame
- Thermal expansion for active control mechanism

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.

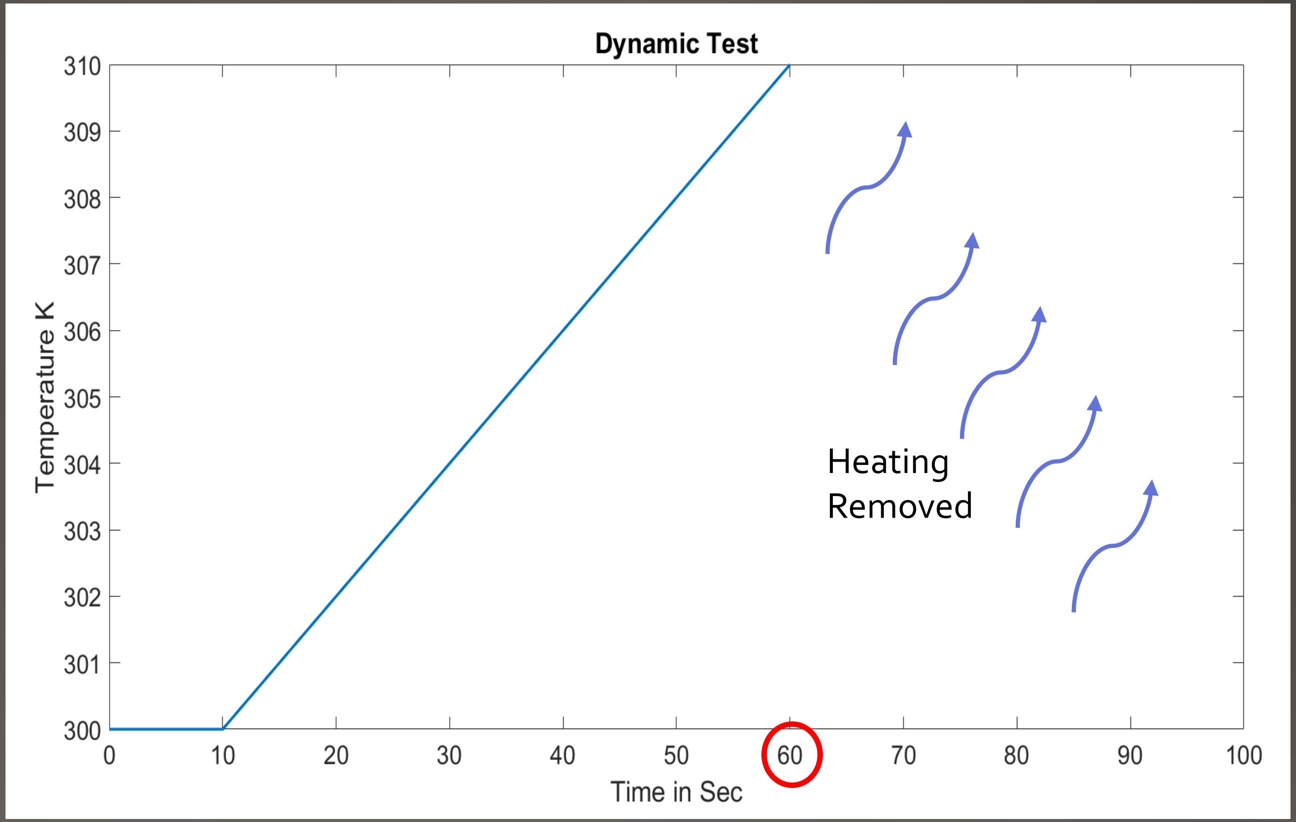
Functional Requirements

FR1.	The Alignment Correction System (ACS) shall provide **corrective capabilities** to adjust a flat mirror in **two axes of rotation and one axis of translation**, in response to thermally induced misalignment.
FR2.	The test bed shall introduce **controllable alignment error** to a flat mirror or representative surface, in order to **simulate 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.

System Validation Testing

- Static Test
  - Correct for a 50µm displacement within 120 seconds
  - Motivation: First level of success

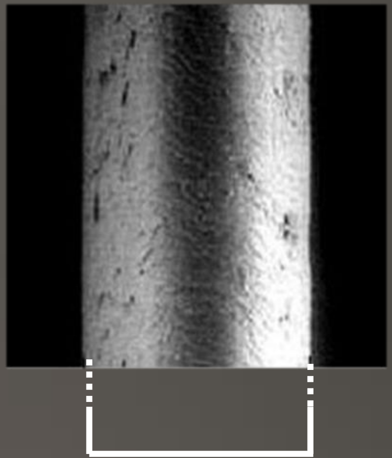
- Dynamic Test
  - Heat the system following temperature profile
  - Motivation: On orbit temperature fluctuations



Project Description | Alignment Measurement System | Test Bed | Alignment Correction System | Electronics Package | Summary

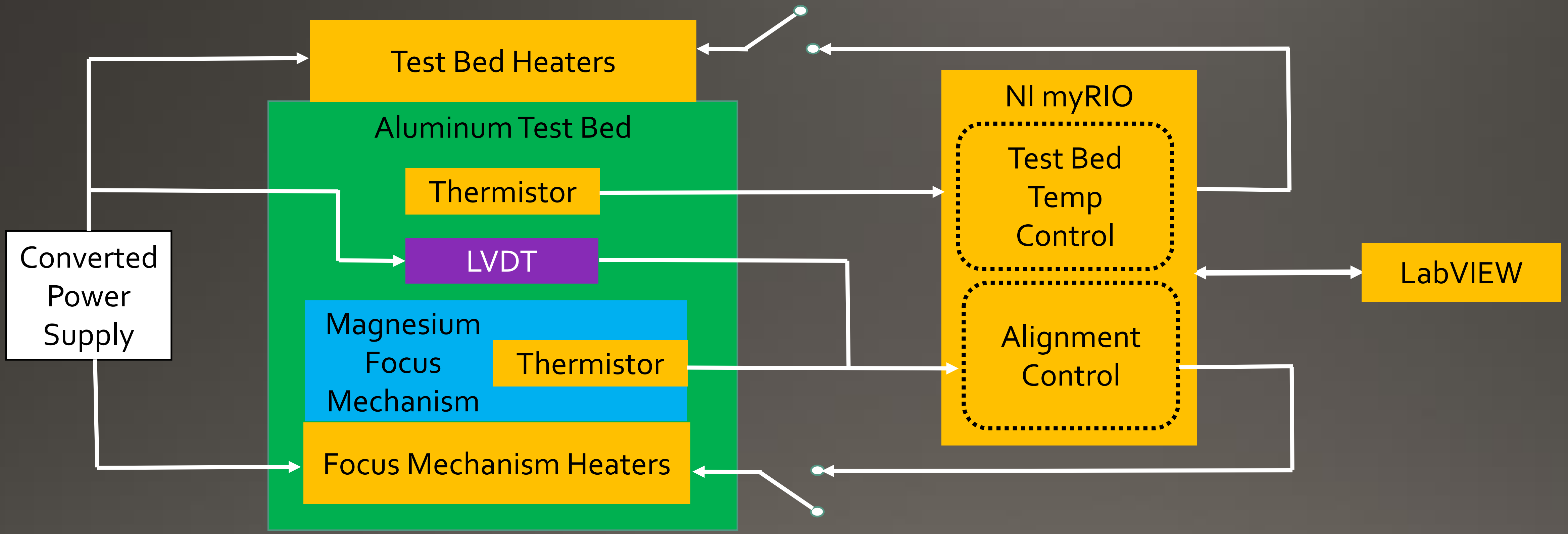
Derived Requirement Constraints

	Characteristic	Requirement
Test Bed	Linear Displacement	> 100 µm over 10K
	Rotation Displacement	> 50 µradians
Alignment Correction System	Linear Translation Correction	± 2 µm
	Rotation Correction	± 20 µrad
	Time Requirement (Static Test)	120 seconds
Alignment Measurement System	Linear Displacement	± 1 µm
	Rotation Displacement	± 10 µrad
Electronics Package	Temperature measurement accuracy	0.1K


Human Hair
60 µm

Functional Block Diagram

AMS | ACS | Test Bed | Electronics



Critical Project Elements

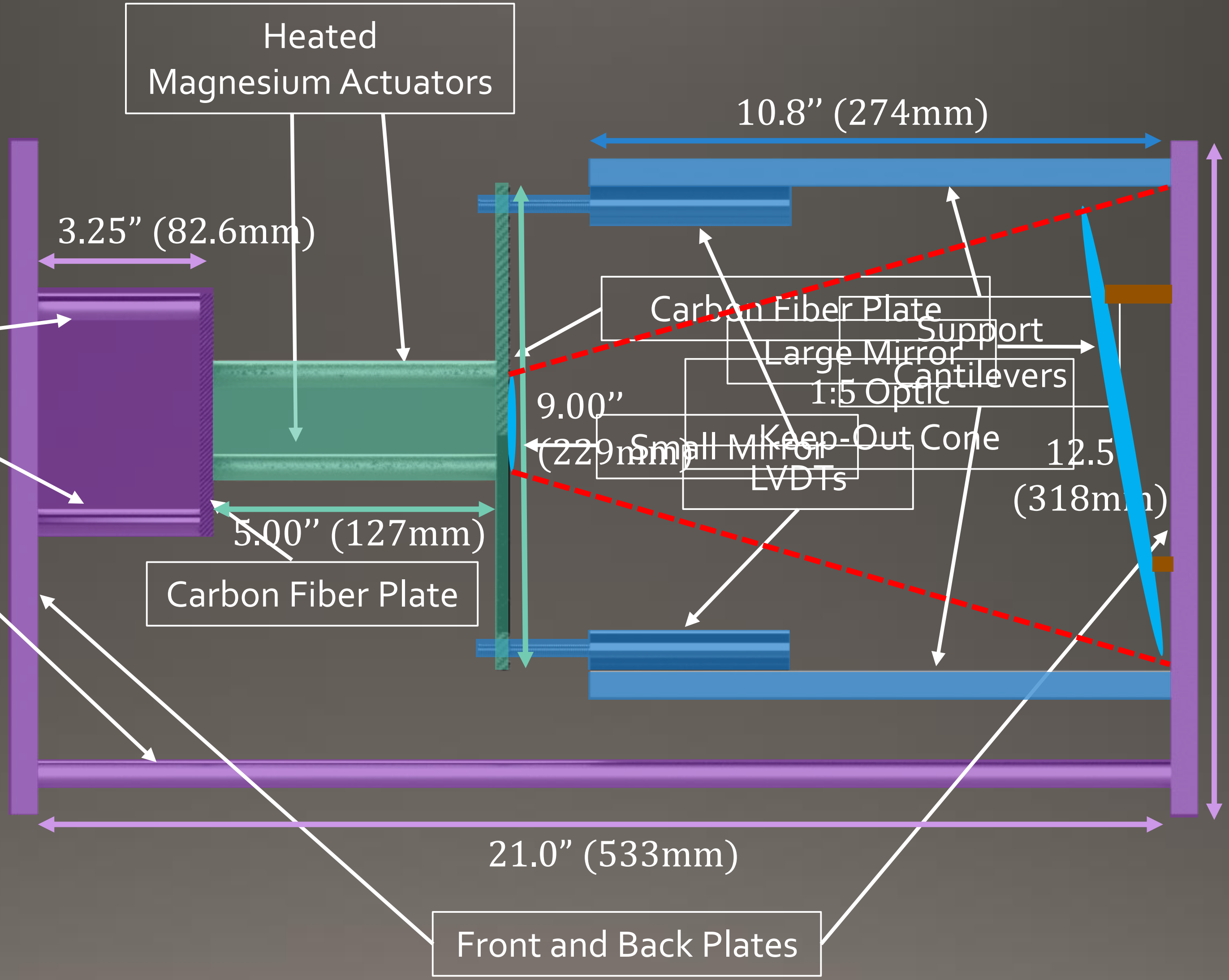
Critical Project Elements	System Solution
Active control of mirror alignment using a high CTE material	Alignment Correction System (ACS)
Three-axes measurement of mirror alignment	Alignment Measurement System (AMS)
Design and control of aluminum test bed	Test Bed
Data acquisition and software package	Electronics Package

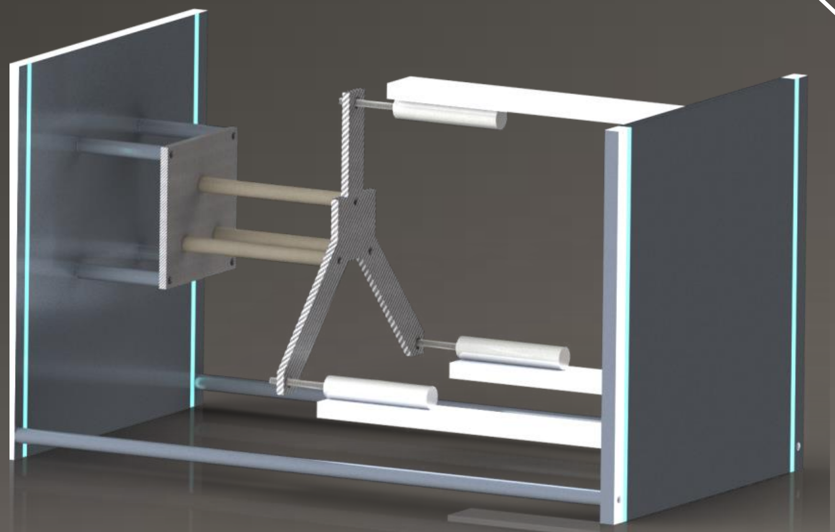
Design Overview

Test Bed

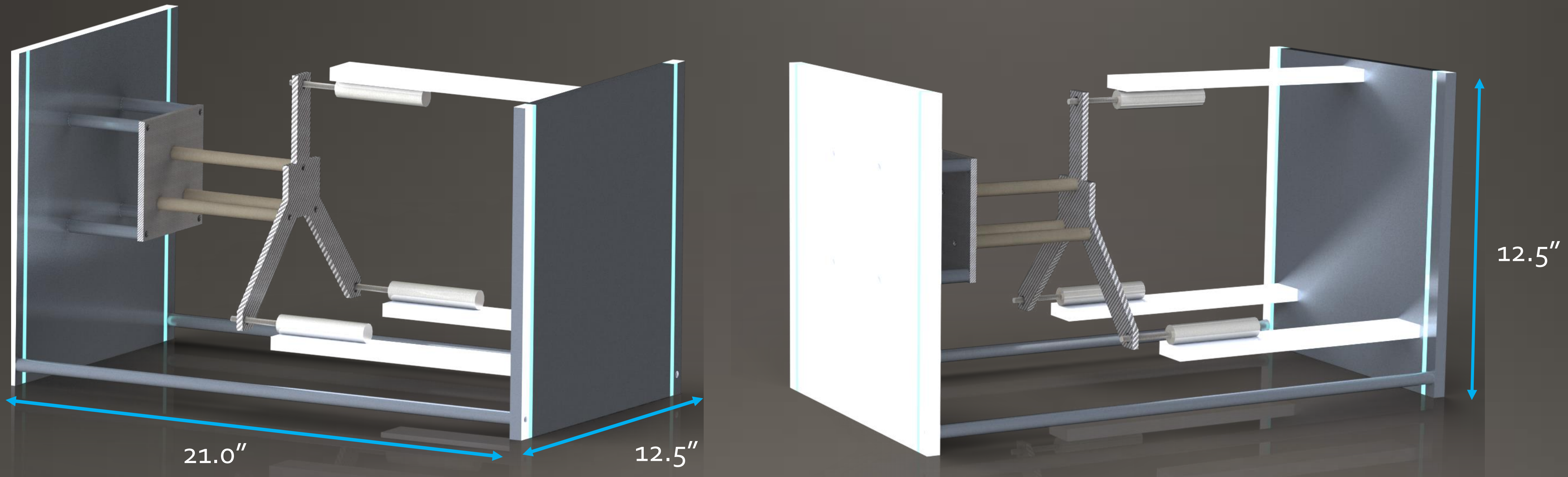
Alignment Measurement System

Alignment Correction System





Design Overview



Project Description → Alignment Measurement System → Test Bed → Alignment Correction System → Electronics Package → Summary

Alignment Measurement System (AMS)

Alignment Measurement System

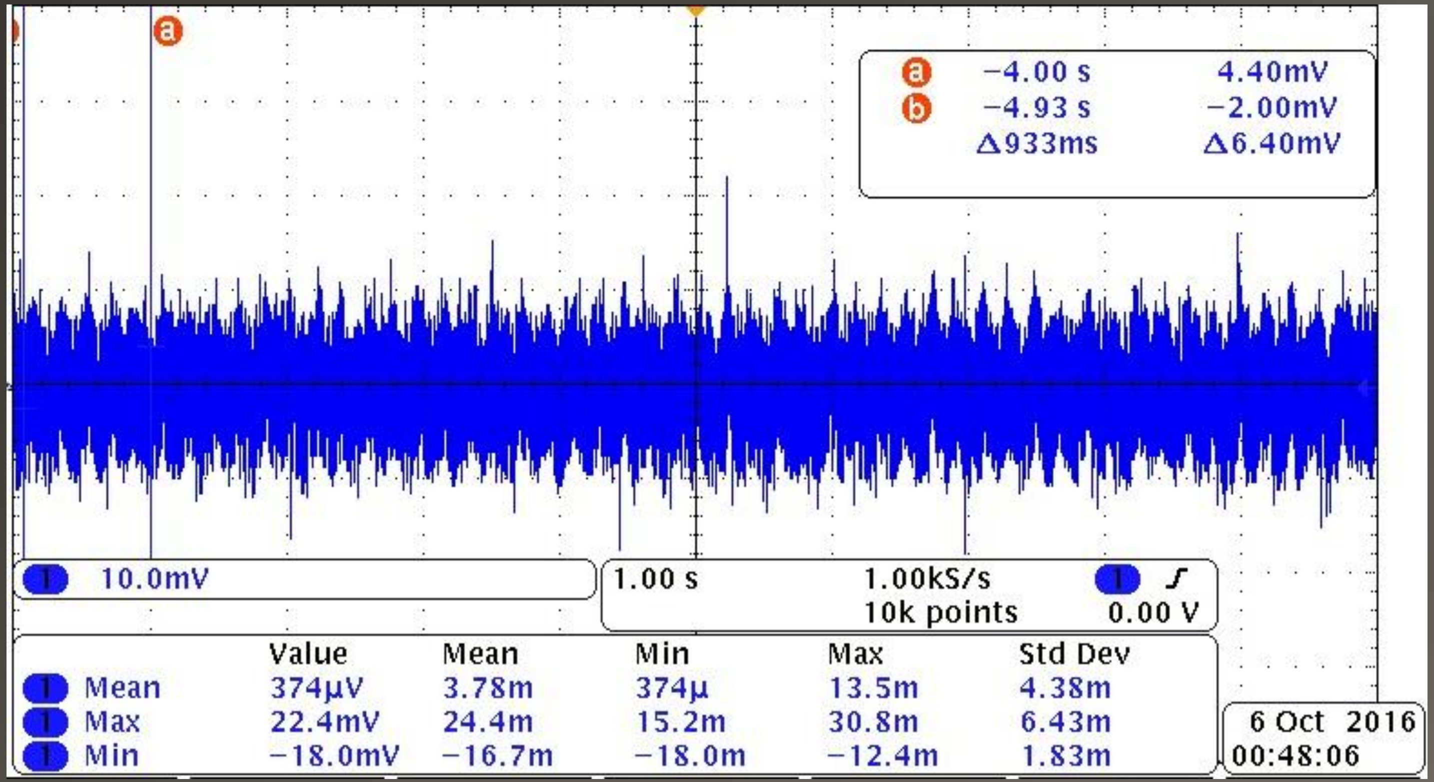
- Displacement Transducers (LVDTs)
- Output a voltage directly proportional to translation of shaft inside of cylinder
- Required resolution: ±1 µm
- LD620-2.5 specs show 2 mV/µm with infinite resolution

Alignment Measurement System

Potential sources of uncertainty:

- Electrical noise
  - Other electronic devices interfering with LVDT signal
- Physical noise
  - Vibrations (people walking, truck driving by, etc.)
- Thermal error
  - Variations in room temperature
- Heat transfer error
  - Test bed will be transferring heat to LVDTs

Electrical and Vibrational Noise Test

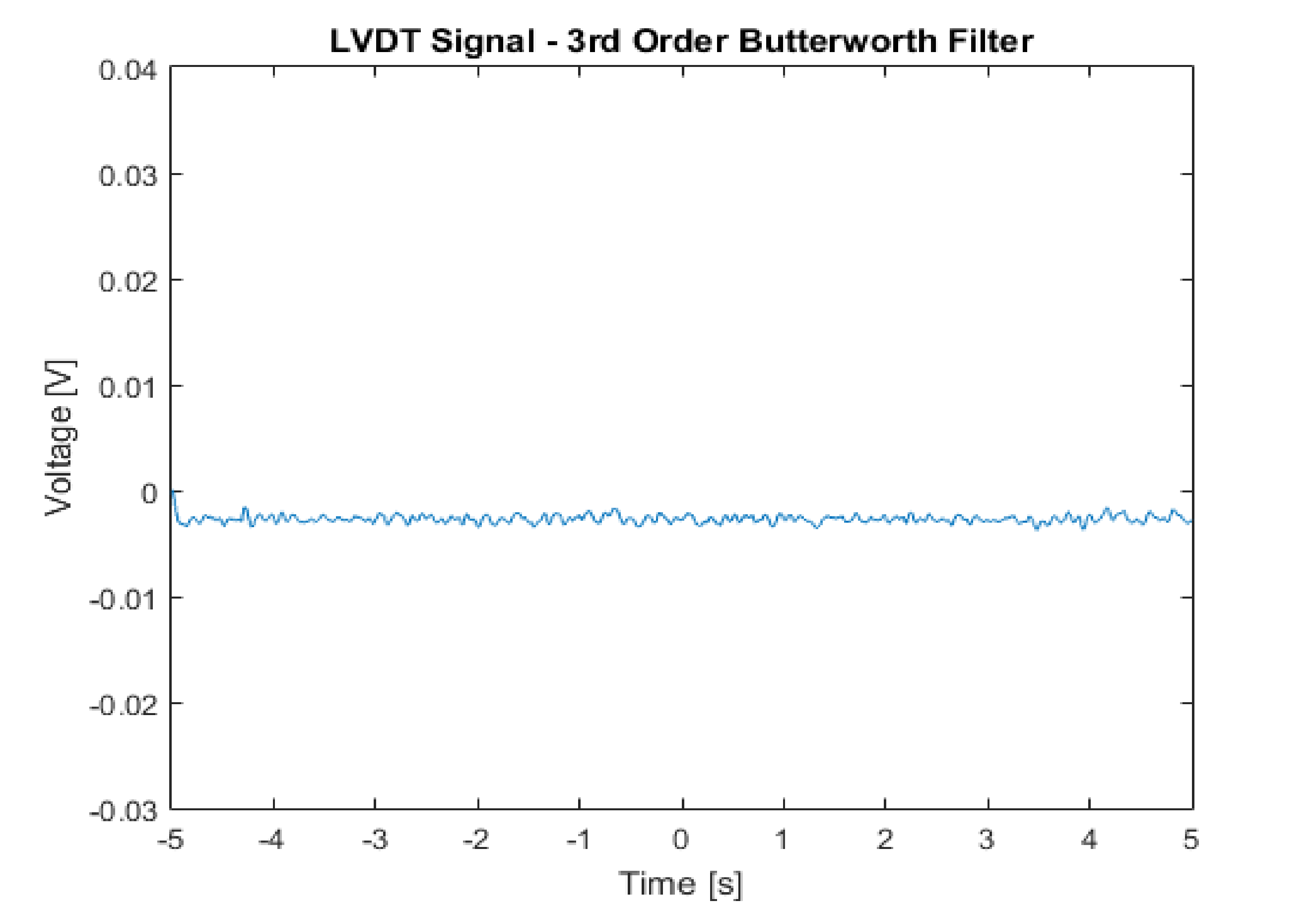


Static LVDT voltage readings from oscilloscope: no filtering of any sort applied

Total Range	41.1 mV
Voltage Uncertainty	+/- 20.6 mV
Position Uncertainty	+/- 10.3 µm

Does not fulfill FR3

Electrical and Vibrational Noise Test

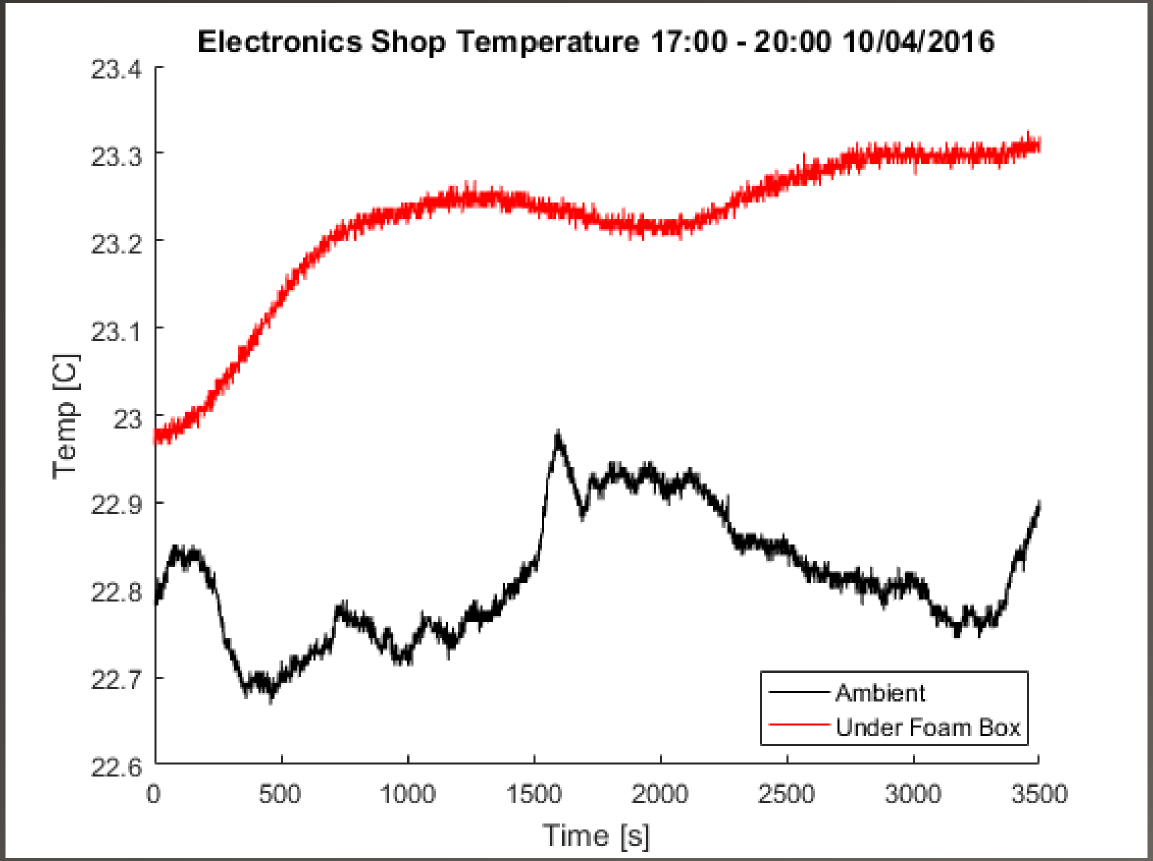


Static LVDT voltage readings from oscilloscope: 4 Hz low-pass RC filter and 4 Hz 3rd order Butterworth digital filter applied

Total Range	3.58 mV
Voltage Uncertainty	+/- 1.85 mV
Position Uncertainty	+/- 0.92 μm

Fulfill FR3
FEASIBLE

Static Thermal Conditions Test



BMP180 (0.5 °C accuracy, 0.1°C resolution)
Sampled at 1 Hz over 60 minutes

Sensor Location	Open Air	Styrofoam Box
Measured Max Fluctuation	+/- 0.1582 C	+/- 0.0631 C (Steady State)
Including Sensor Error	+/- 0.2582 C	+/- 0.1631 C
Voltage Uncertainty	+/- 0.03 mV	+/- 0.02 mV

Environment has minimal impact

Total Electrical Uncertainty

Error Source	Uncertainty (+-mV)	Position Uncertainty
Electrical/Vibrational Noise	±1.847 mV	±0.924 μm
Ambient Thermal Conditions	±0.03 mV	±0.015 μm
Heat Transfer from Test Bed	±0.6 mV	±0.3 μm
Total Uncertainty	±1.942 mV	±.972 μm

Fulfill DR3.1
FEASIBLE

Analog to Digital Error

	Uncertainty (+-mV)	Position Uncertainty
Total Uncertainty	$\pm$ 1.942 mV	$\pm$ 0.972 µm
12 Bit ADC	$\pm$ 2.442 mV	$\pm$ 1.221 µm
16 Bit ADC	$\pm$ 1.984 mV	$\pm$ 0.992 µm

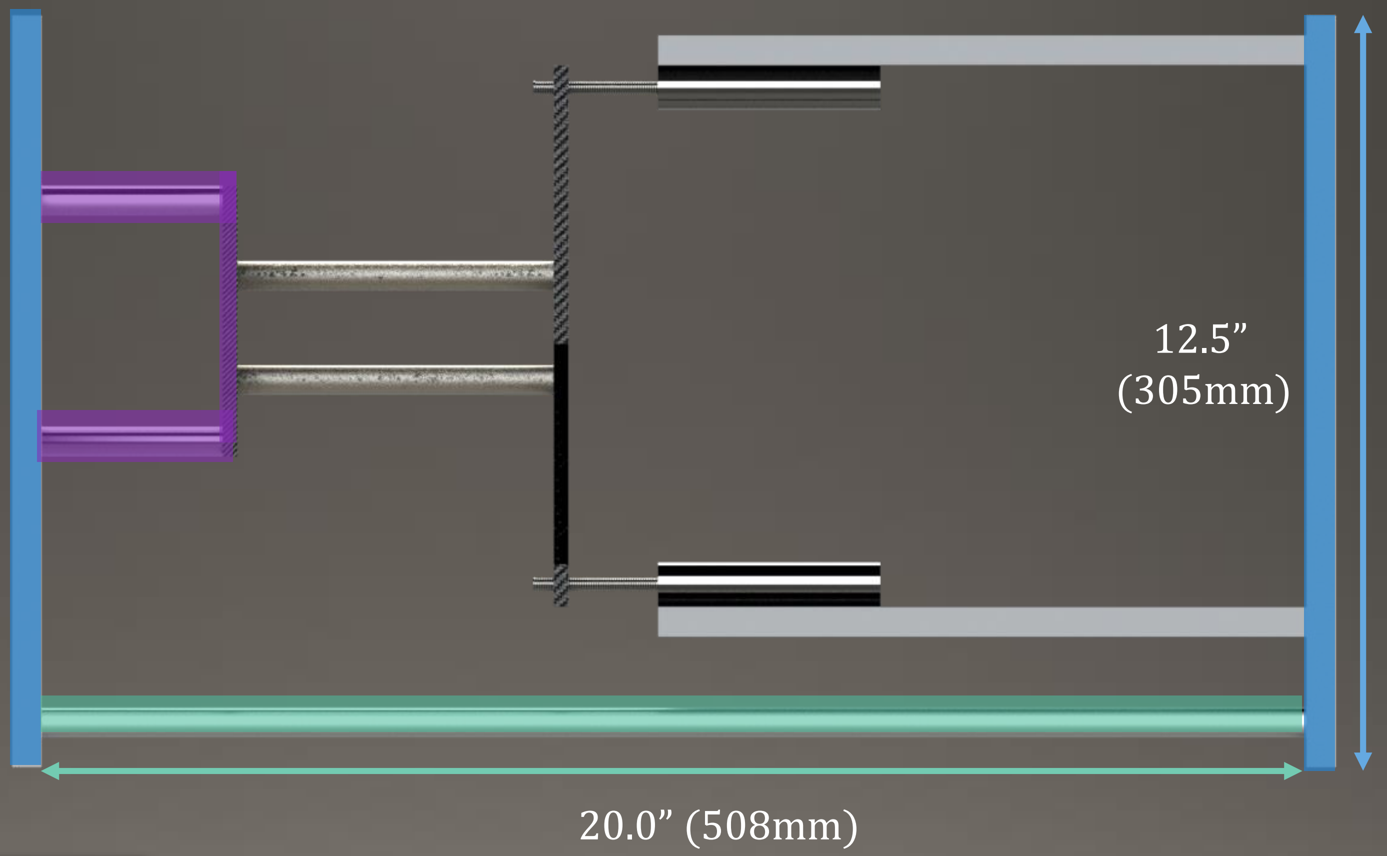
Fulfills FR3
FEASIBLE

Test Bed

Decomposition of Test Bed

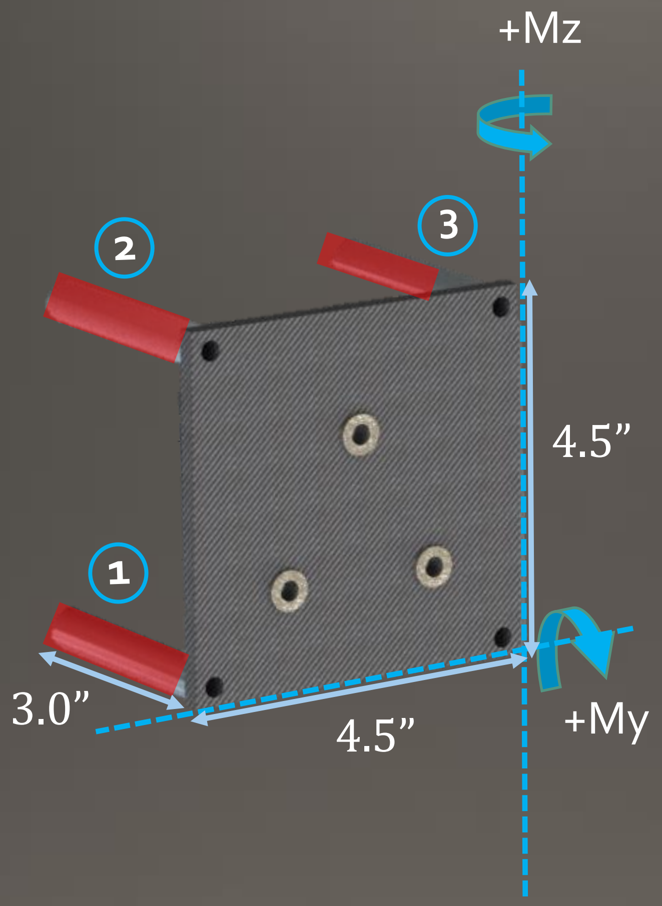
1. Cage
   - Four aluminum actuators mounted to rigid plate
   - Induces rotation in two axes which ACS corrects
2. Aluminum translation actuators
   - Two, 20" aluminum rods with ½" diameter
   - Sized to induce ≥ 100µm of displacement
3. Front and back mounting plates
   - Support plates for mounting the cage and cantilevers

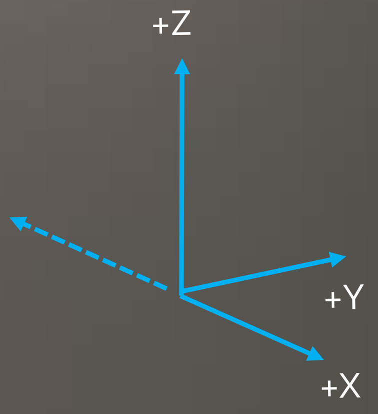
SIDE VIEW



Cage

- 3" Aluminum rods of cage are heated to introduce rotational misalignment of at least 50μrad
- Heating of selective rods enables rotations about multiple axes
  - +Mz induced by heating rods 1 and 2
  - +My induced by heating rods 2 and 3
    - Rod 4 omitted from graphic for clarity

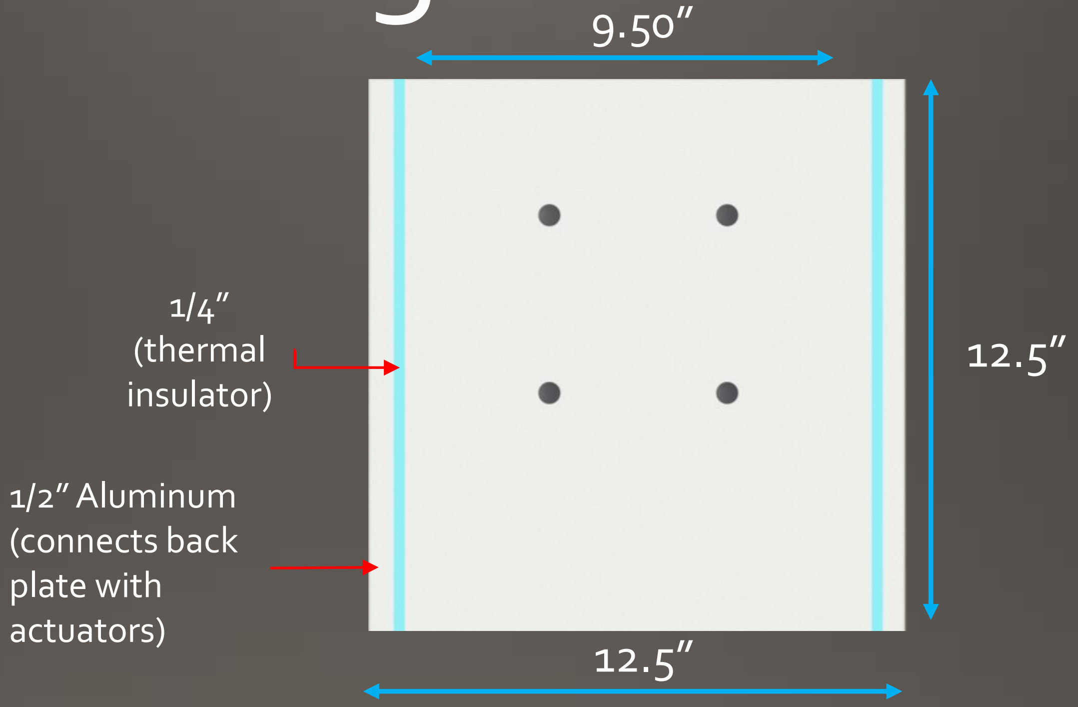


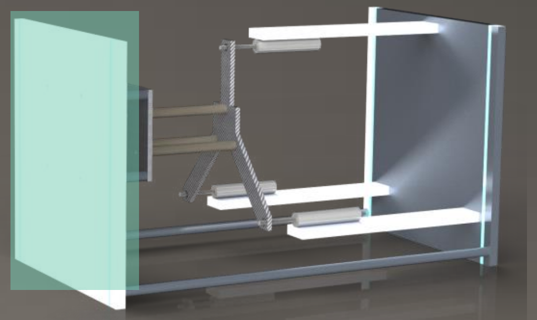


Supports FR2

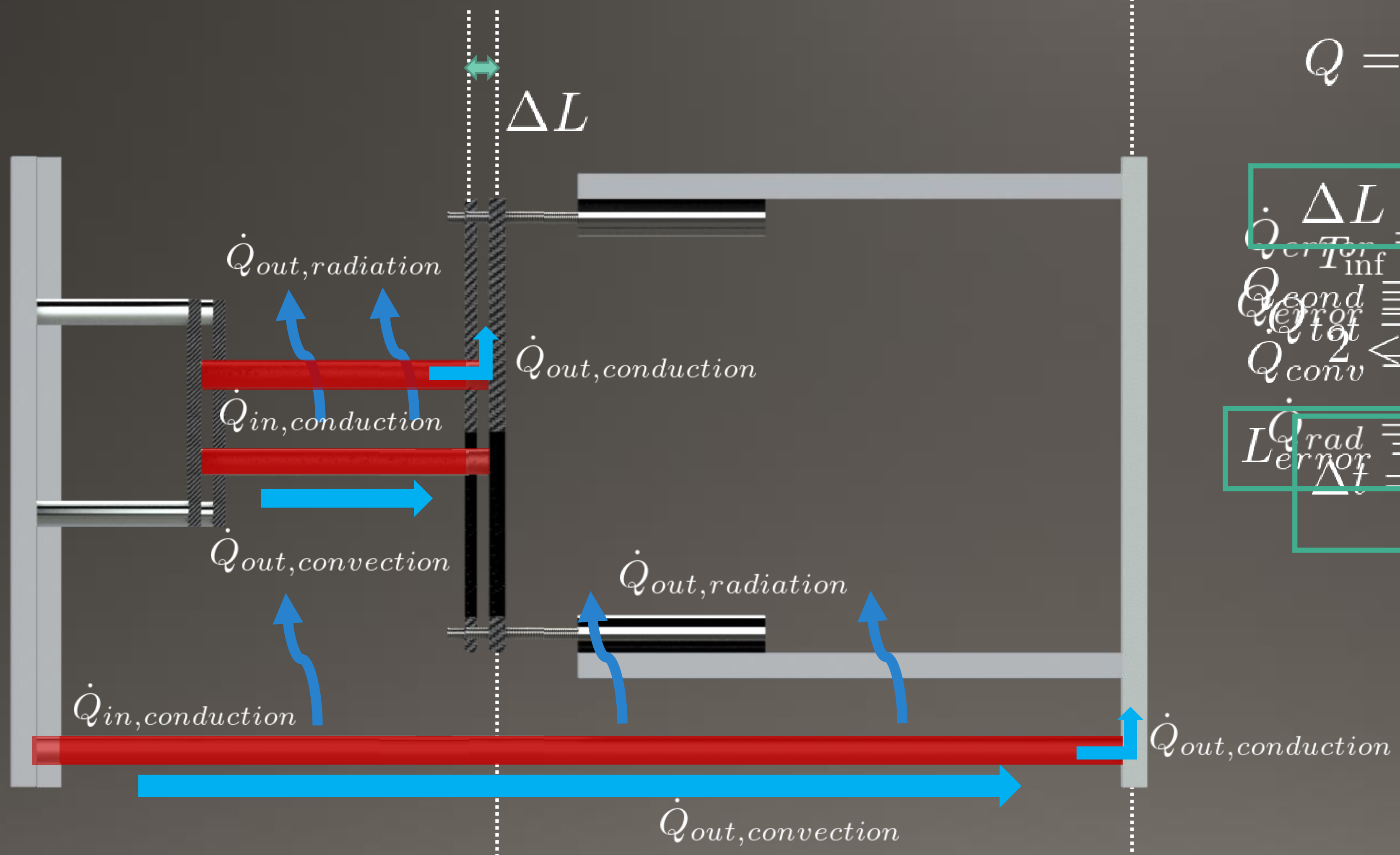
Front and Back Mounting Plate

- Cage mounting plate is isolated from the long aluminum actuators by thermally-invariant material
  - Eliminates heat transfer from long actuators to cage





Thermal Model



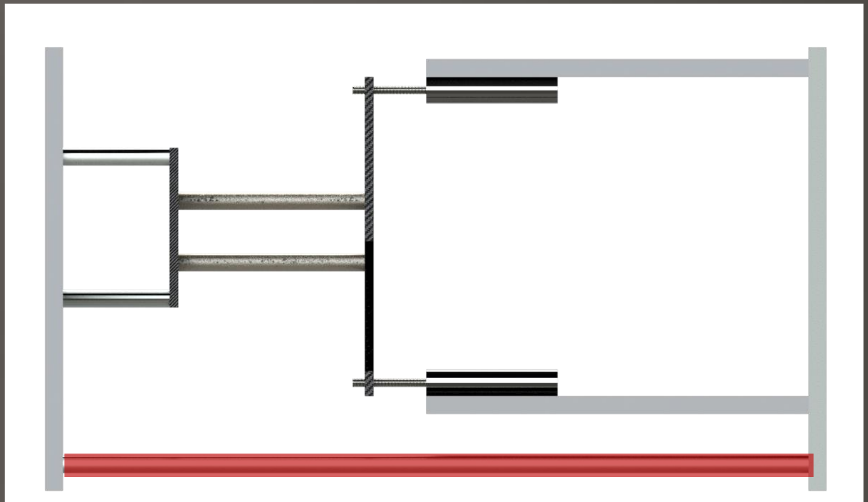
$$Q = mc_p\Delta T$$

$$\Delta L = L_i \alpha \Delta T$$

Test Bed Thermal Model

- Total Length Expanded: 112.78 µm

DR2.5
FEASIBLE



- Time to reach ΔT: 15.09 s

DR 2.2.2.1
FEASIBLE

Length Uncertainty: .355 µm

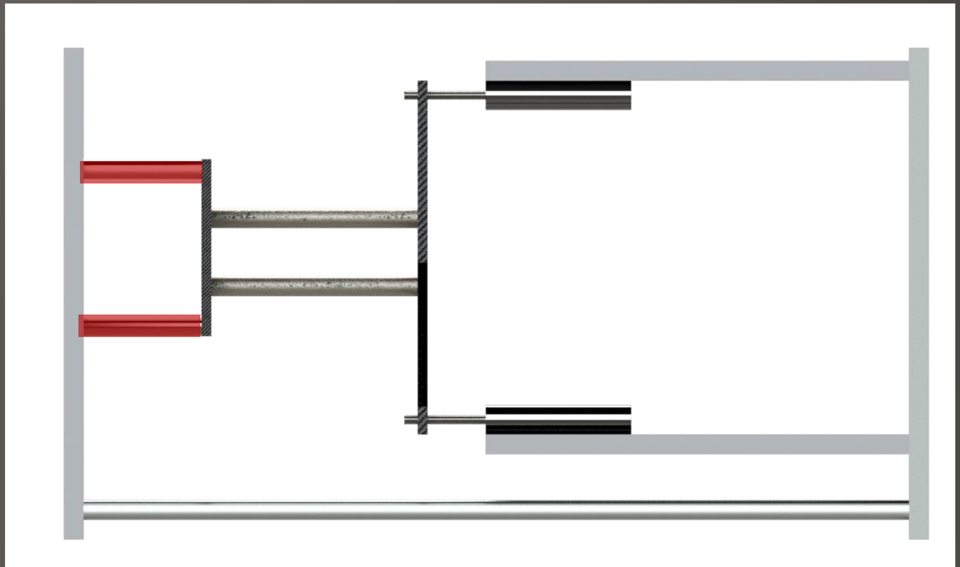
Supports DR1.3

Margin

	Expected Value	Requirement Feasibility	Margin
Time to Heat	15.08 [s]	DR 2.2.2.1	87.4 %
Length Change	112.78 [μm]	DR 2.5	12.78 %
Control	0.355 [μm]	DR 1.3	93.7 %

Test Bed Thermal Model

- Total Rotation induced : 169 μrad



DR2.6
FEASIBLE

- Time to reach ΔT: 1.98 s

Length Uncertainty: .008 μm

DR 2.2.2.1
FEASIBLE

Supports DR1.3

Margin

	Expected Value	Requirement Feasibility	Margin
Time to Heat	1.98 [s]	DR 2.6	98%
Angle Change	169 [μrad]	DR 2.2.2.1	238%
Control	0.008[μm]	DR 1.3	99%

Alignment Correction System (ACS)

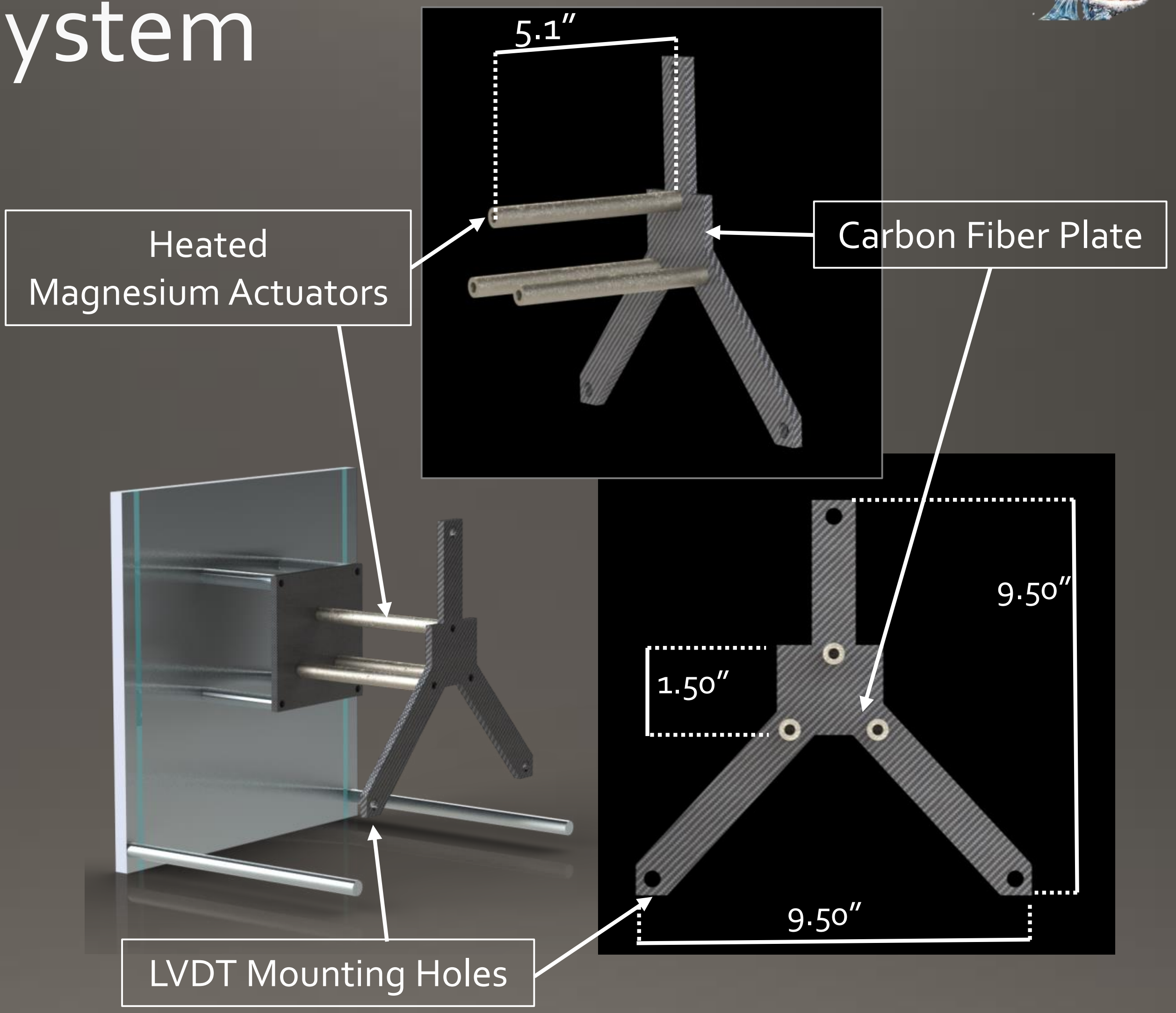
Alignment Correction System

System Hardware:

- Three 5″ magnesium rods with ½″ diameter.
- 9.5″ x 9.5″ x 1/8″ stiff carbon fiber Y-plate
- Heater for each rod

Control mechanism consists of three magnesium cylindrical actuators

Isolated heating of specific rods will induce rotation and translation to the Y-plate to correct for error

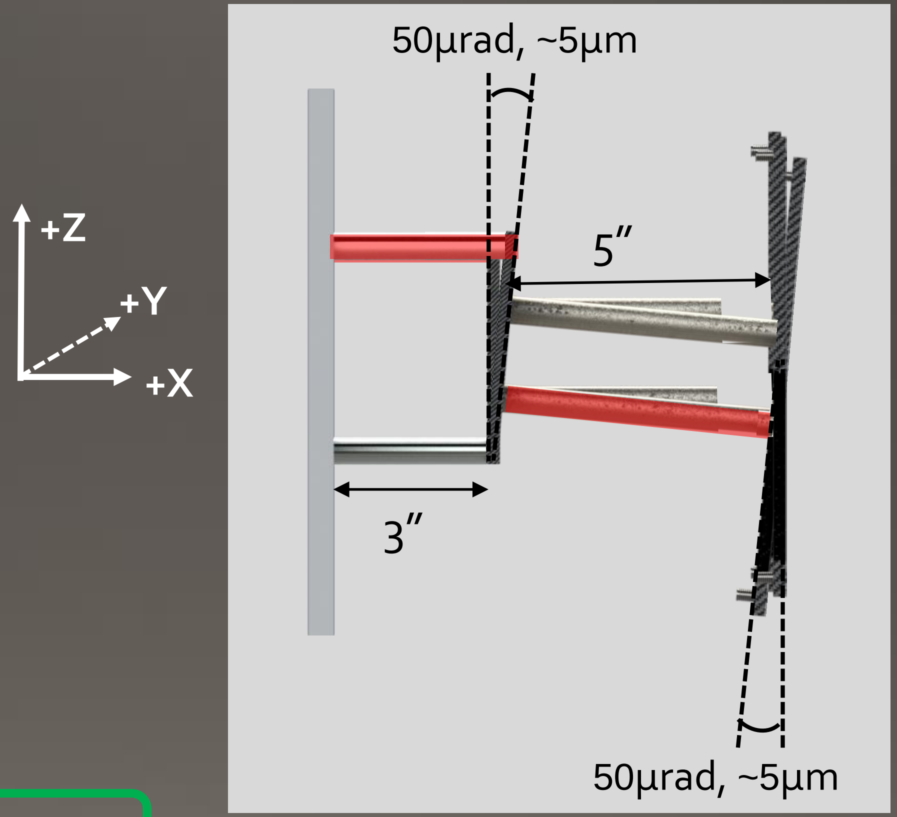


Alignment Correction System

CONOPS:

1. Cage induces >50 μrad of rotation about the +Y axis
2. ACS heaters apply ΔT to magnesium rods to induce corrective rotation about –Y

Rod layout and individual heating of Mg rods accommodates two axes of rotation and translation

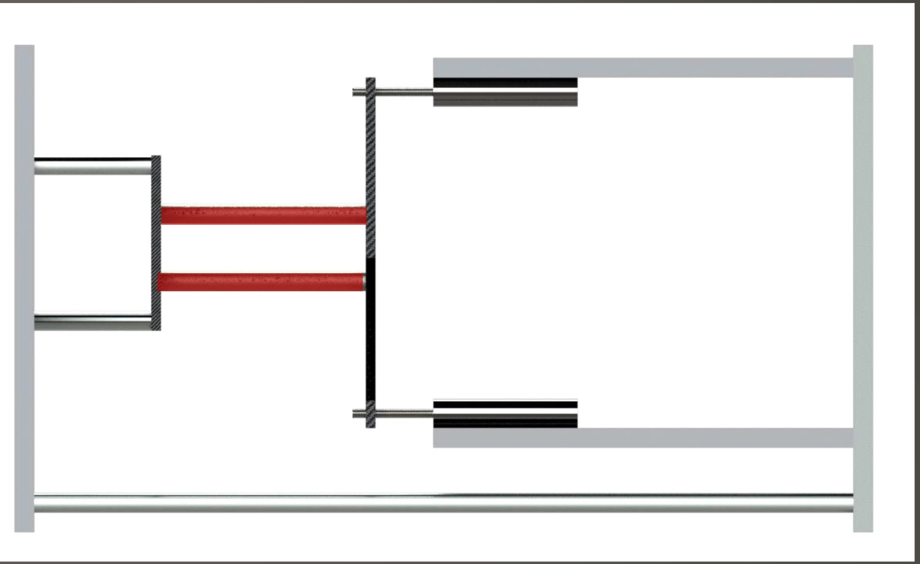


Supports FR1

ACS Thermal Model

- Change in Temperature: 34.15 K

Supports DR 1.1, DR1.2



- Time to reach ΔT: 45.74 s

Length Uncertainty: 0.47 μm

DR 1.5, DR 1.6
FEASIBLE

DR1.3,DR1.5
FEASIBLE

Project Description → Alignment Measurement System → Test Bed → Alignment Correction System → Electronics Package → Summary

Margin

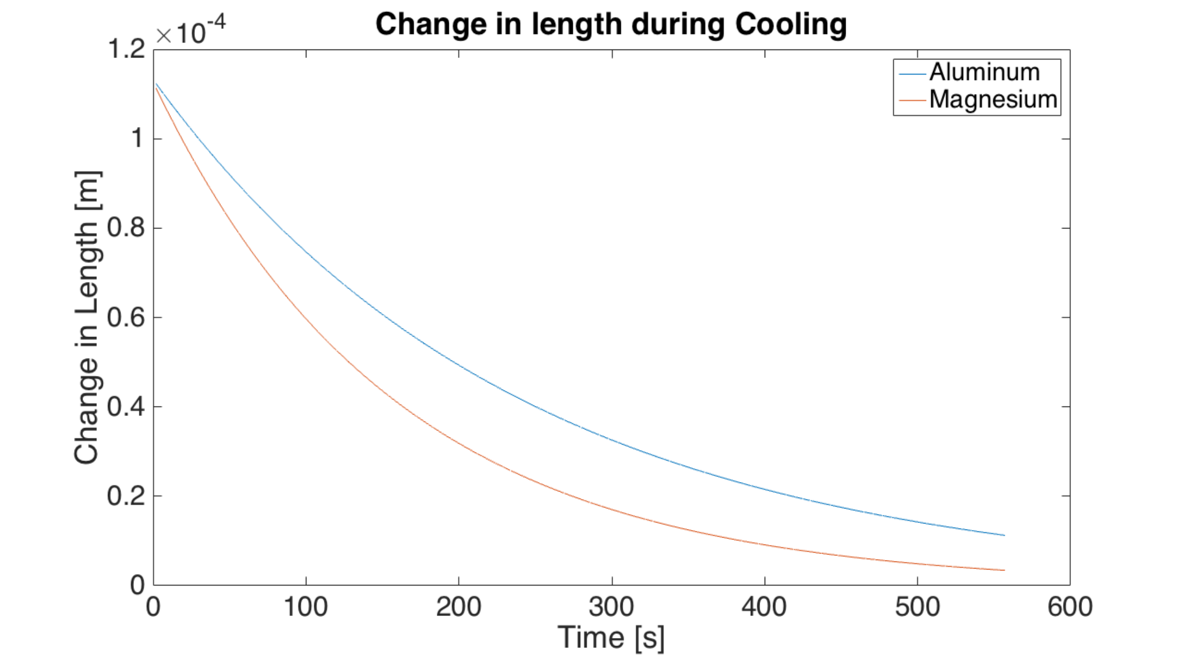
	Expected Value	Requirement Feasibility	Margin
Time [s]	45.74	DR 1.5, DR 1.6	61.8 %
Control [μm]	0.472	DR 1.3, DR 1.5	76.4 %
Safe ΔT [℃]	34.15	DR 1.1, DR 1.2	n/a

Cooling Stage: ACS vs. Test Bed

System	Heat Lost at Steady State [W]	Temperature Change per second [°C]
Aluminum, Long	6.48	.0413
Aluminum, Short	0.13	.005
Magnesium	6.18	.2168

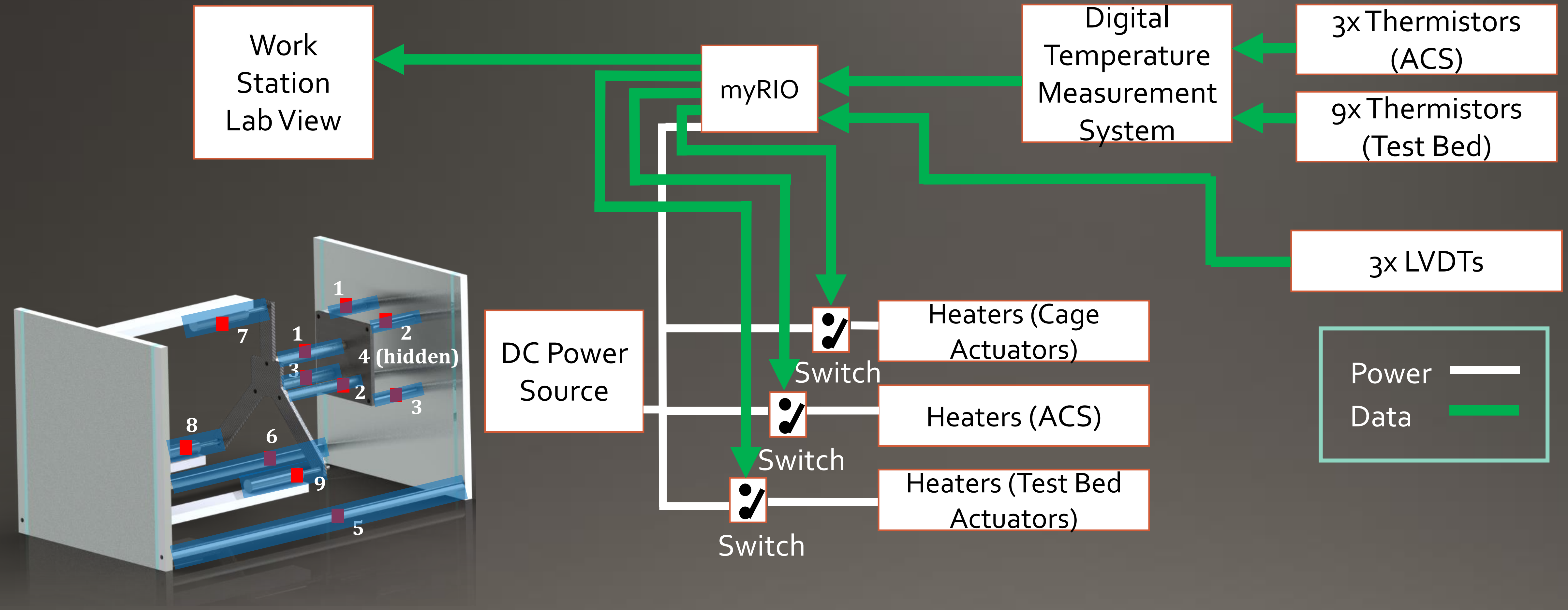
ACS will cool faster than TDU

DR 2.2.2
FEASIBLE



Electronics Package

Electrical Overview

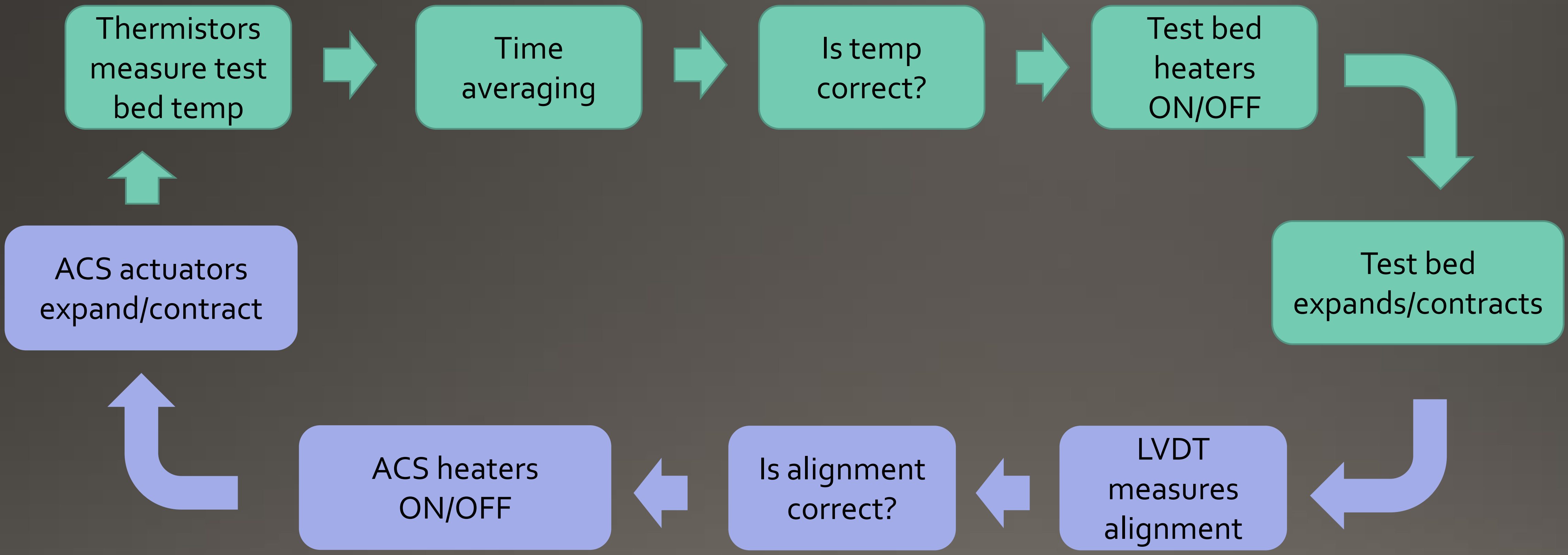


Temperature Sensors

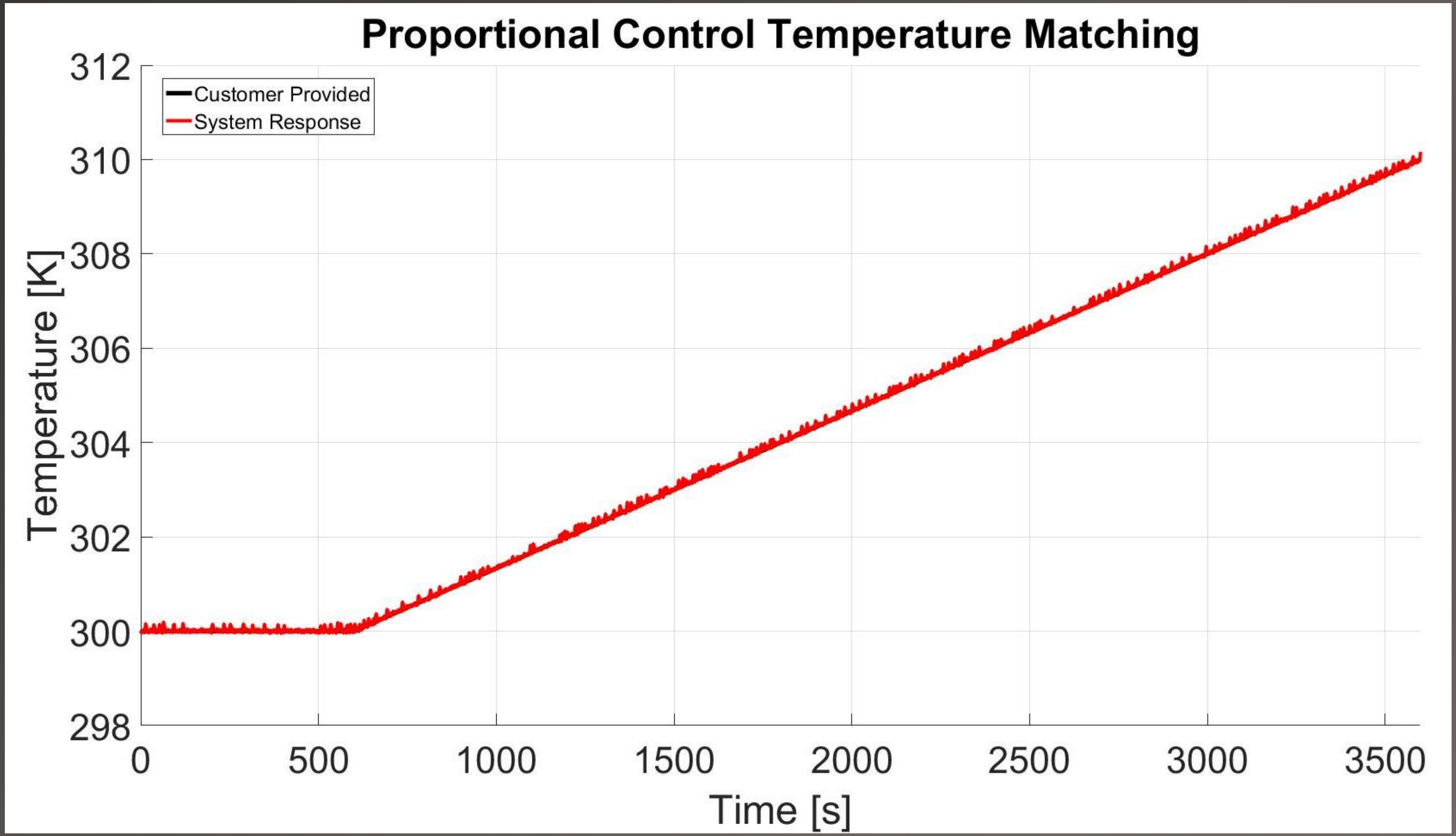
Initial System Capabilities	Requirements	Capabilities with Correction System
0.2°C Temperature Sensor Resistance Tolerance Error	0.1°C Total Error	0.1°C Total Error (Verification for CDR necessary)

DR2.3
FEASIBLE

Control System: Thought Process



Control System Response: Temperature

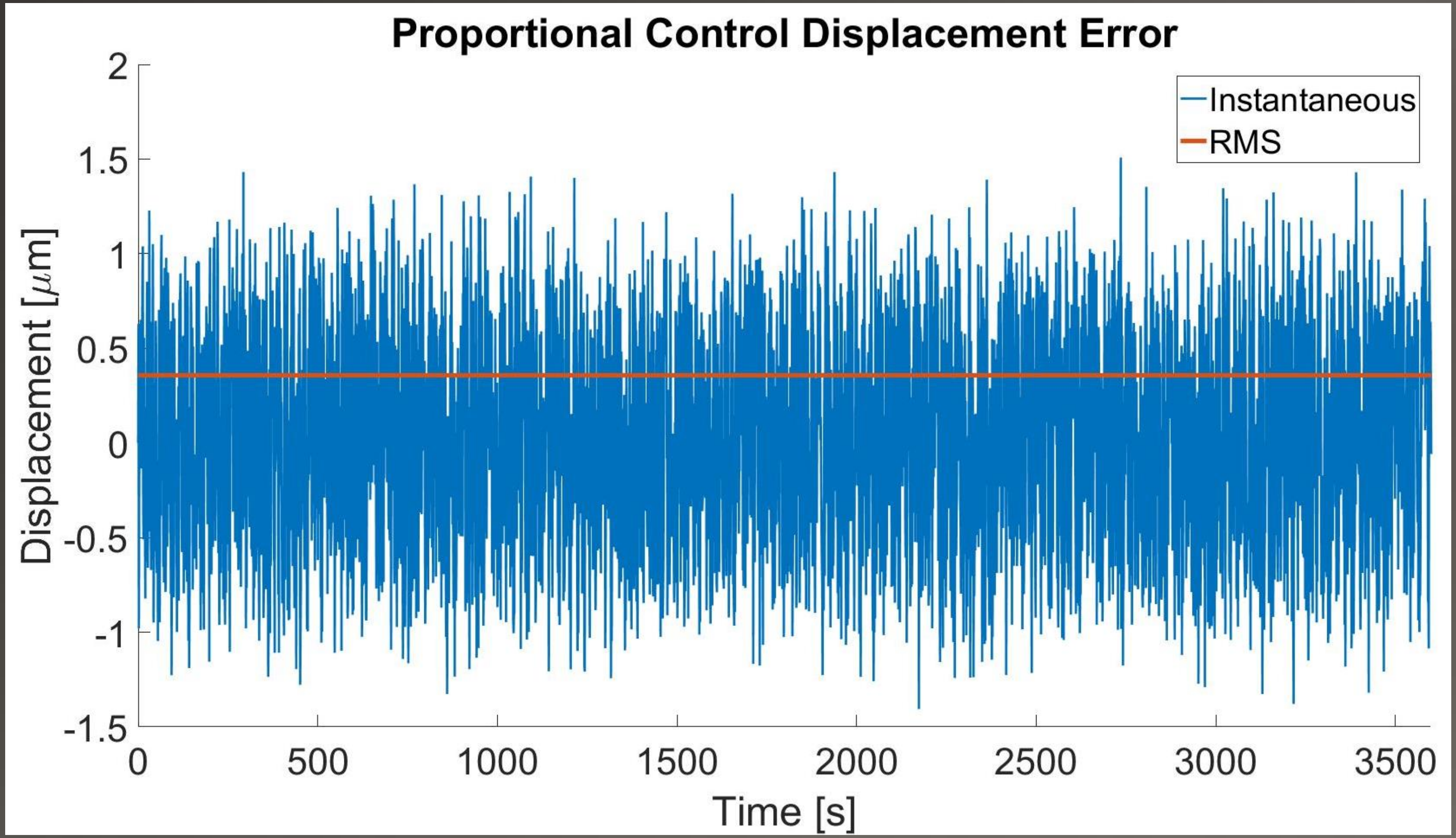


Thermistor resolution: 0.1 K
Time averaging over 20 samples

+/- 0.1 K

DR1.2, DR4.1, DR4.2
FEASIBLE

Control System Response: Alignment



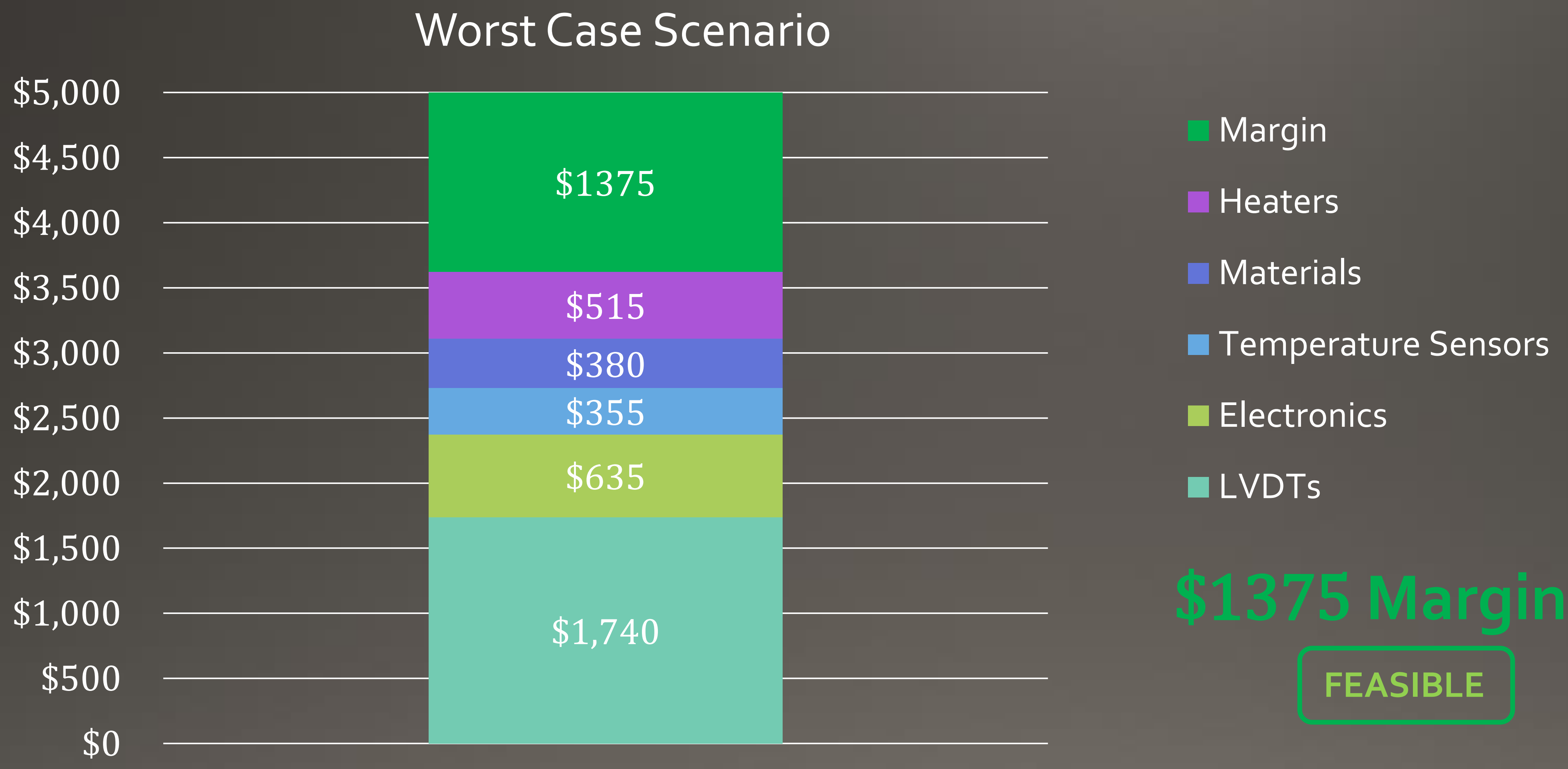
LVDT resolution: 1.6 μm

+/- 2 μm

DR1.3, DR3.1, DR3.2
FEASIBLE

Summary

Budget



$1375 Margin

FEASIBLE

Feasibility and Next Steps

	Functional Requirement	Feasibility Shown	Next Steps
FR1	The ACS shall provide **error correction** in two axes of rotation and one of translation.	Temperature sensor resolution ✓ Correction for induced error ✓ Response time ✓	• Heater and temp sensor placement • Detailed thermal model • Preliminary alignment tests
FR2	The test bed shall **introduce alignment error** to a flat mirror.	Temperature sensor resolution ✓ Introduction of alignment error ✓	• Heater and temp sensor placement • Detailed thermal model
FR3	The AMS shall **measure thermally induced alignment error**, to feed back to the ACS.	Displacement resolution ✓	• Select insulation for AMS • Define insulation locations
FR4	The software package shall provide **active control of both the ACS and testbed.**	Temperature control ✓ Alignment control ✓	• Software design of control law • LabVIEW mock up

Resources/References

- "LD620 Series Spec Sheet." (n.d.): n. pag. *High Accuracy Displacement Transducers*. Omega. Web.
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- "LVDT Tutorial." *Basics of the Linear Variable Differential Transformer (LVDT)*. TE Connectivity, n.d. Web. 10 Oct. 2016.
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- Çengel, Yunus A., and Robert H. Turner. *Fundamentals of Thermal-fluid Sciences*. Boston: McGraw-Hill, 2001. Print.
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Questions?

Directory

Backup Slides:

Backup Slides

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 $+100$ μm, with an accuracy of ± 2 μm.

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 ± 0.1K 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 and Analysis

DR1.5 The ACS shall be able to return to the mirror to its initial position ±2 μm within 120 seconds, after the mirror is exposed to a 50 μm translation 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) The ACS is activated to correct for error with the test bed held at constant temperature (± 0.1 K).

DR1.6 The ACS shall be able to return the optical element to its initial position (±20 μradians) within 60 seconds, after the mirror is exposed to 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 μradian rotation displacement is induced to the optical element in a single axis via thermal expansion of the test bed.
3) The ACS is activated to correct for error with the test bed held at constant temperature (± 0.1 K).
4) Following correction of the first axis, repeat steps 1-3 for the second axis.

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.

<u>Verification</u>: 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.

<u>Verification</u>: Inspection, 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 $\pm$ 0.1 Kelvin of the commanded temperature.

Motivation: Validation of DR1.3 and FR1

<u>Verification</u>: 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 control members, with a maximum error of ±0.5K 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: Analysis and Test

Requirements: FR2

DR2.3 The temperature of the test bench structural elements shall be known to within 0.1K 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: Inspection

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 μm.

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

Verification: Analysis and Test

DR3.2 The OAMS shall be capable of measuring at least 20 μradians of rotational displacement with a resolution of $\pm$ 10 μradians.

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 0.1K, over a 10K temperature range, with a 1% settling time of less than 120 seconds.

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: Analysis 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 Analysis

Requirements: FR4

DR4.2 The electronics package shall enable active temperature control of the ACS high CTE actuators to within 0.1K with a 1% settling time of less than 120 seconds, 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

Baseline Design

Analyzed Rod Type	Max ΔT Needed [°C]	Power Loss at SS [W]	Minimum Power Density Required [W/in²]
Magnesium (ACS)	34.15	6.18	1.91
Aluminum, Long (TDU)	10	6.48	0.63
Aluminum, Short (TDU	.59	0.07	0.05

$$Q = mc_p\Delta T$$

$$Q_{convection} = h * A_{surf} * \Delta T$$

$$Q_{radiation} = \varepsilon\sigma A_{surf}(T^4 - T_\infty^4)$$

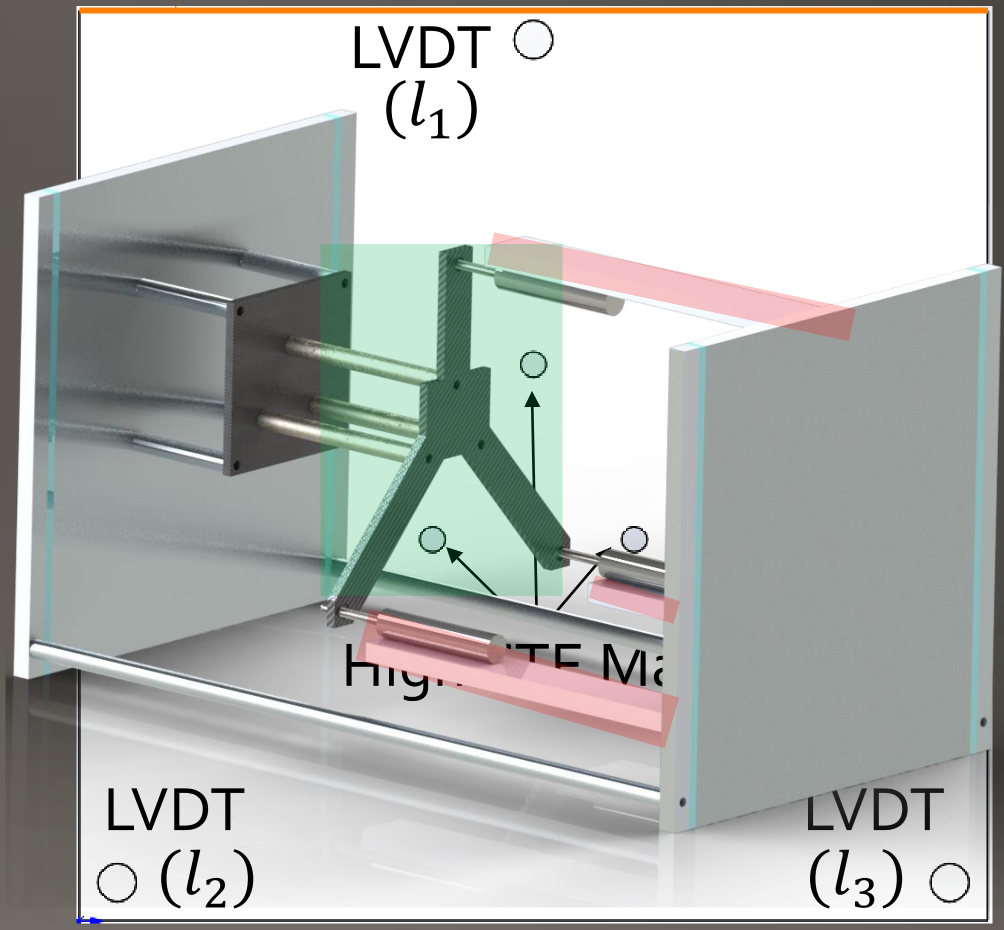
$$Q_{conduction} = kA_{cross}\left(\frac{dT}{dx}\right)$$

$$Q_{in} = Q + Q_{convection} + Q_{conduction} + Q_{radiation}$$

$$t = \frac{(Q_{in})}{\left(\frac{P}{A}\right) * (A_{surf})}$$

Alignment Measurement System (AMS)

- Three LVDTs placed on the 'mirror' as shown.
- With three distance measurements, the AMS can calculate displacement about one axis and deflection angles about two axes.
- $l_1, l_2,$ and l_3 are the distances measured by LVDT 1, 2, and 3 respectively.



Alignment Measurement System (AMS)

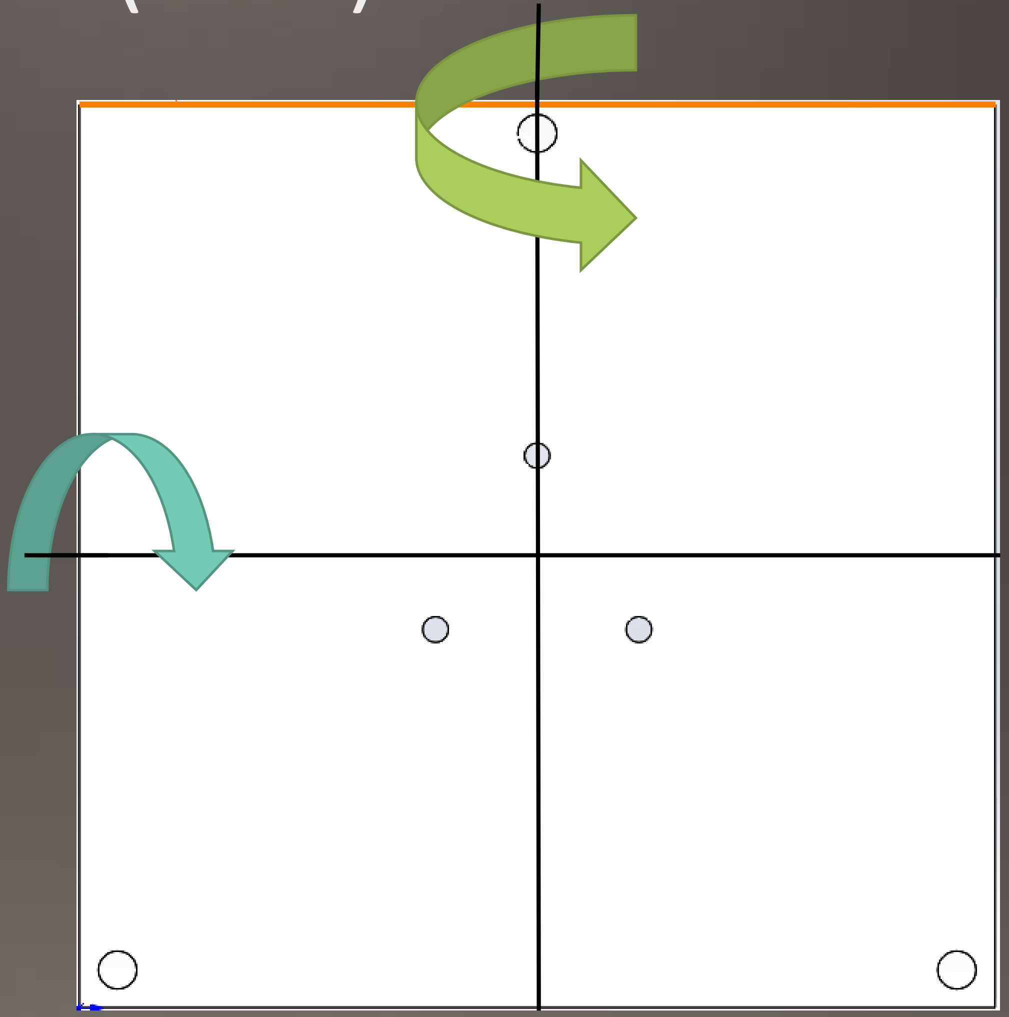
With three transducers, equations can be obtained for the displacement (δ) and two angles of deflection(α, β).

<u>Summary of Equations</u>

$$\delta = \frac{2l_1 + l_2 + l_3}{4}$$

$$\alpha = tan^{-1}(\frac{l_1 - \frac{l_2+l_3}{2}}{L})$$

$$\beta = tan^{-1}(\frac{l_3 - l_2}{L})$$



Sources of Error (AMS)

Error Source	Position Change
Cantilever Bending	1.524 µm
Linear Tilt	0.000009289 μm
Total Possible Position Change	1.524 μm

Alignment Measurement System (AMS)

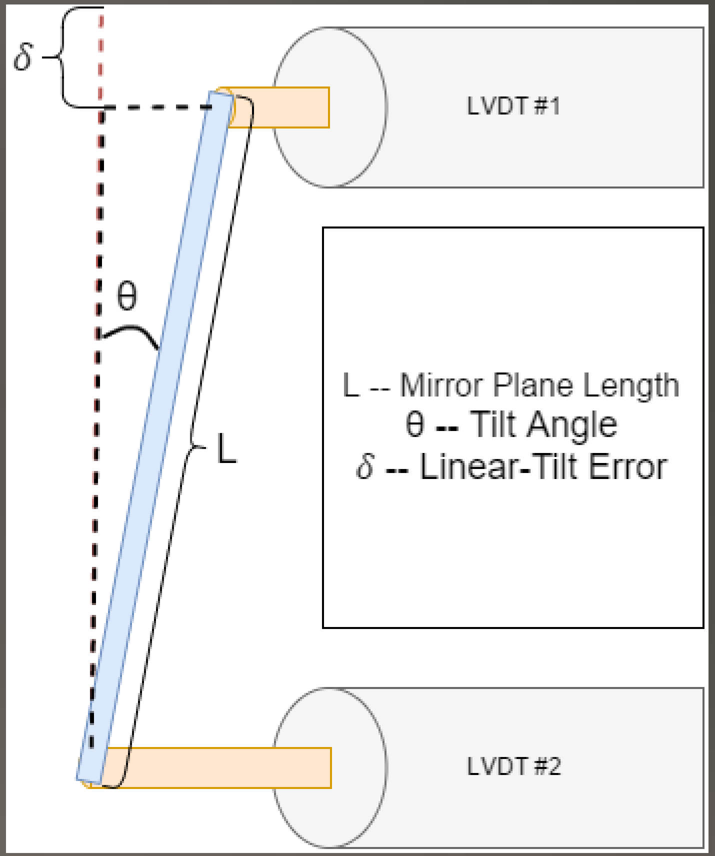
Linear-Tilt Error

- Loss in linear displacement measurement due to tilt

$$\delta = L(1 - cos\theta)$$

Set L = 9in = 22.86cm and θ = 20μrad

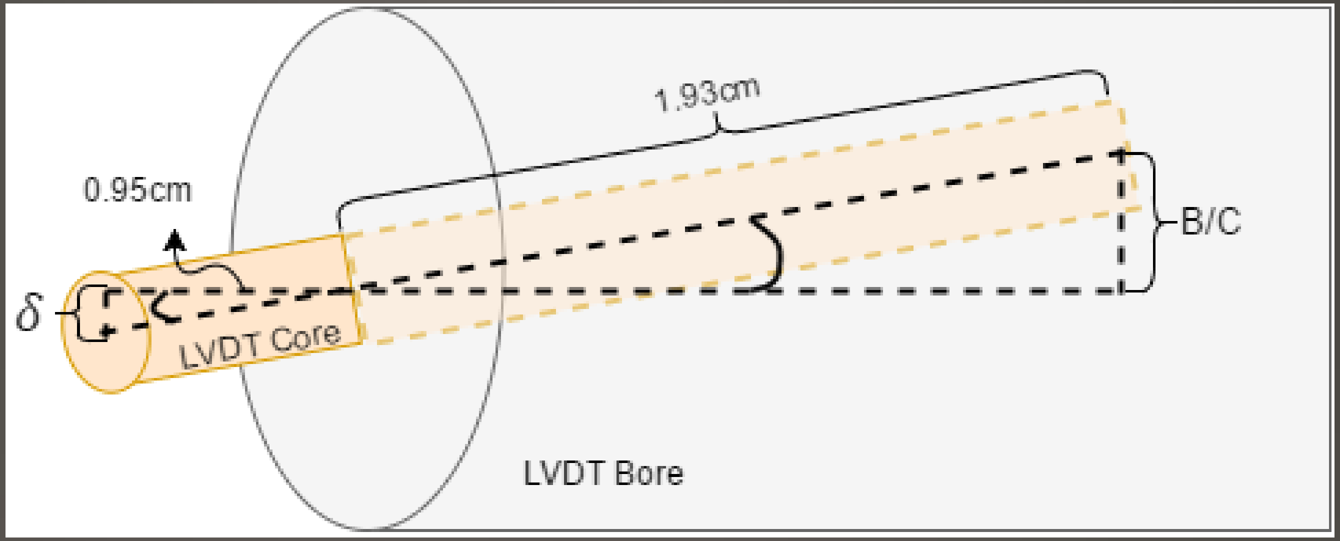
δ = 4.572e-9 cm



Alignment Measurement System (AMS)

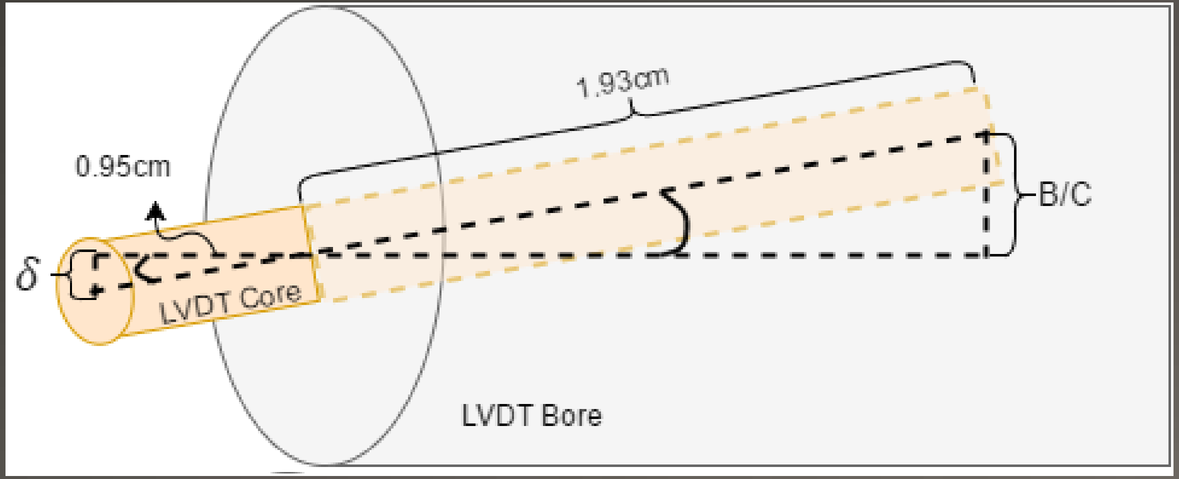
Bore to Core Clearance

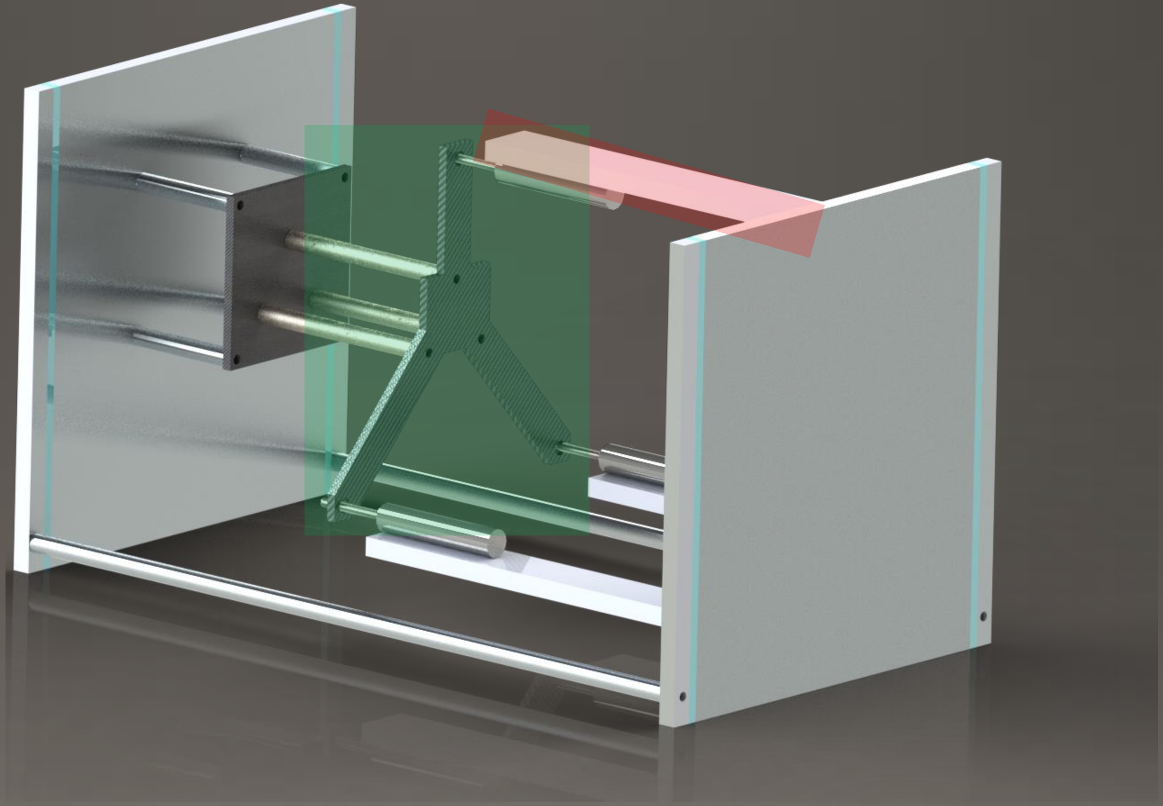
- Treat entrance to LVDT bore as fulcrum about which rotation occurs
- Worst case: full core insertion



Alignment Measurement System (AMS)

- Physical alignment errors
- Could limit operation of LVDT
  - Cantilever bending
  - Deflection induced misalignment





Alignment Measurement System (AMS)

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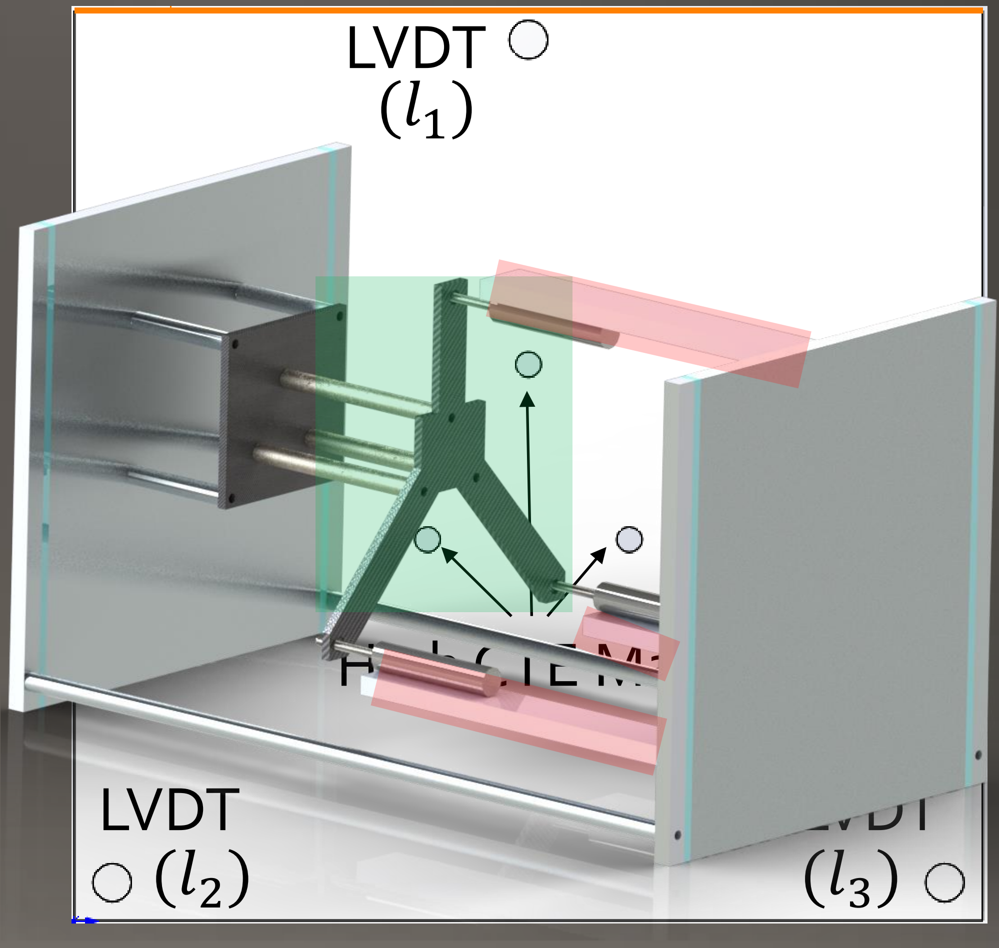
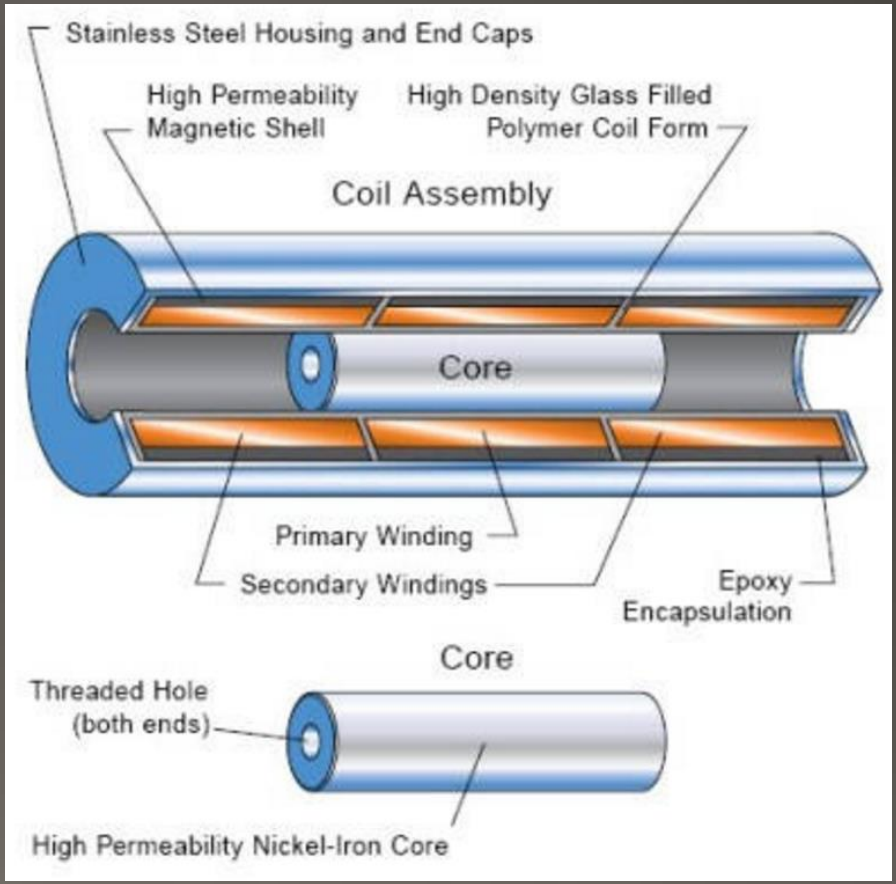
- With three distance measurements, the AMS can calculate displacement about one axis and deflection angles about two axes.
- l_1, l_2, and l_3 are the distances measured by LVDT 1, 2, and 3 respectively.



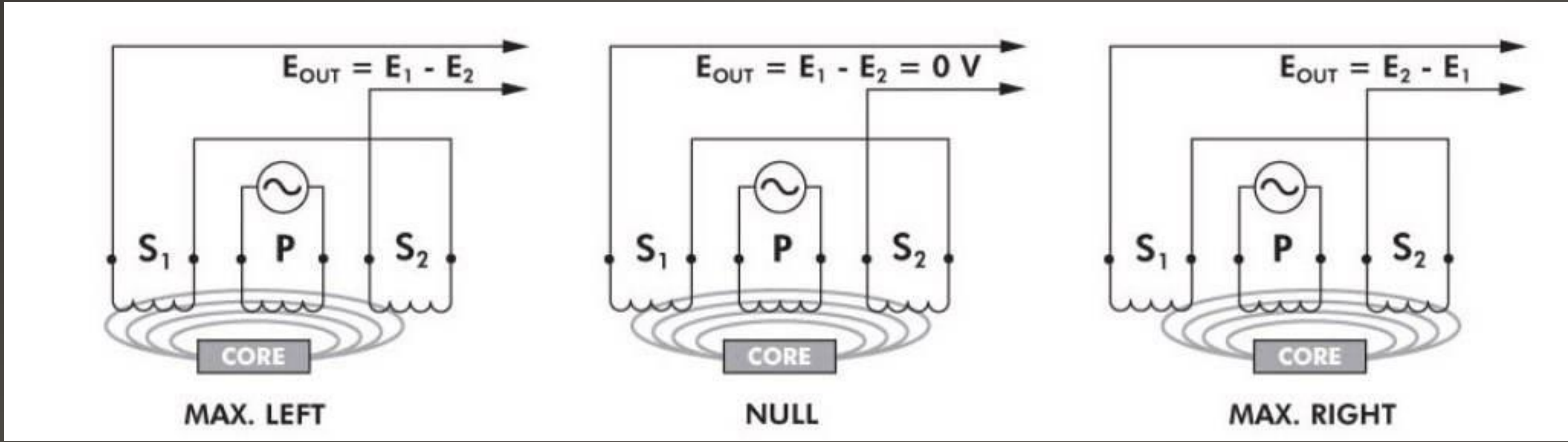
LVDT Theory: Backup

Linear Variable Differential Transformer (LVDT)

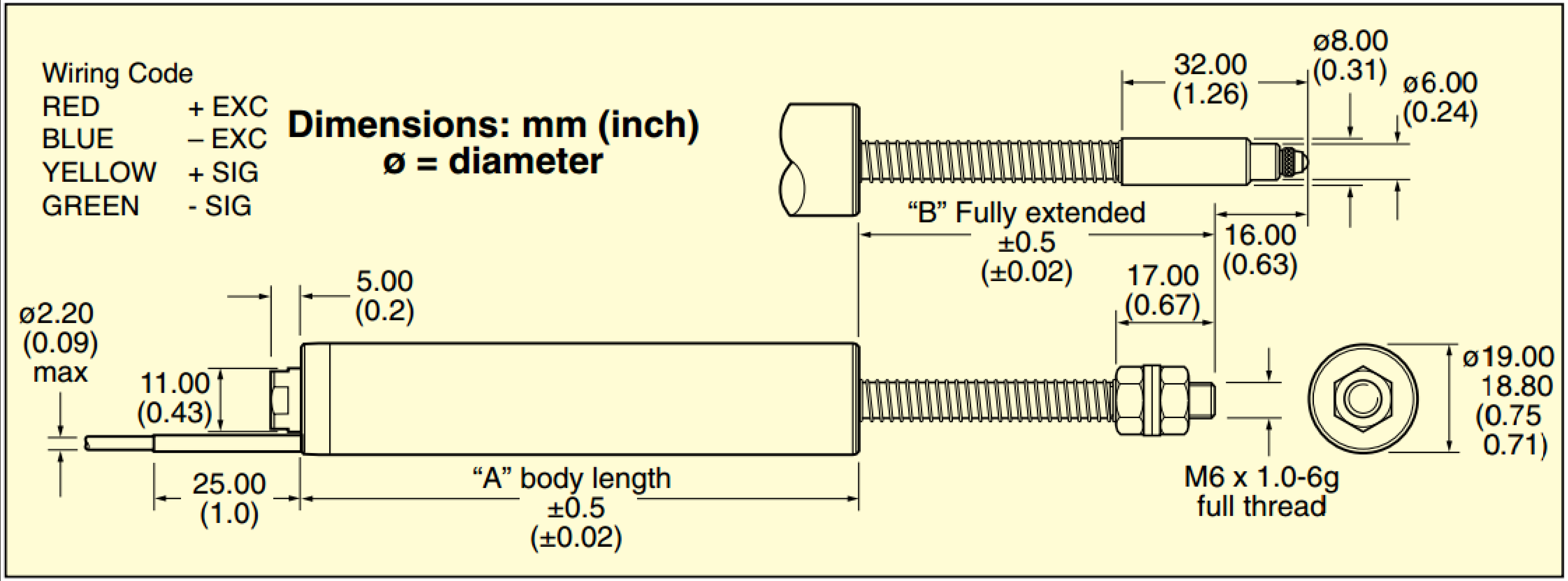
- Contains three windings: a primary and two secondary
- The primary winding receives power and generates a magnetic flux, which is then coupled to the secondary windings
- The difference in induced flux between the two secondary windings is compared, giving a corresponding output voltage



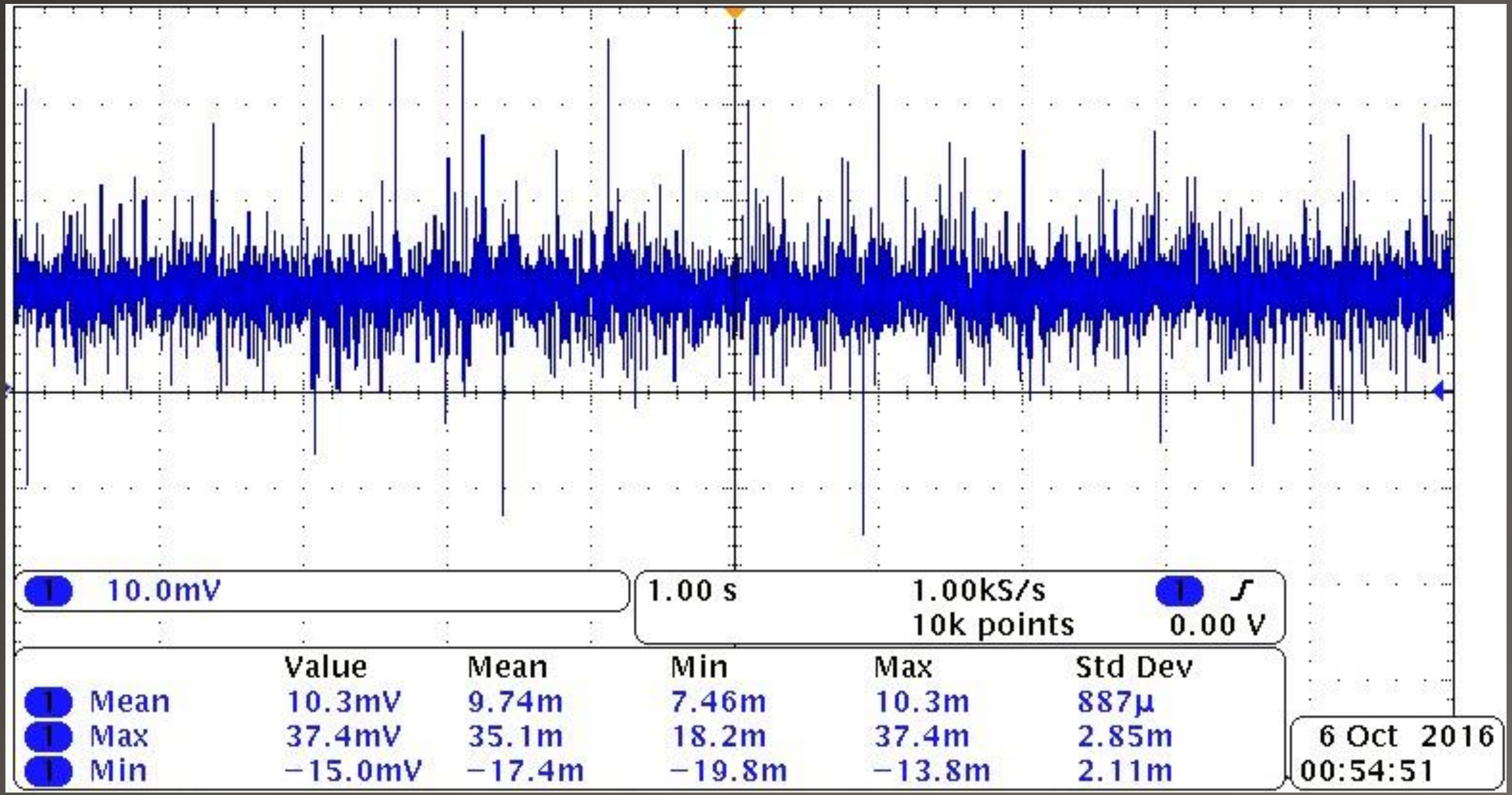
LVDT Theory: Backup



LD620-2.5 Dimensions



Electrical and Vibrational Noise Test



Static LVDT voltage readings from oscilloscope: 4 Hz low-pass RC filter applied

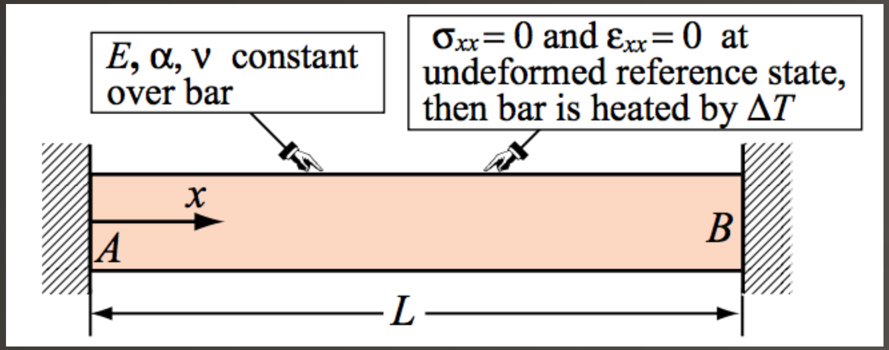
Total Range	52.5 mV
Voltage Uncertainty	+/- 26.25 mV
Position Uncertainty	+/- 13.125 µm

Does not fulfill DR3.1

Bending of Cage Mounting Plate

- Weight of cage and ACS
  - 0.511lbf
- Lever arm (bolt connection)
  - 6.25”
- Moment about Y
  - 3.14in-lbf

Thermally-Induced Bending Stress



Known Values

$$\alpha = 26.1\frac{\mu m}{m°C}$$

$$E_{Mg} = 6.38Msi$$

$$E_{carbon fiber} = 15Msi$$

$$\sigma_{minproof_{bolt}} = 85ksi$$

$$A_{rod} = 0.1963in^2$$

$$A_{bolt} = 0.049in^2$$

Equations used

$$\epsilon = \frac{\sigma}{E}$$

$$\epsilon_T = \alpha\Delta T$$

$$\sigma_{rod} = -E\alpha\Delta T$$

$$K = \frac{EA}{L}$$

$$y_{max_{plate}} = \frac{PL^2}{6EI} * (2L)$$

Calculated Values

$$F_{rod} = F_{bolt} = 327lbf$$

$$\sigma_{rod} = 1.6ksi = \frac{F_{rod}}{A_{rod}}$$

$$\sigma_{bolt} = 6.66ksi \leq 85ksi$$

$$\sigma_{bolt_{\frac{3}{8}"}} = 2.96ksi$$

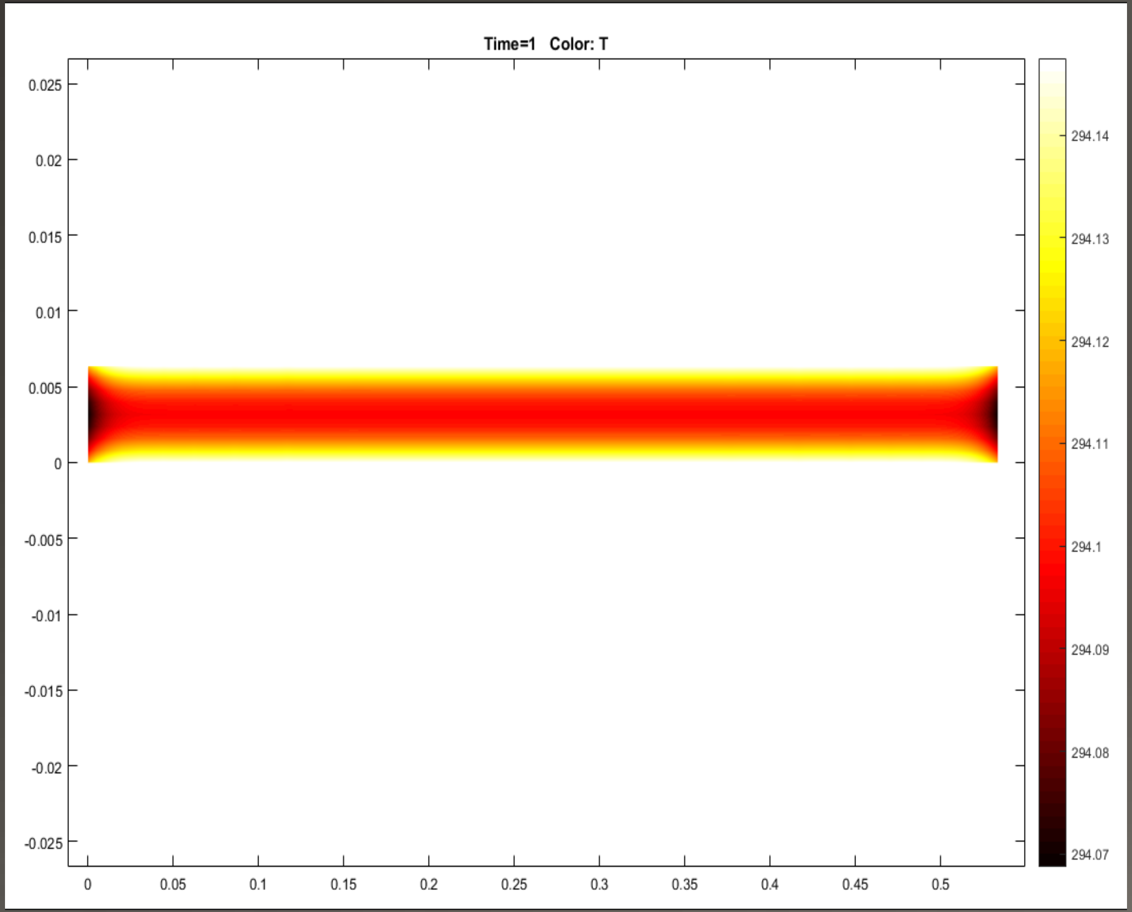
$$K_{plate} = 1,600,000\frac{lbf}{in}$$

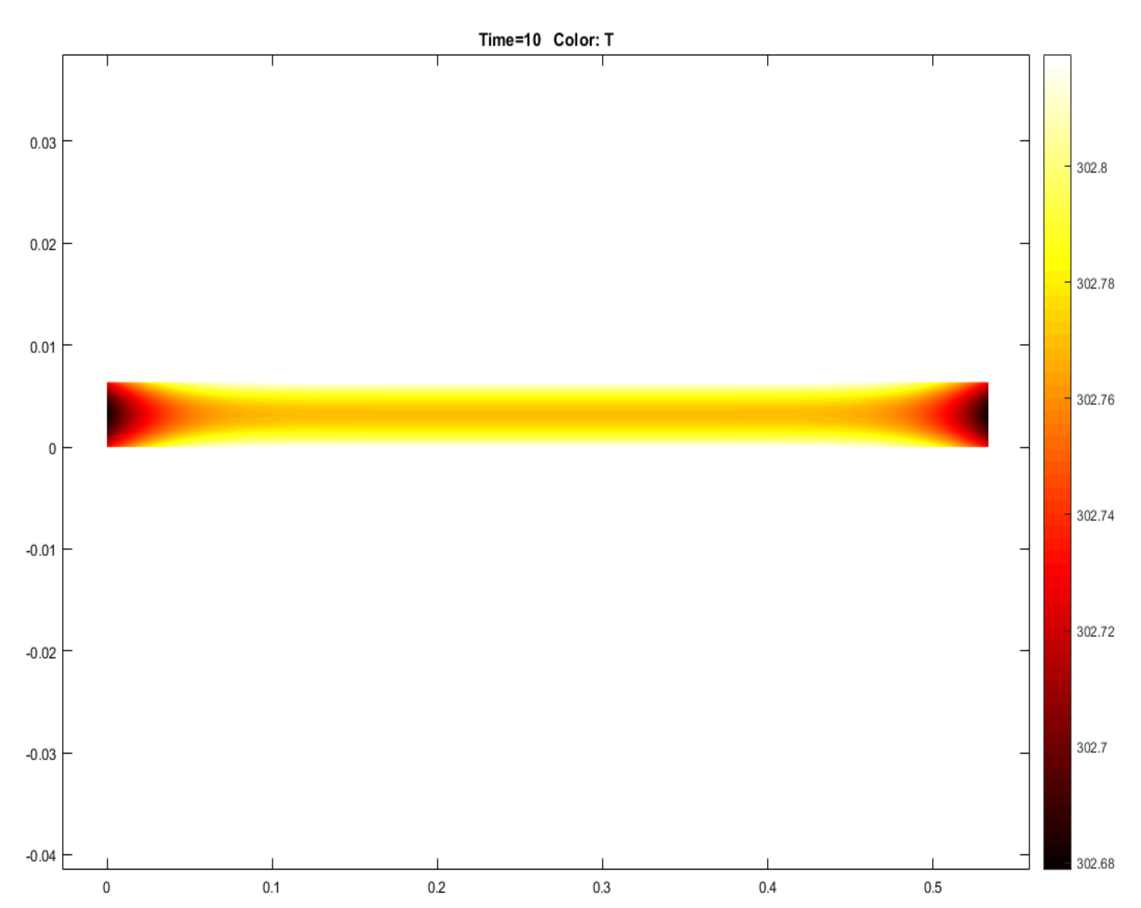
$$K_{bolt} = 770,000\frac{lbf}{in}$$

$$y_{carbon fiber} = 0.635\mu m$$

Test Bed Transient Conduction

How will the rods heat up through time?





Measurement System Trade Study Criteria 1

Criteria	Rank					Rational
	1	2	3	4	5	
Achievable Resolution [μm]	Greater than 10	5-10	1-5	0.5-1	Less than 0.5	A smaller resolution is desired
Operable Temp. Range [Degrees C]	Quartic	Triadic	Quadratic	Linear	No Drift	Higher operating temperatures may decrease the resolution or accuracy of the measurements.
Information Output	Display Only		PC connectivity only		Voltage signals	Voltage signals as output interface more readily with the data acquisition system.
Price	Greater than $5k	$1k - $5k	$500 - $1k	$1 - $500	Free	Inexpensive systems are desired.

Measurement System Trade Study Criteria 2

Criteria	Rank					Rational
	1	2	3	4	5	
Ease of Use	Not operable without professional assistance		Multiple components interacting.	Multiple components.	One component, easily set up	An easily operable systems with little set up complications is more desirable.
Design Impact	Requires significant changes in design.		Requires some changes in design.		Not dependent on design of test bed.	A measurement system which requires little change in design of the test bed is desired.
Material Limitations	Only a few materials can be used.		Only metals can be used.		Any material can be used.	Fewer material limitations are desired.

Measurement System Trade Study Results

Criteria	Weight	Eddy Current Sensors	Strain Gauges	LVD Ts	CCD Camera	Interferometer
Achievable Resolution	0.20	5	4	5	3	3-4
Operable Temp. Range	0.05	2	4	4	5	5
Information Output	0.05	5	5	5	3	5
System Price	0.30	1	5	2	2	1-5
Ease of use	0.20	4	4	4	3	4
Design Complications	0.10	3	2	3	3	1
Material Limitations	0.10	5	1	5	5	5
Weighted Total	1	3.25	3.85	3.65	3.0	2.8-3.4

Material Selection Trade Study

Material	CTE Value (µm/m°C)	Thermal Conductivity (W/mK)	Cost	Machine Ability	Structural Rigidity
Aluminum 6061	23.6	167	$3.08	Easy	Common structural support material
Magnesium AZ31B	26	96	$6.80	Hard	Used often in automotive parts
Zinc	31.2	112.2	$29.92	Very Difficult	Very malleable and not cast
Delrin	1-167	~0.85	$1.55	Easy	Similar structural traits to aluminum
Teflon	100	~0.9	$7.35	Hard	Very soft and easily deformed

Insulation Options

- Ceramics
  - Custom fit ceramic insulation sleeves from Zircar Ceramics
    - Custom machined to fit part in question
    - Expensive with prices from $400 - $700 for the material alone
- Kevlar (Other plastic insulators)
  - High heat resistance to be used around heating devices
  - Low thermal conductivity values

Max Stress in Bolts

$$W_{cant} = 0.773 lbs$$

$$W_{LVDT} = 0.223 lbs$$

$$\sum M_A = \frac{3}{2} L_{cant} W_{cant} - \frac{3L_{cant}}{4} W_{cant} - \frac{L_{rod}}{2} W_{rod}$$

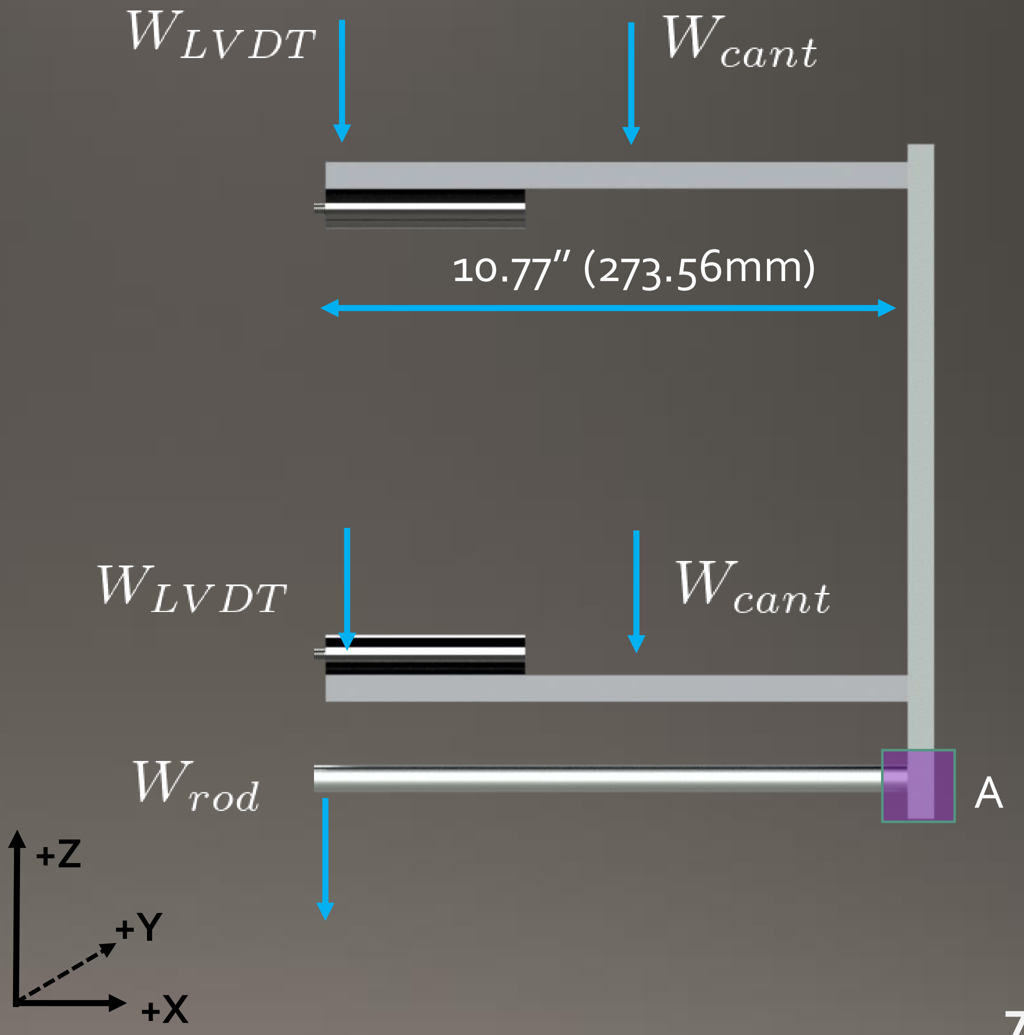
$$\sum M_A = -11.80 in - lbs$$

- For worst case, assume mounting plate is offset from vertical by 10 degrees

$$\sum M_{A\,max} = -33.34 in - lbs$$

$$\sigma_{bolt\,max} = \frac{M}{Z_{bolt}}, Z_{bolt} = 0.00153 in^3$$

$$\sigma_{bolt\,max} = 21.8 ksi \leq 85 ksi$$



Temperature Sensor Trade Study Criteria

Criteria	Rank					Rational
	1	2	3	4	5	
Accuracy	Greater than 1K	1-0.5K	0.5-0.2K	0.2-0.1K	0.1K or Less	Accuracy is derived from requirement DR2.3
Linearity at 23-33°C	Quartic	Triadic	Quadratic	Linear	No Drift	Linearity is analogous to how easy it will be to correct for inaccuracies over the desired range.
Long Term Stability	Greater than 0.2K per year	0.2-0.1K	0.1-0.005K	0.005-0.001K	Less than 0.001K	Stability is necessary as experiments will be run over the course of several hours and over several days. Constant recalibration is a drain on time and monetary resources.

Temperature Sensor Trade Study Results

Criteria	Weight	Thermocouples	RTD's	Thermistors
Accuracy	0.65	1	4	5
Linearity	0.30	3	4.5	3
Long Term Stability	0.05	5	4	5
Weighted Total	1	1.8	4.15	4.4

LTC2983-Thermistor Accuracy System Feasibility

LTC2983 Data Sheet

Table 51. Thermistor Type: $1/T = A + B \bullet \ln(R) + C \bullet \ln(R)^2 + D \bullet \ln(R)^3 + E \bullet \ln(R)^4 + F \bullet \ln(R)^5$

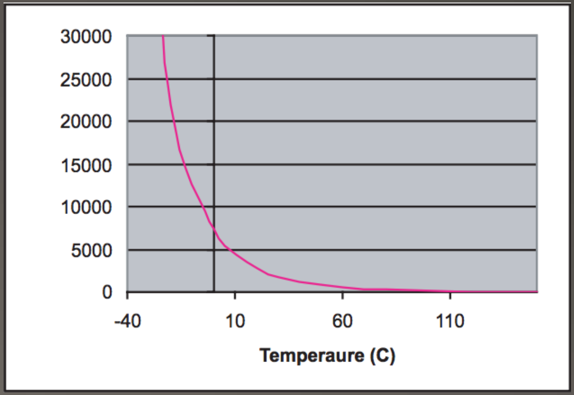
B31	B30	B29	B28	B27	THERMISTOR TYPE	A	B	C	D	E	F
1	0	0	1	1	Thermistor 44004/44033 2.252kΩ at 25°C	1.46800E-03	2.38300E-04	0	1.00700E-07	0	0
1	0	1	0	0	Thermistor 44005/44030 3kΩ at 25°C	1.40300E-03	2.37300E-04	0	9.82700E-08	0	0
1	0	1	0	1	Thermistor 44007/44034 5kΩ at 25°C	1.28500E-03	2.36200E-04	0	9.28500E-08	0	0
1	0	1	1	0	Thermistor 44006/44031 10kΩ at 25°C	1.03200E-03	2.38700E-04	0	1.58000E-07	0	0

OMEGA Thermistor Data Sheet

$1/T = A + B [\ln(R)] + C [\ln(R)]^3$

Table 1: Steinhart-Hart Constants

Model Number	Model Number	R25°C	A	B	C
44004	44033	2252	1.468×10^{-3}	2.383×10^{-4}	1.007×10^{-7}
44005	44030	3000	1.403×10^{-3}	2.373×10^{-4}	9.827×10^{-8}
44007	44034	5000	1.285×10^{-3}	2.362×10^{-4}	9.285×10^{-8}
44006	44031	10000	1.032×10^{-3}	2.387×10^{-4}	1.580×10^{-7}
44008	44032	30000	9.376×10^{-4}	2.208×10^{-4}	1.276×10^{-7}



LTC2983-Thermistor Accuracy System Feasibility

Table 1. LTC2983 Error Contribution and Peak Noise Errors

SENSOR TYPE	TEMPERATURE RANGE	ERROR CONTRIBUTION	PEAK-TO-PEAK NOISE
Type K Thermocouple	–200°C to 0°C 0°C to 1372°C	±(Temperature • 0.23% + 0.05)°C ±(Temperature • 0.12% + 0.05)°C	±0.08°C
Type J Thermocouple	–210°C to 0°C 0°C to 1200°C	±(Temperature • 0.23% + 0.05)°C ±(Temperature • 0.10% + 0.05)°C	±0.07°C
Type E Thermocouple	–200°C to 0°C 0°C to 1000°C	±(Temperature • 0.18% + 0.05)°C ±(Temperature • 0.10% + 0.05)°C	±0.06°C
Type N Thermocouple	–200°C to 0°C 0°C to 1300°C	±(Temperature • 0.27% + 0.08)°C ±(Temperature • 0.10% + 0.08)°C	±0.13°C
Type R Thermocouple	0°C to 1768°C	±(Temperature • 0.10% + 0.4)°C	±0.62°C
Type S Thermocouple	0°C to 1768°C	±(Temperature • 0.10% + 0.4)°C	±0.62°C
Type B Thermocouple	400°C to 1820°C	±(Temperature • 0.10%)°C	±0.83°C
Type T Thermocouple	–250°C to 0°C 0°C to 400°C	±(Temperature • 0.15% + 0.05)°C ±(Temperature • 0.10% + 0.05)°C	±0.09°C
External Diode (2 Reading)	–40°C to 85°C	±0.25°C	±0.05°C
External Diode (3 Reading)	–40°C to 85°C	±0.25°C	±0.2°C
Platinum RTD - PT-10, R_{SENSE} = 1kΩ Platinum RTD - PT-100, R_{SENSE} = 2kΩ Platinum RTD - PT-500, R_{SENSE} = 2kΩ Platinum RTD - PT-1000, R_{SENSE} = 2kΩ	–200°C to 800°C –200°C to 800°C –200°C to 800°C –200°C to 800°C	±0.1°C ±0.1°C ±0.1°C ±0.1°C	±0.05°C ±0.05°C ±0.02°C ±0.01°C
Thermistor, R_{SENSE} = 10kΩ	–40°C to 85°C	±0.1°C	±0.01°C

DR2.3
FEASIBLE

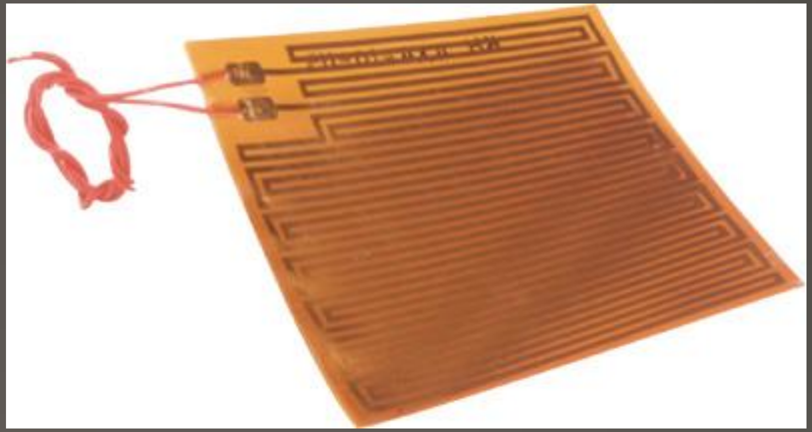
83

Heaters

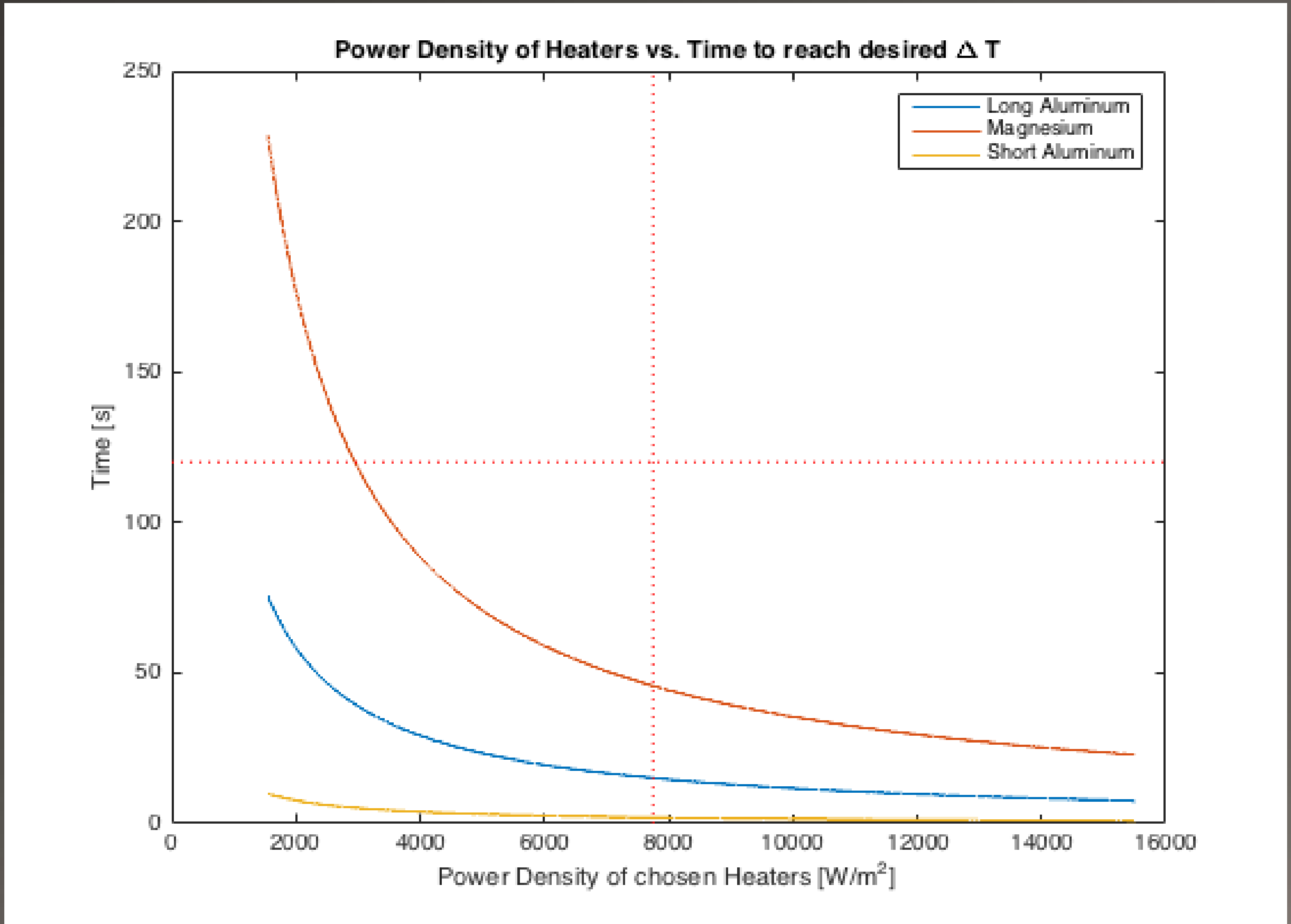
Example of Standard Patch Heater

Kapton KHLV-101/5

- Malleable construction
- 1.55 W/cm² Wattage Density
- Rated to 200°C
- Maximum thickness of 0.01 in
- Cost $36.50 each



Heaters

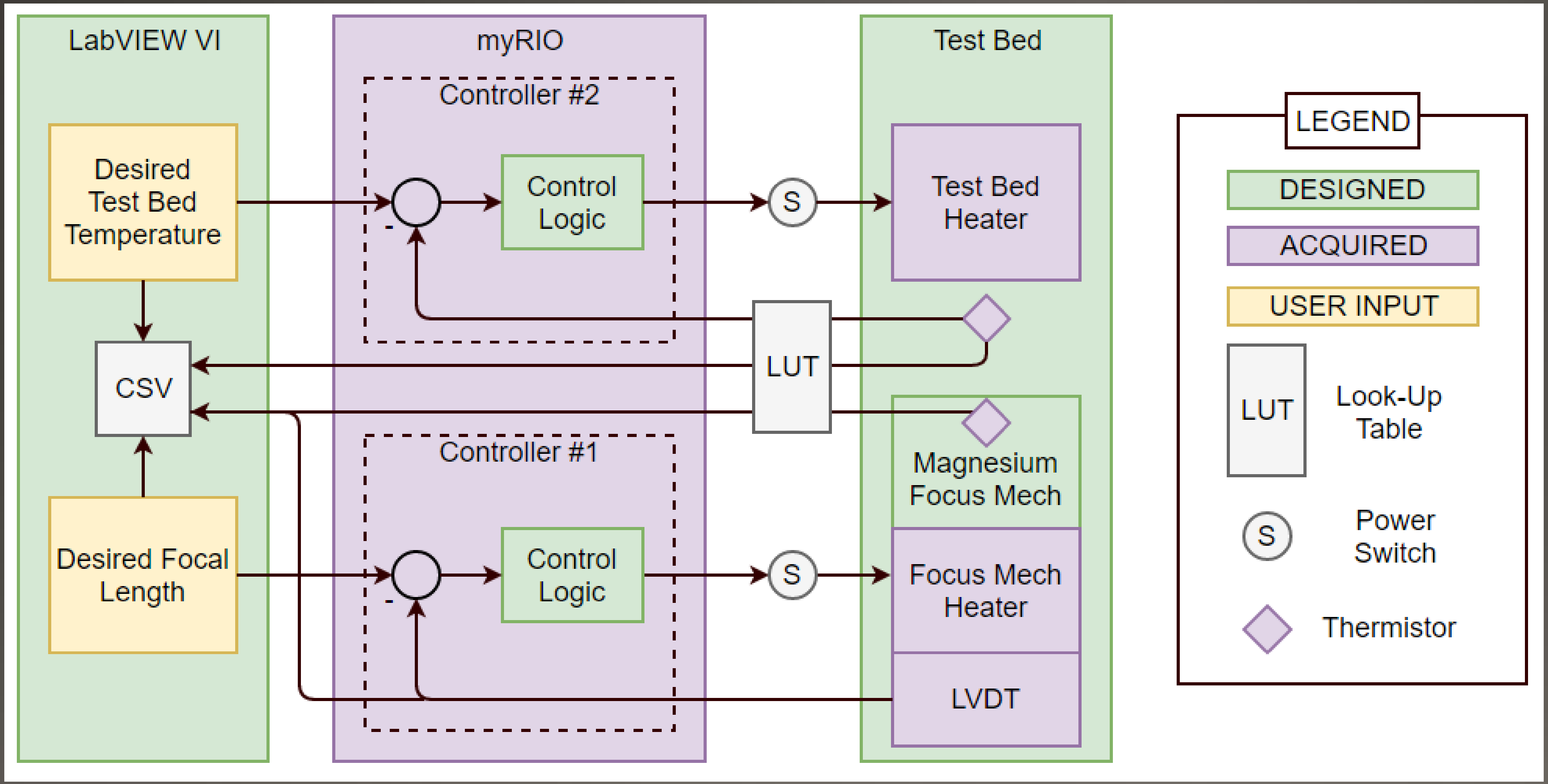


- What type of Power do we need?

Power Budget

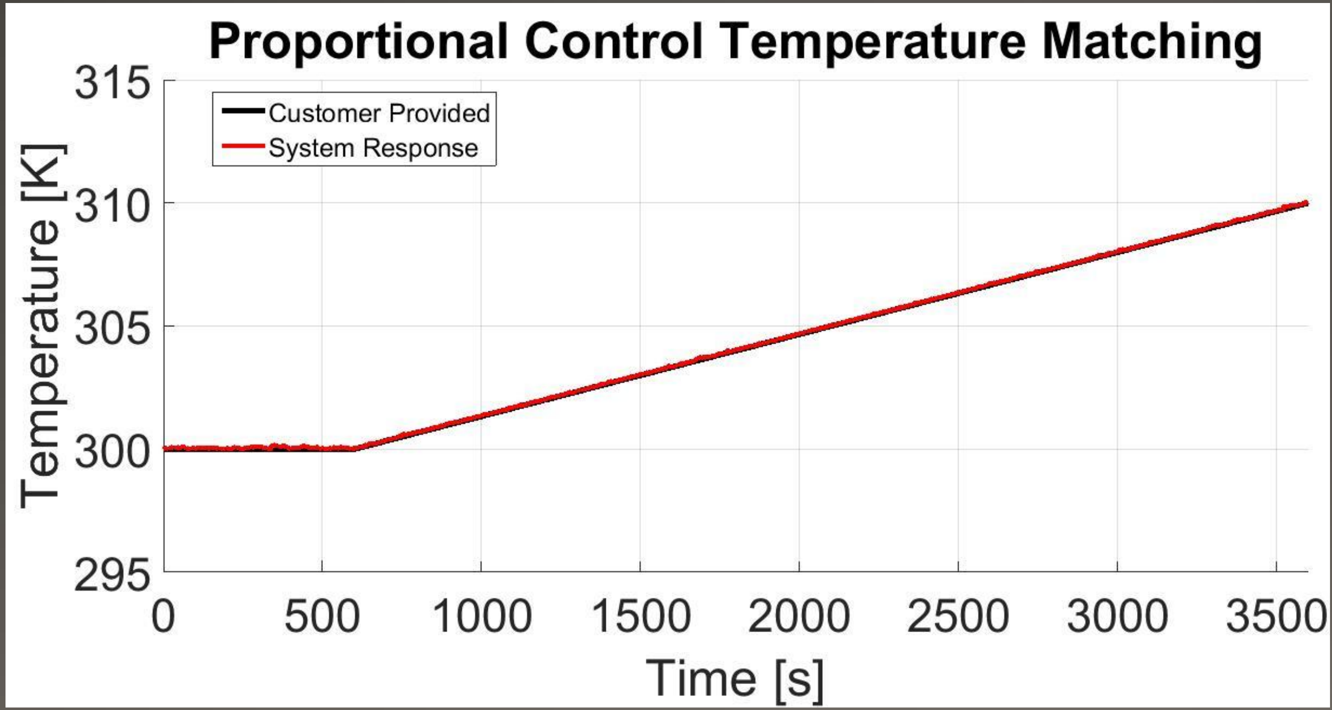
Component	Power [W]
Heaters	526.23
LTC 2983	1
LVDT's	3
myRIO	14
Total	**544.23**

Control System: Functional Block Diagram



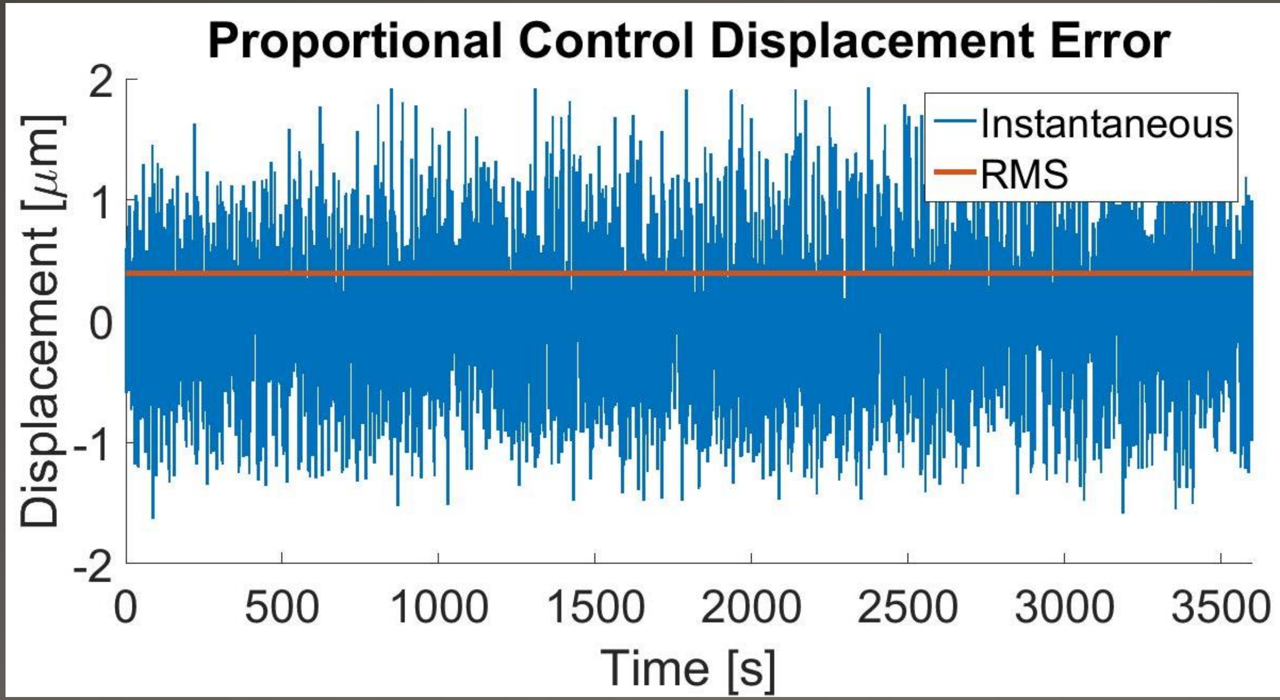
Temperature Matching: 5% Predicted Heat Loss

- Heaters are wrapped around aluminum and magnesium rods, potentially providing insulation (simulation run at 95% insulation)



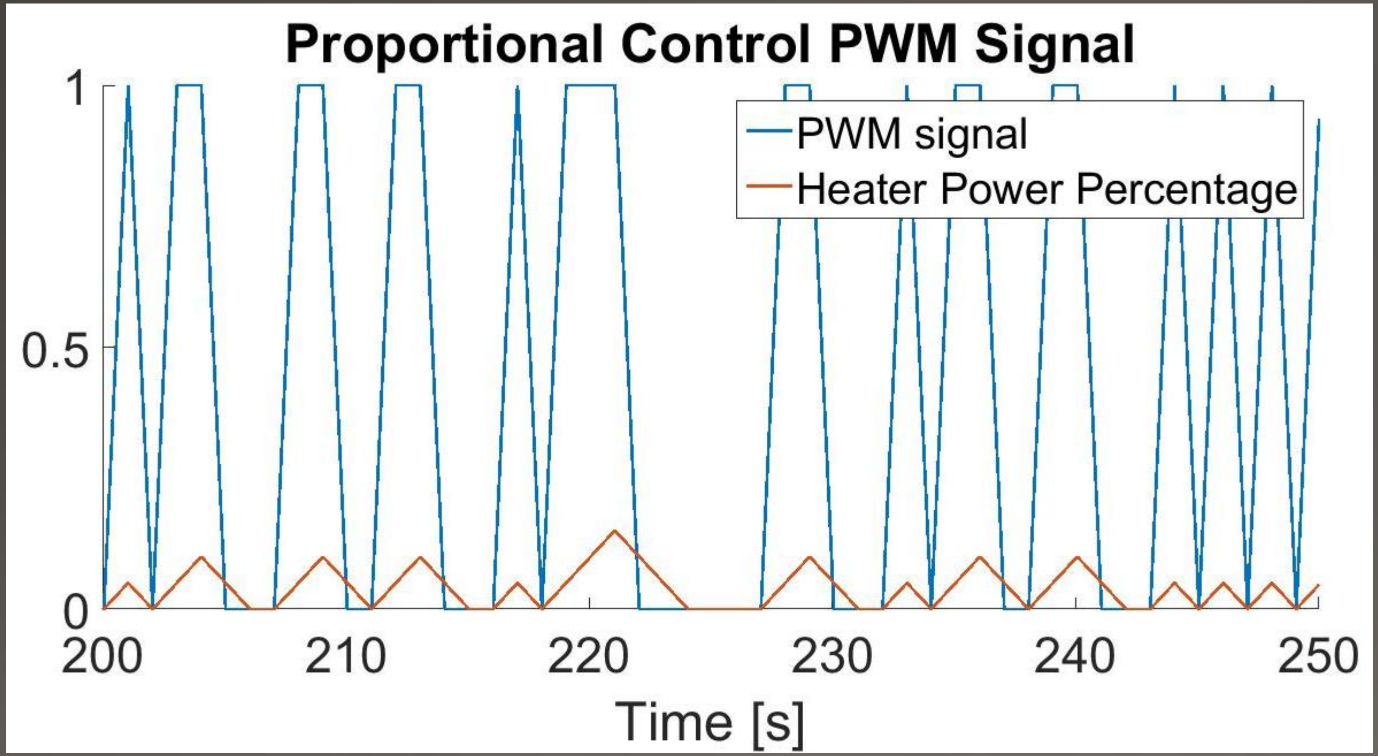
Displacement: 5% Predicted Heat Loss

- Heaters are wrapped around aluminum and magnesium rods, potentially providing insulation (simulation run at 95% insulation)



PWM Signal

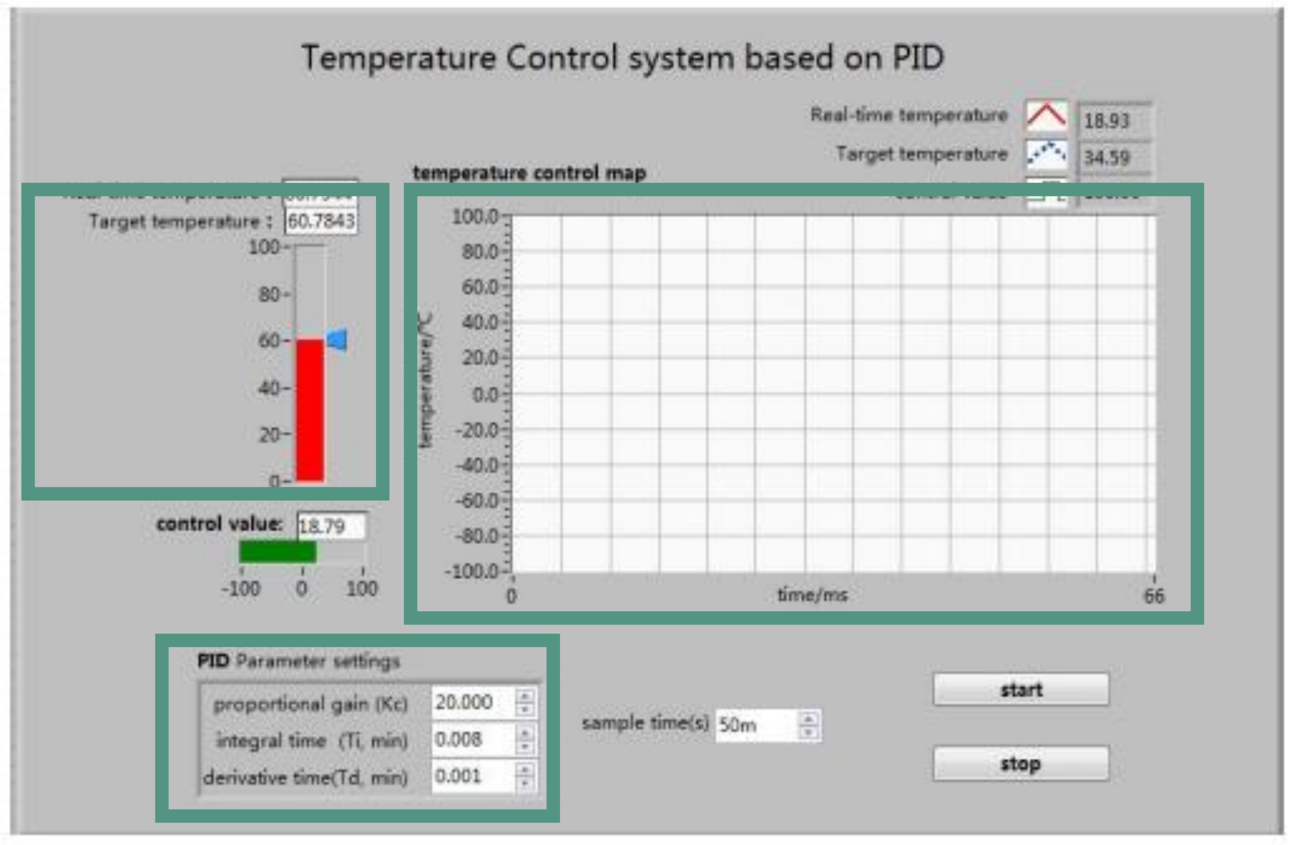
- Heater warm-up and cool-down profiles monitored as linear functions (i.e. heater can gain/lose 5% power per second)



LabVIEW VI Mockup: Backup

Control Input

PID or Digital Logic Parameters



Graphical Display
(Data also saved to CSV)

91

Budget Breakdown

Materials

Category	Cost
Aluminum Rods	$20.00
Aluminum Plates	$100.00
Magnesium Rods	$11.00
Carbon Fiber Plate	$200.00
Shipping	$50.00
Total	**$381.00**

Heaters

Category	Cost
4x KH-208	$200.00
3x KH-205	$135.00
4x KH-203	$160.00
Shipping	$20.00
Total	**$515.00**

LVDTs

Category	Cost
3x LD-620-2.5	$1,710.00
Shipping	$30.00
Total	**$1,740.00**

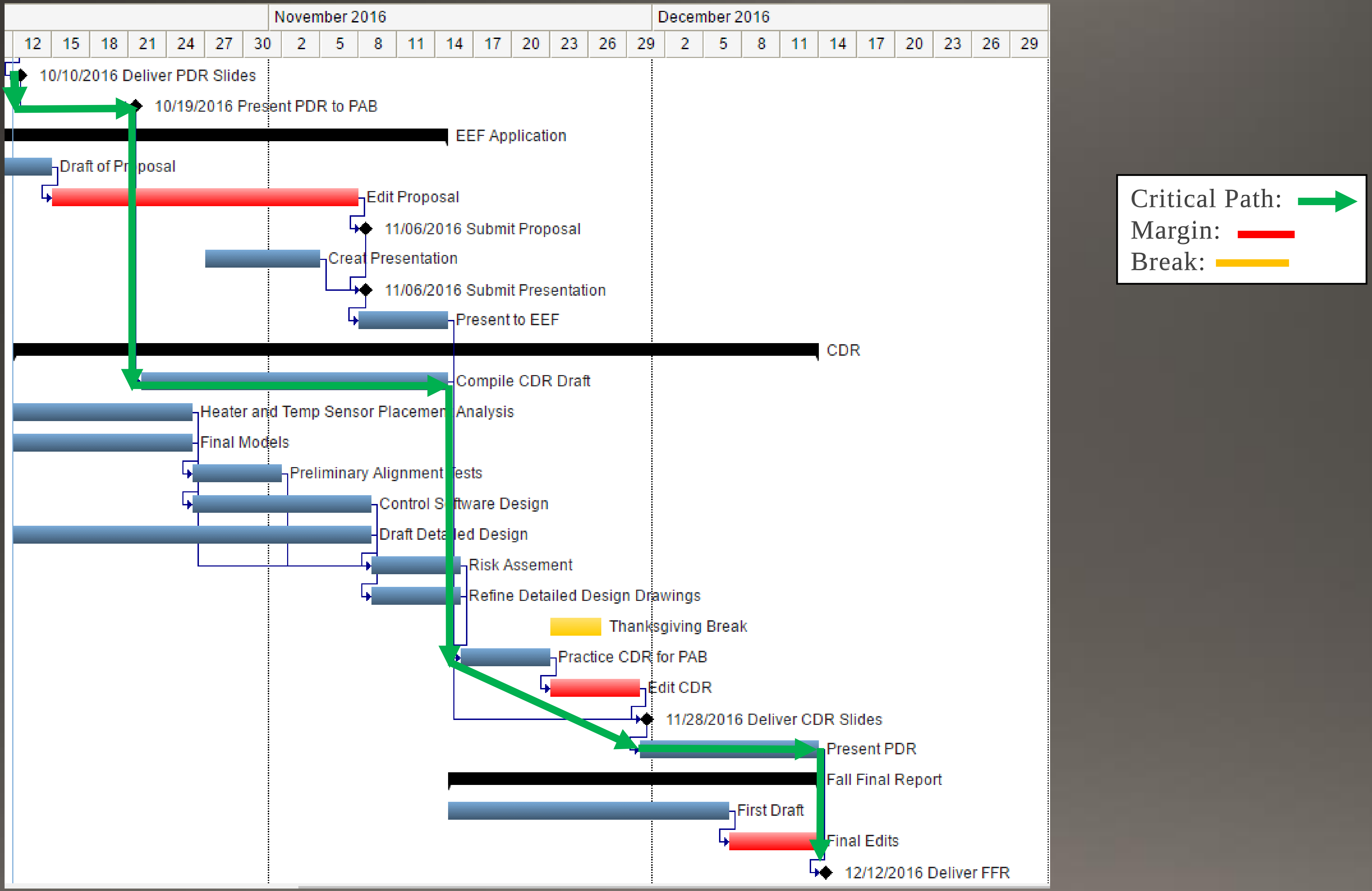
Electronics

Category	Cost
MyRio	$500.00
NI Breakout Board	$62.00
Advanced Circuits PCB	$33.00
TI 16 bit ADC	$10.00
Shipping	$30.00
Total	**$635.00**

Temperature Sensors

Category	Cost
LTC2983 x 12	$335.00
Shipping	$20.00
Total	**$355.00**

Schedule


November 2016
December 2016
12 15 18 21 24 27 30 2 5 8 11 14 17 20 23 26 29 2 5 8 11 14 17 20 23 26 29
10/10/2016 Deliver PDR Slides
10/19/2016 Present PDR to PAB
EEF Application
Draft of Proposal
Edit Proposal
11/06/2016 Submit Proposal
Creat Presentation
11/06/2016 Submit Presentation
Present to EEF
CDR
Compile CDR Draft
Heater and Temp Sensor Placement Analysis
Final Models
Preliminary Alignment Tests
Control Software Design
Draft Detailed Design
Risk Assement
Refine Detailed Design Drawings
Thanksgiving Break
Practice CDR for PAB
Edit CDR
11/28/2016 Deliver CDR Slides
Present PDR
Fall Final Report
First Draft
Final Edits
12/12/2016 Deliver FFR
Critical Path:
Margin:
Break: