Critical Design Review

Pulsed Plasma Thruster Test Stand

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Mentor: Dr. Justin Little

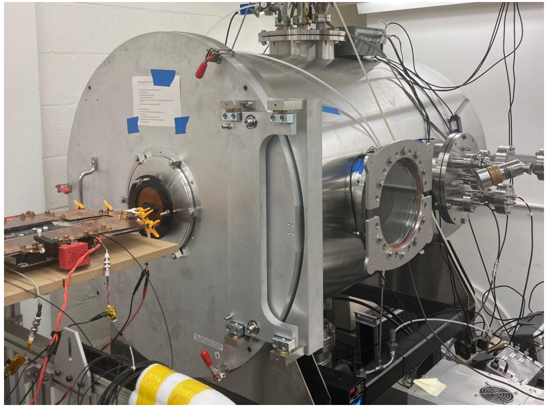
Agenda

NC

- **Motivation and Objective**
- System Overview
  - CONOPS
  - Functionality
  - Requirements
  - Architecture
- Subsystems
  - Chamber Interface
  - Leveling System
  - Thrust Measurement
  - PPT Mount
  - Data Analysis
- Budget Evaluation, Risk Assessment, & Next Steps
- Conclusion

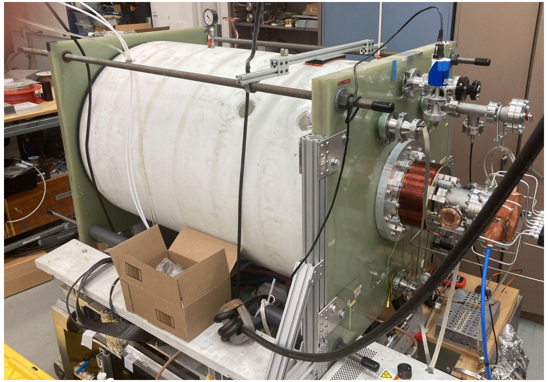
Mission Overview: Motivation

- The SPACE Lab recently acquired a **new vacuum chamber** from the Earth and Space Sciences department.
- Lab staff have designated it to be used for the purposes of characterizing **pulsed plasma thruster (PPT) performance.**
- **A new test stand** must be designed that can be integrated into both the new chamber and a pre-existing composite chamber.



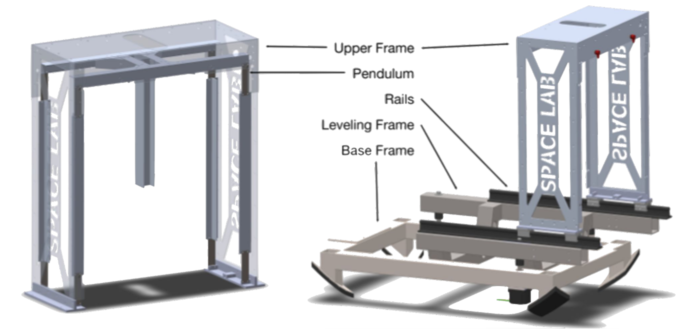
Above: New vacuum chamber (VC-01)

Below: Composite Chamber (VC-02)

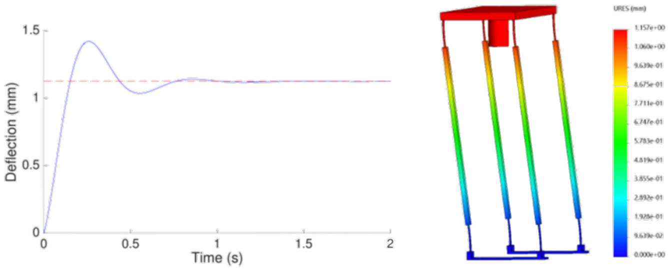


Mission Overview: What is a Test Stand?

- In electric propulsion applications, test stands are used to **measure micro quantities of thrust**
  - The limited thrust of electric propulsion systems means that the stand must **resolve deflections of 0.00118-0.197 in,** to measure impulses ranging from 2.25 μlbf*s to 22.5 mlbf*s (10 μN*s to 100 mN*s)
- Inverted pendulums are particularly useful for resolving extremely low thrusts, as the force of gravity acting on its center of mass **increases the stand's measurable deflection** for a given impulse



Pendulum Impulse Deflection



Pendulum Impulse Deflection

Image Credit: [1]

Mission Objective

NC, FC, AD, BF, LL, KLV, WW

To design and build an **operational, minimally conductive, inverted pendulum test stand** for the University of Washington’s SPACE Lab with the ability to accurately **resolve impulses from pulsed plasma thrusters from 2.25 μlbf*s to 22.5 mlbf*s** (10 μN*s to 100 mN*s) and with the capacity to **accommodate a variety of thruster dimensions and masses**

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CONOPS (1/3)

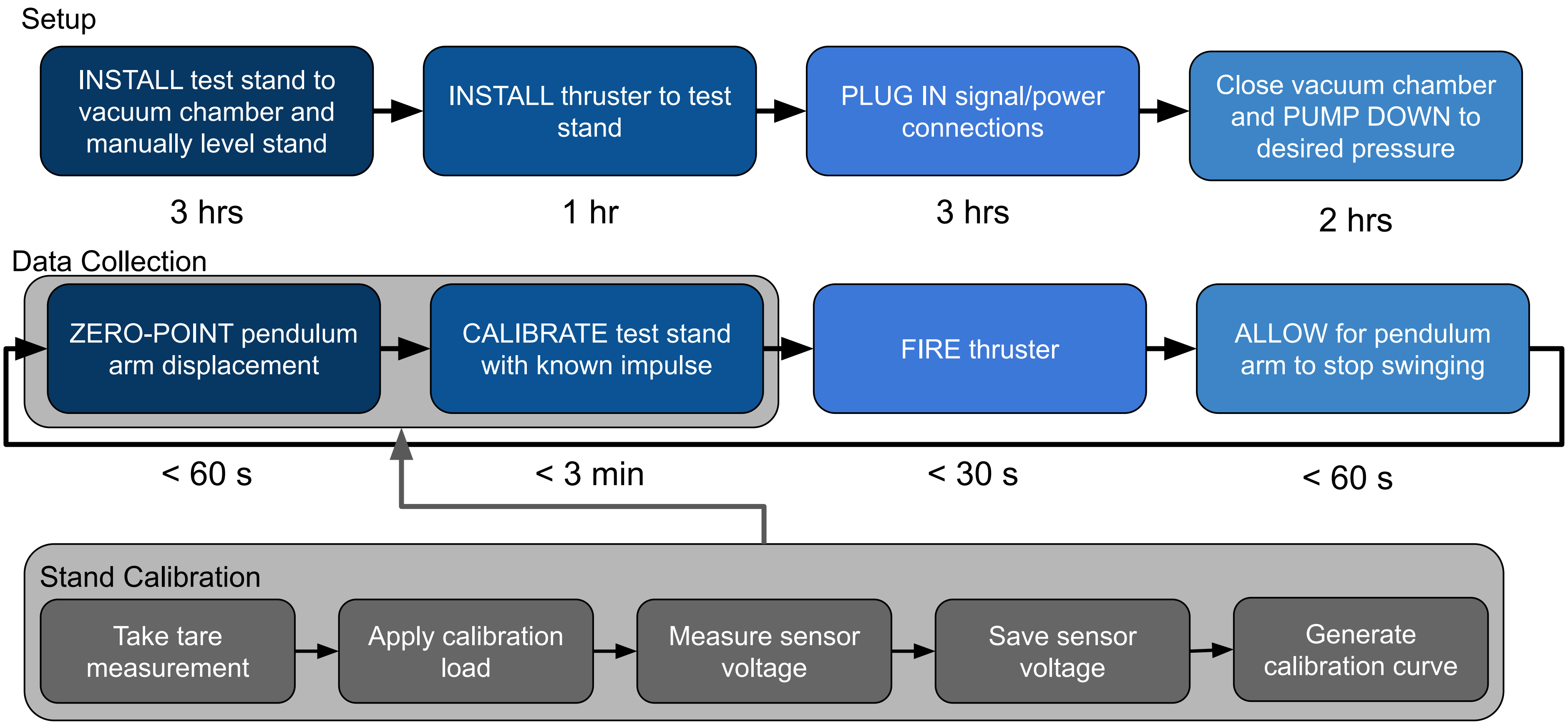
NC

Setup

1. INSTALL test stand to vacuum chamber and manually level stand → 3 hrs
2. INSTALL thruster to test stand → 1 hr
3. PLUG IN signal/power connections → 3 hrs
4. Close vacuum chamber and PUMP DOWN to desired pressure → 2 hrs

CONOPS (2/3)

NC


Setup
INSTALL test stand to vacuum chamber and manually level stand
3 hrs
INSTALL thruster to test stand
1 hr
PLUG IN signal/power connections
3 hrs
Close vacuum chamber and PUMP DOWN to desired pressure
2 hrs
Data Collection
ZERO-POINT pendulum arm displacement
< 60 s
CALIBRATE test stand with known impulse
< 3 min
FIRE thruster
< 30 s
ALLOW for pendulum arm to stop swinging
< 60 s
Stand Calibration
Take tare measurement
Apply calibration load
Measure sensor voltage
Save sensor voltage
Generate calibration curve

CONOPS (3/3)

NC

Setup

1. INSTALL test stand to vacuum chamber and manually level stand — 3 hrs
2. INSTALL thruster to test stand — 1 hr
3. PLUG IN signal/power connections — 3 hrs
4. Close vacuum chamber and PUMP DOWN to desired pressure — 2 hrs

Data Collection

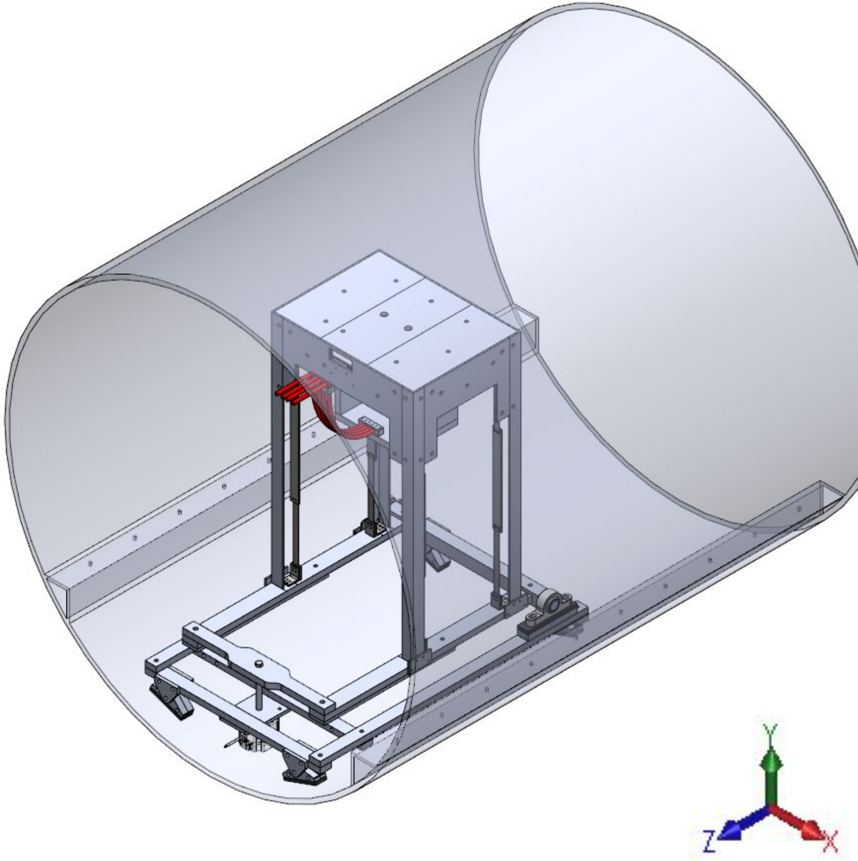
1. ZERO-POINT pendulum arm displacement — < 60 s
2. CALIBRATE test stand with known impulse — < 3 min
3. FIRE thruster — < 30 s
4. ALLOW for pendulum arm to stop swinging — < 60 s

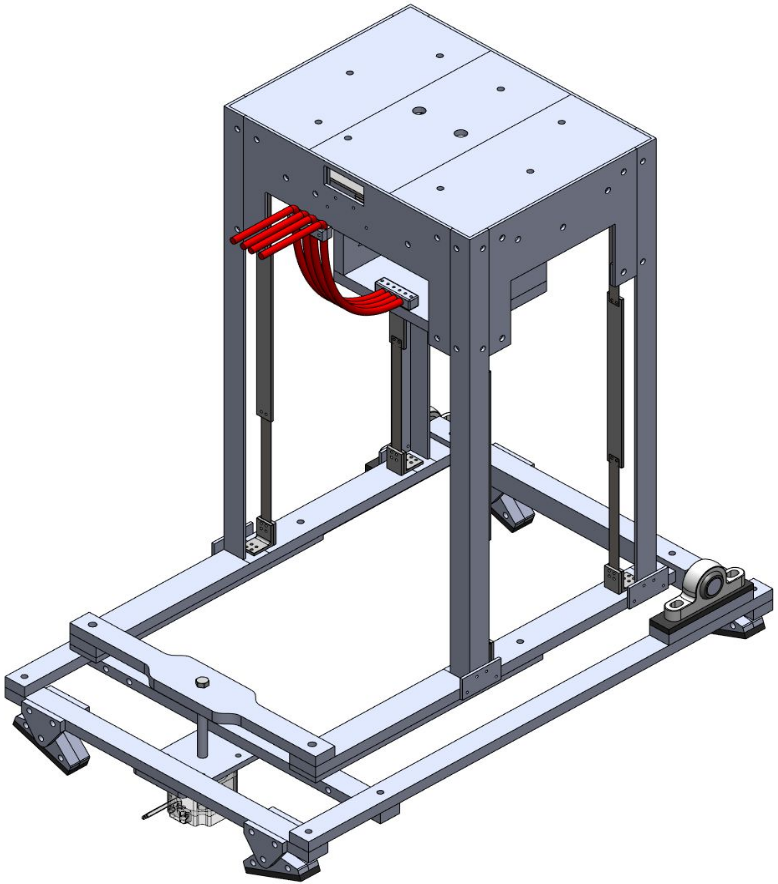
Disassembly

1. Repressurize, OPEN chamber — 15 min
2. REMOVE signal/power connections — 2 hrs
3. REMOVE thruster from stand — 1 hr
4. REMOVE test stand from vacuum chamber — 2 hrs

Assembly Overview

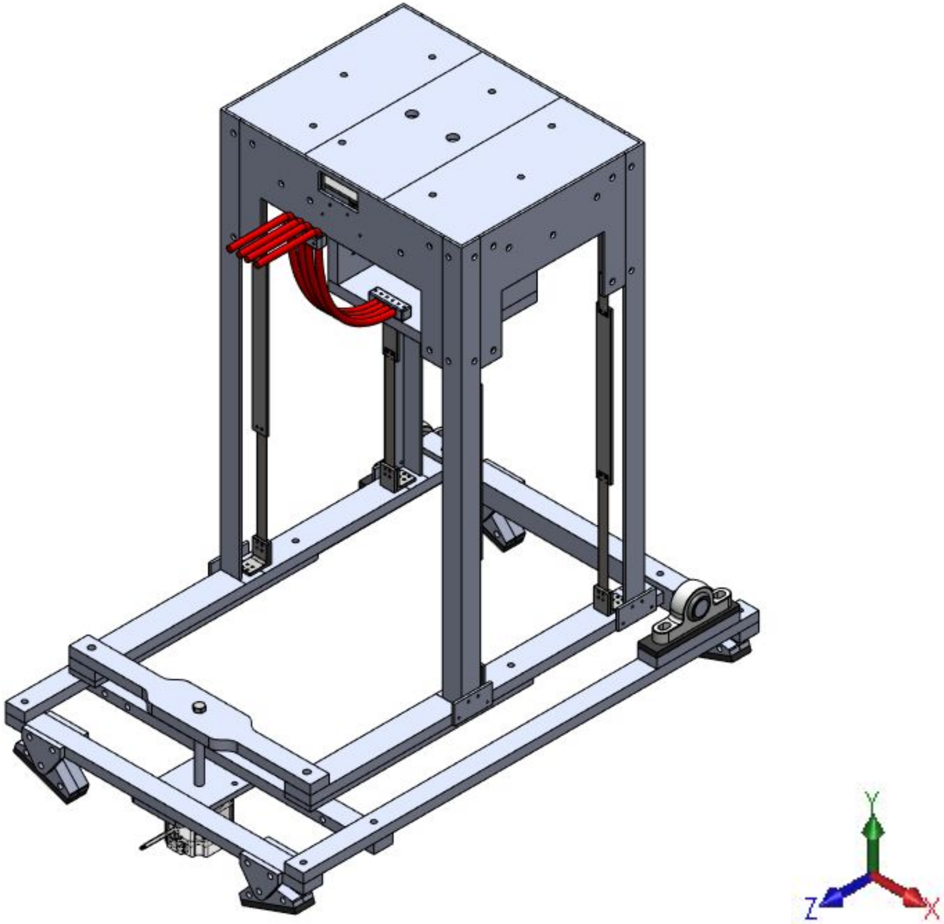
BF

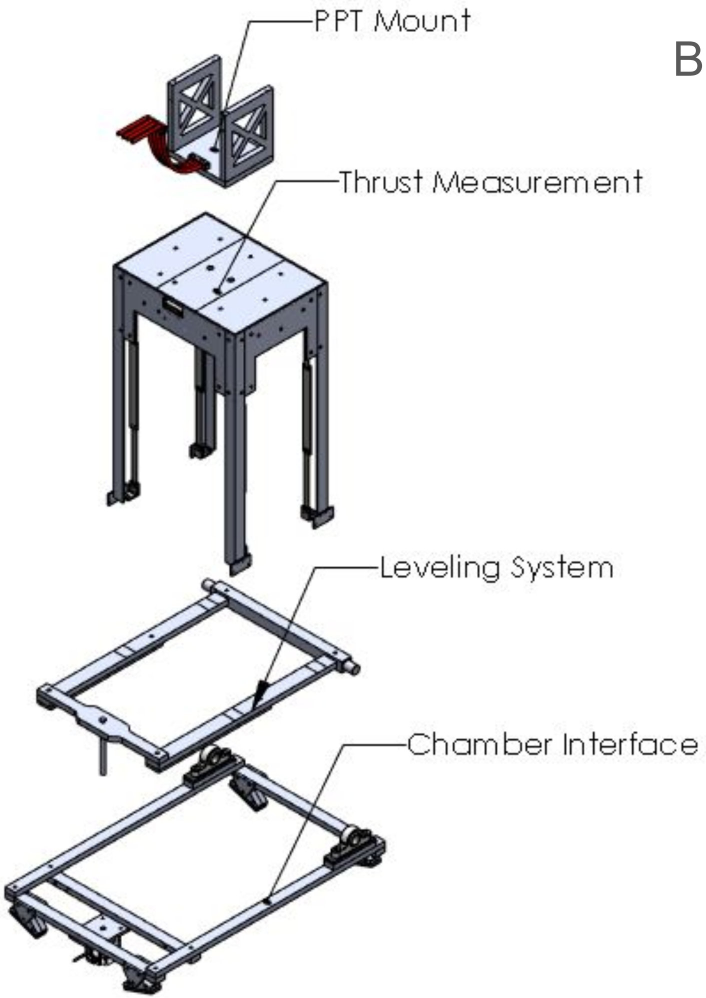




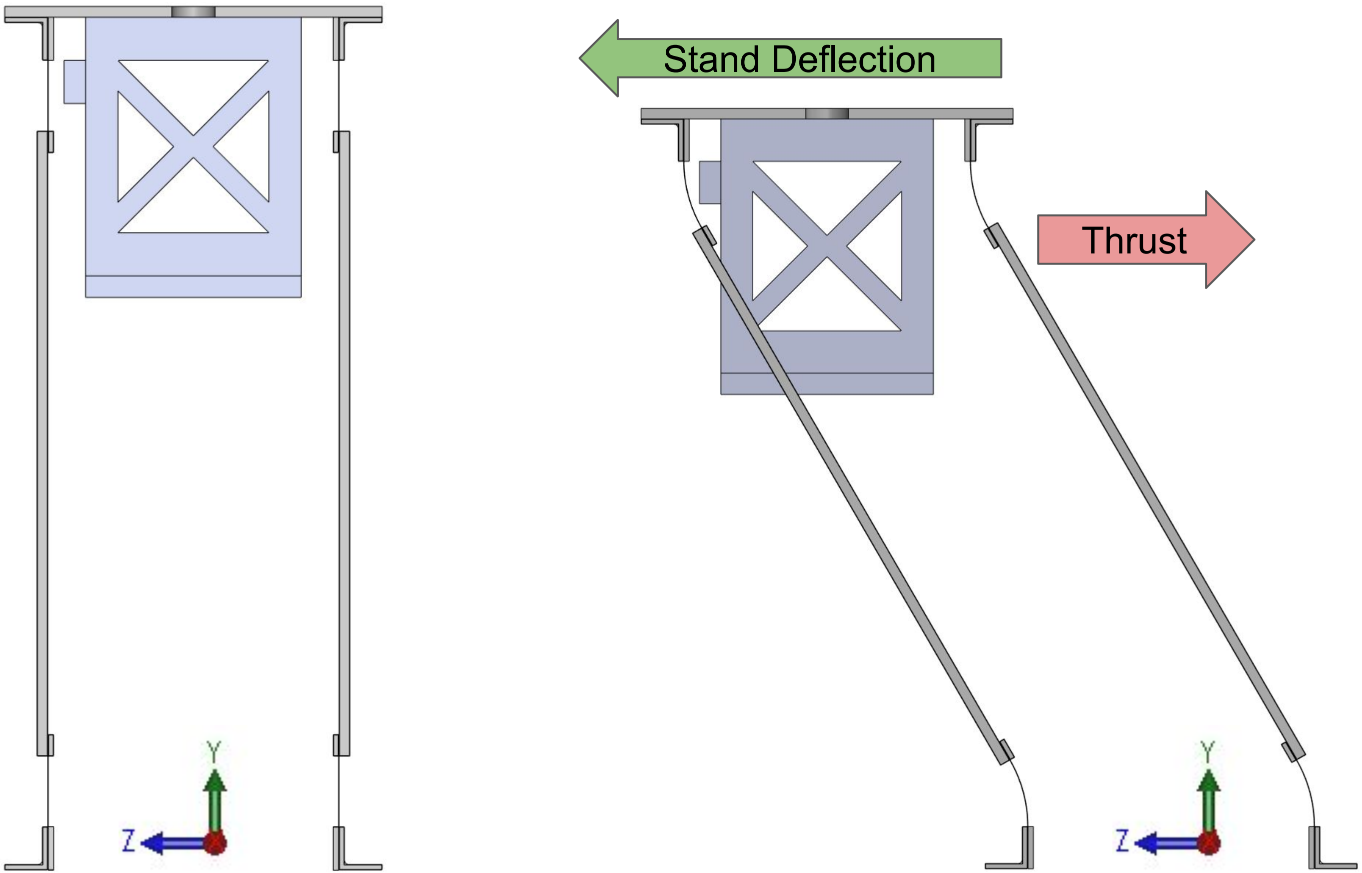
Assembly Overview

BF





Function



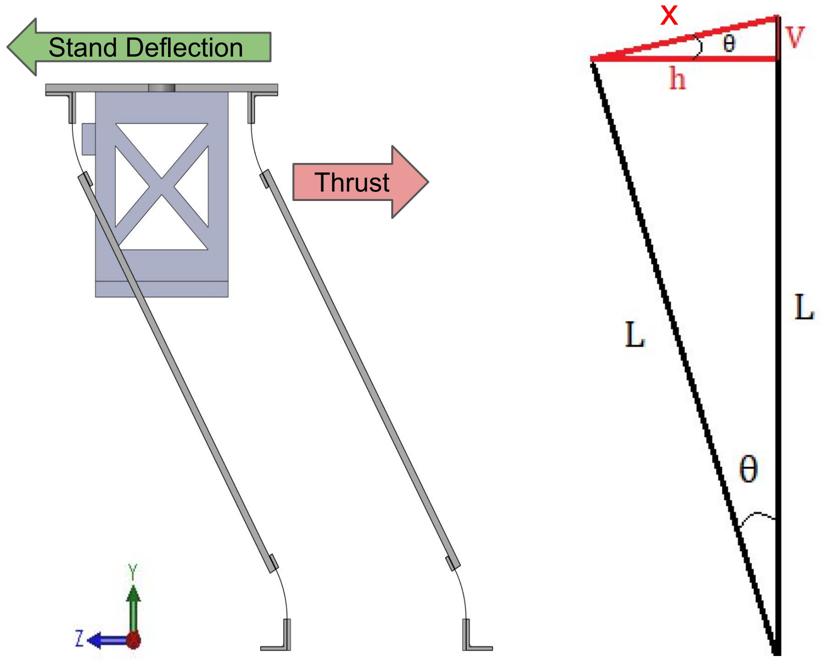
Function

Vertical stand displacement assumption

- Pendulum arm length, L = 19.8”
- Maximum expected horizontal displacement of h = 0.1”
  → Calculate maximum angular displacement, θ:

$$\theta = \sin^{-1}\left(\frac{h}{L}\right) = 0.290^o$$

Low θ → negligible angular displacement → assume **x is horizontal → v = 0 → Negligible!**
Only holds for small angles (<5°)

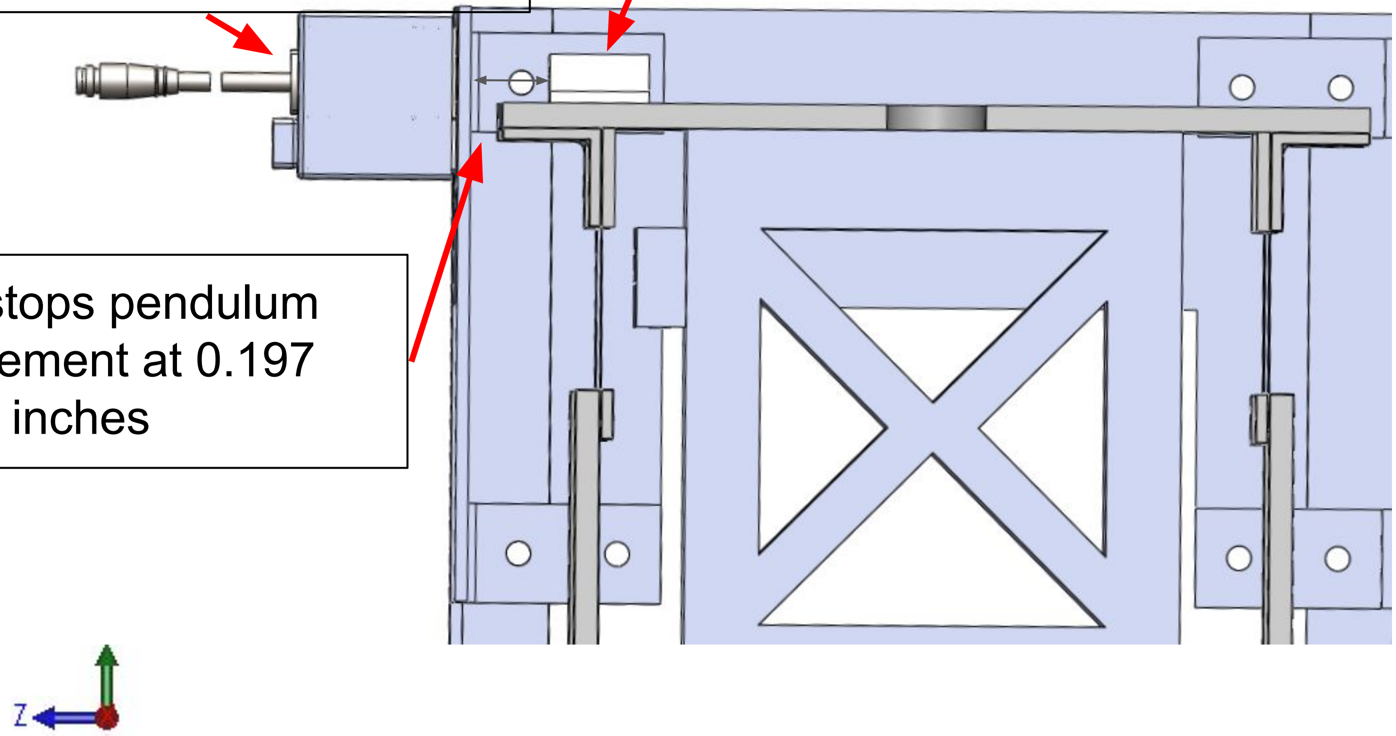


Comparison of stand deflection to similar triangles

Function

Laser Displacement Sensor

Displacement Sensor Target



Stand stops pendulum displacement at 0.197 inches

System Requirements

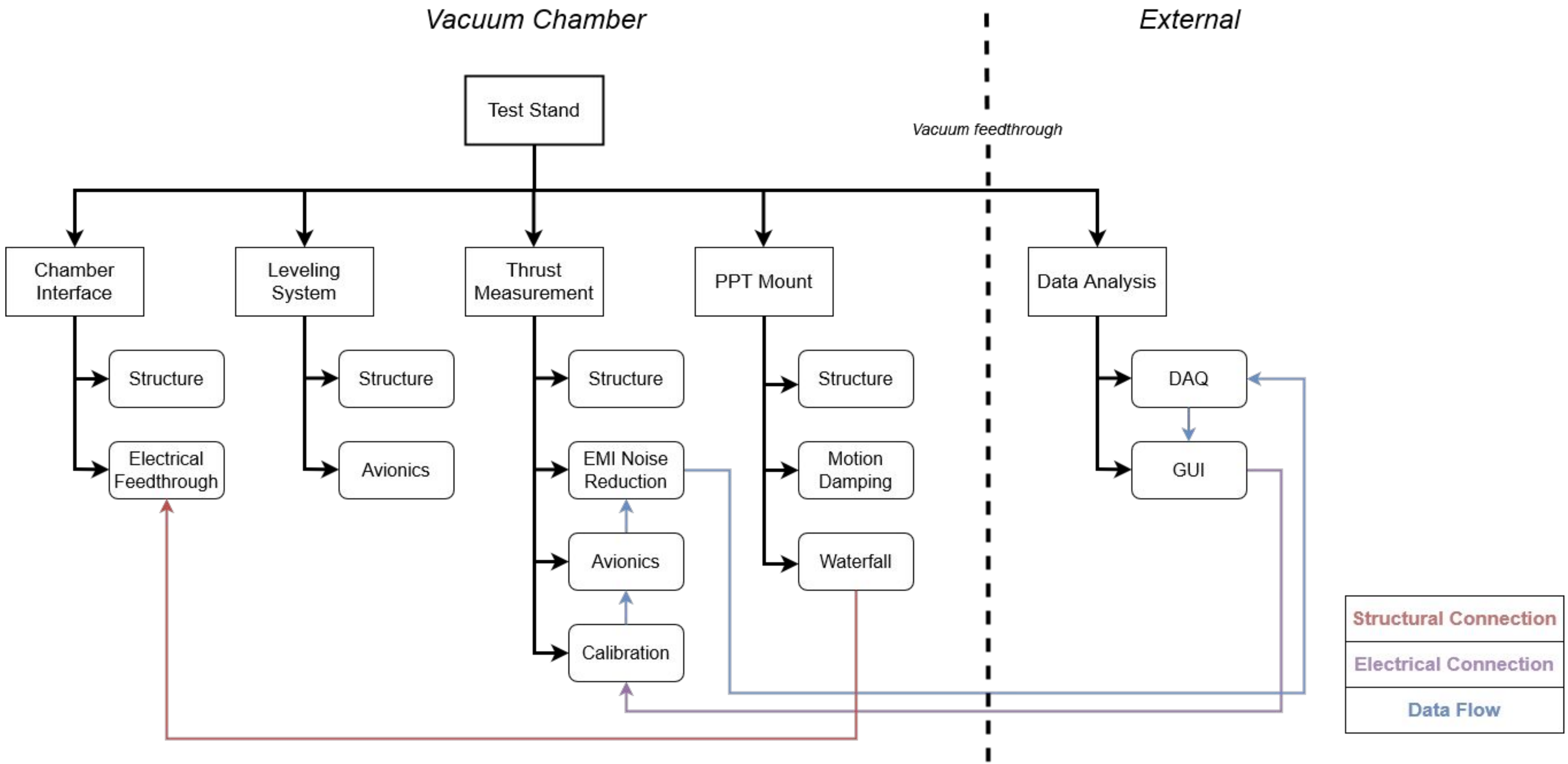
ID	Requirement	Verification Method
Sys.1	Test stand must be an **inverted pendulum style**	*Inspection*
Sys.2	Test stand shall **minimize the use of conductive materials**	*Inspection*
Sys.3	Test stand must be able to **resolve a minimum stand deflection of half the lowest predicted deflection** such that **impulse bits ranging from 2.25 μlbf*s to 22.5 mlbf*s ± 11.2 μlbf*s (10 μN*s to 100 mN*s ± 5 μN*s)** can be measured	*Test*
Sys.4	Test stand must be able to **resolve a minimum stand deflection of half the lowest predicted deflection** such that **steady-state thrusts ranging from 22.5 μlbf to 22.5 mlbf ± 11.3 μlbf (0.1 mN to 0.1 N ± 0.05 mN)** can be measured	*Test*

System Requirements

ID	Requirement	Verification Method
Sys.5	Test stand must be able to **support thrusters up to 17.6 lbf** without buckling	*Analysis*
Sys.6	Test stand must accommodate **thruster diameters up to 10.0 in, and thruster lengths up to 9.1 in**	*Demonstration*
Sys. 7	Test stand shall be able to be horizontally leveled to within **±0.05 degrees**	*Demonstration*
Sys.8	Test stand must **return thruster to 0.002 ± 0.001 degrees of zero-point** between tests	*Test*
Sys.9	The stand must be installed, securely operated, and safely removed from the vacuum chamber **without causing any structural or cosmetic damage** to the chamber wall	*Inspection*

System Architecture

WW



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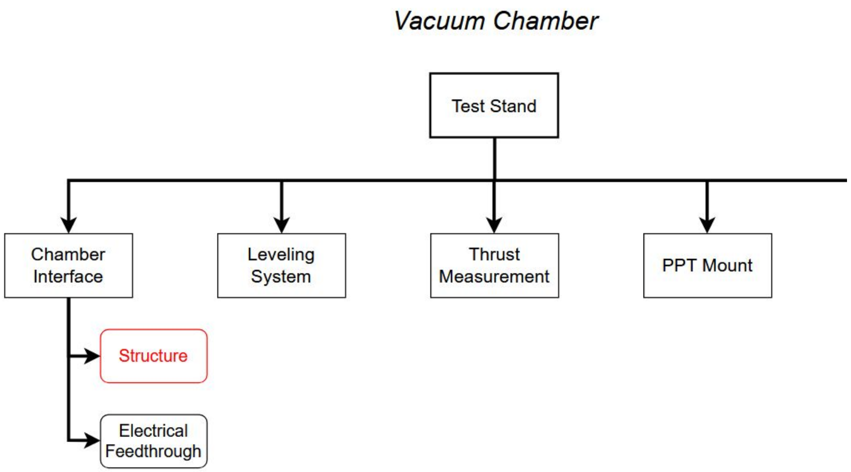
Chamber Interface: Structure

BF

System Architecture



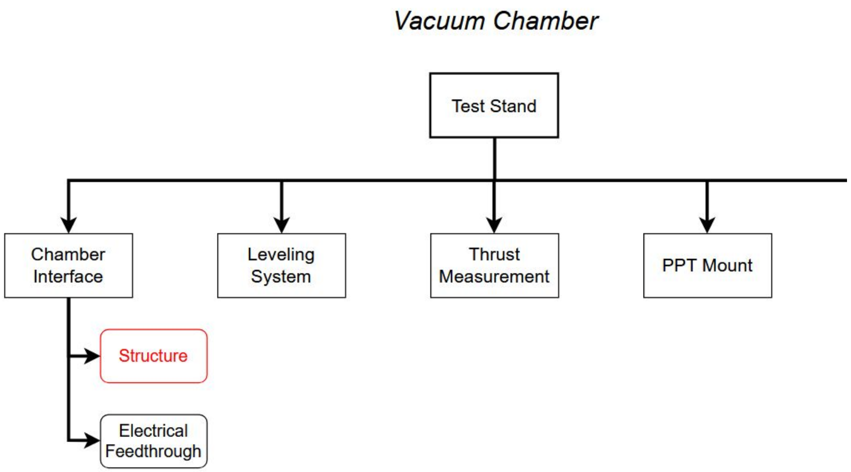
Driving Requirements

ID	Requirement	Verification Method
Ci.1	Test stand must **fit inside** vacuum chamber with **18 inch** radius of curvature, and be able to adapt to a minimum radius of curvature of **15 inches.**	*Inspection*
Ci.2	Chamber interface must **not scratch vacuum chamber walls.**	*Inspection*
Ci.3	Chamber interface must be **isolated from vibrations from vacuum chamber walls** in accordance to SPACE Lab standards.	*Inspection*

Chamber Interface: Structure

BF

System Architecture

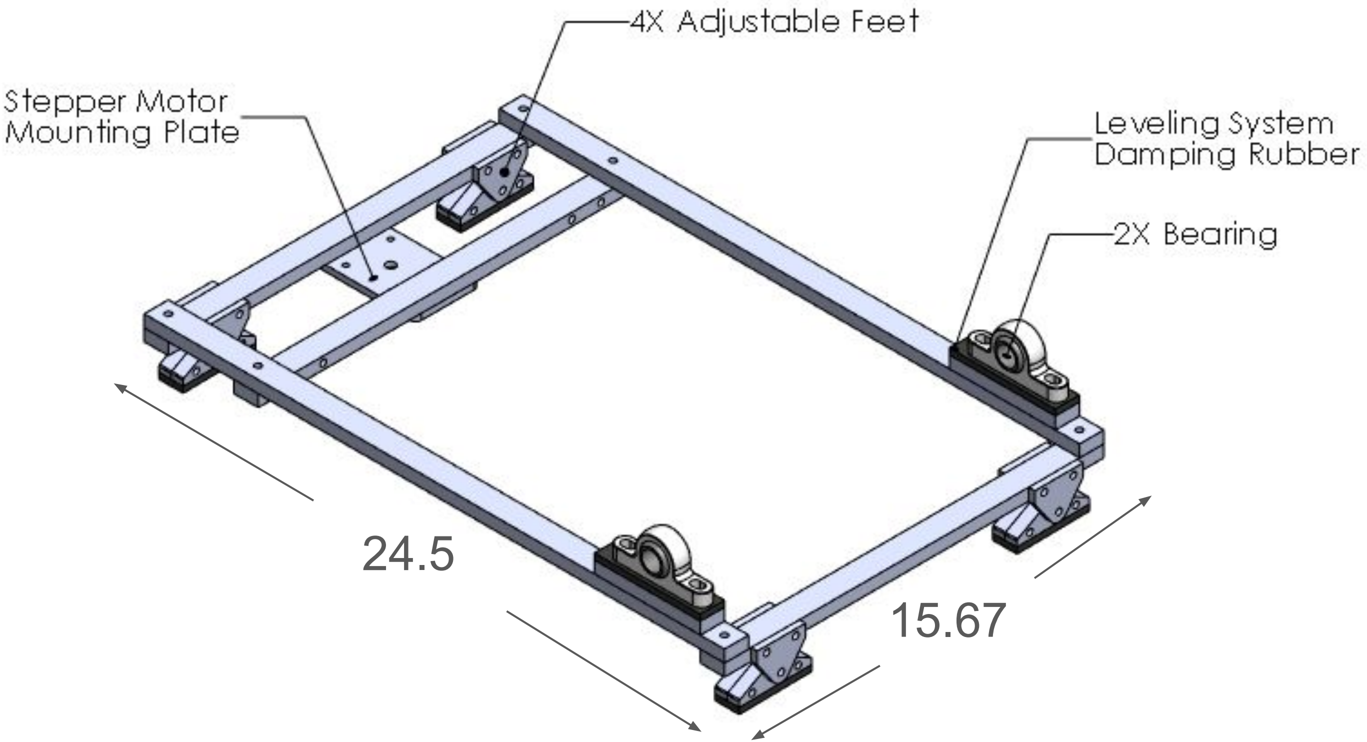


Driving Requirements

ID	Requirement	Verification Method
Ci.4	Chamber interface must **not exceed 0.04 inches of deflection** under the weight of overlying subsystems.	*Analysis*
Ci.5	Chamber interface assembly must have a **minimum safety factor of 2.5**	*Analysis*

Chamber Interface: Structure Overview

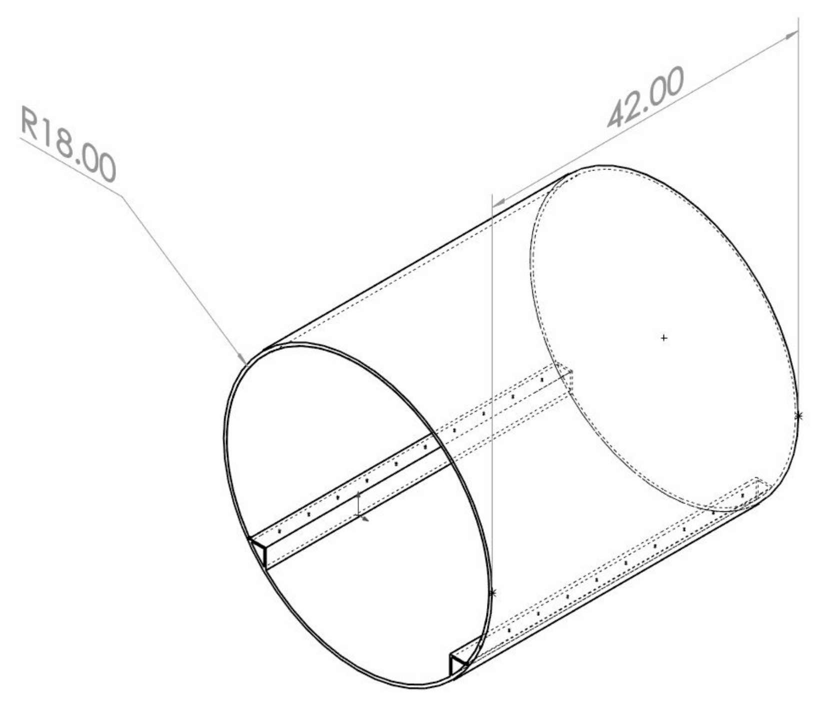
BF



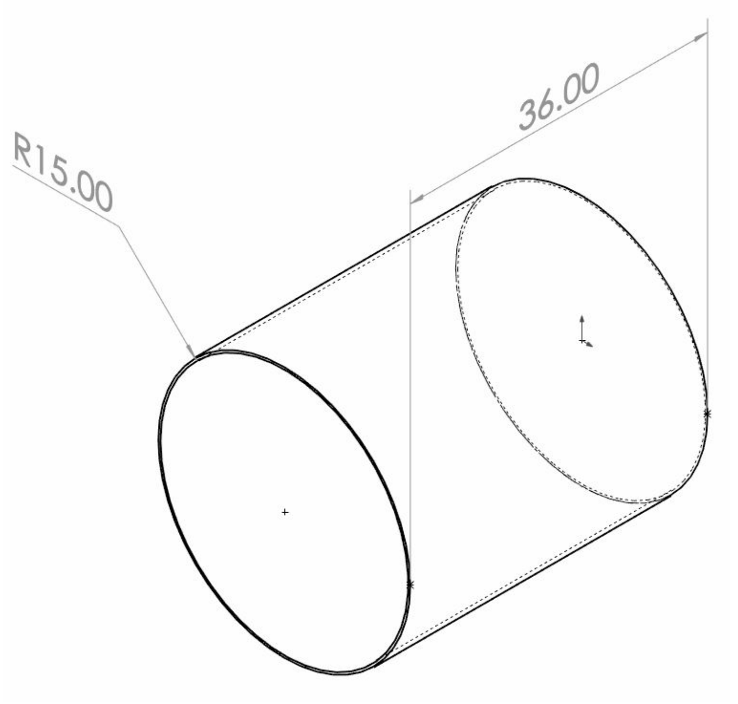
Chamber Interface: Structure

BF

Ci.1: Fit inside 15-18 in radius vacuum chambers



VC-01
Critical Dimensions

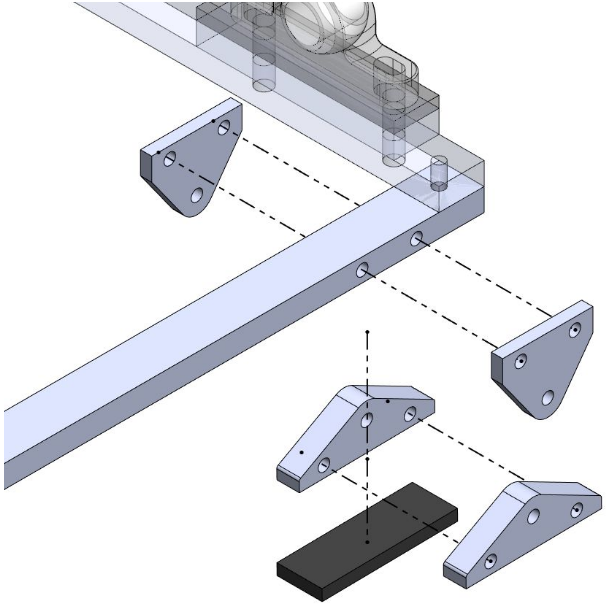


VC-02
Critical Dimensions

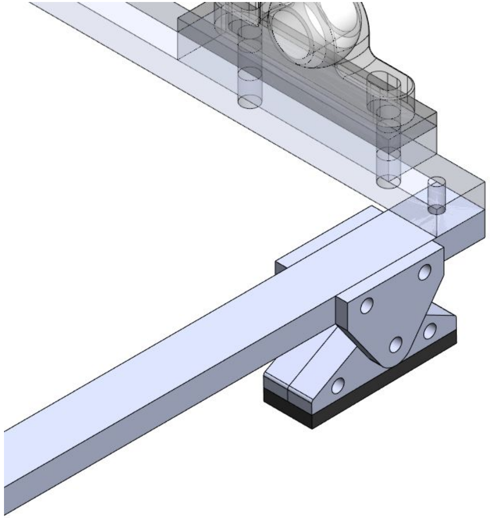
Chamber Interface: Structure

BF

Ci.1: Fit inside 15-18 in radius vacuum chambers



Chamber interface feet exploded view

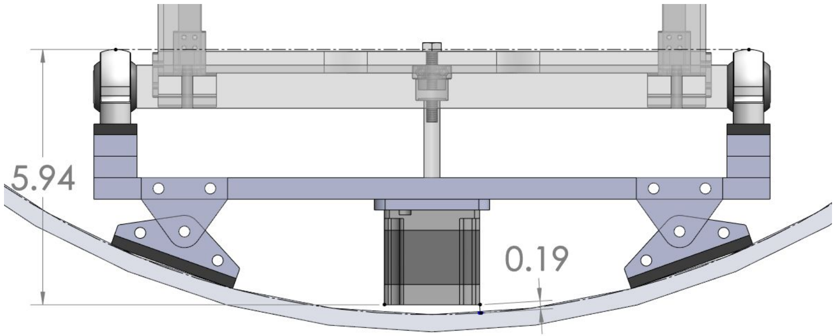


Chamber interface feet assembled on strut

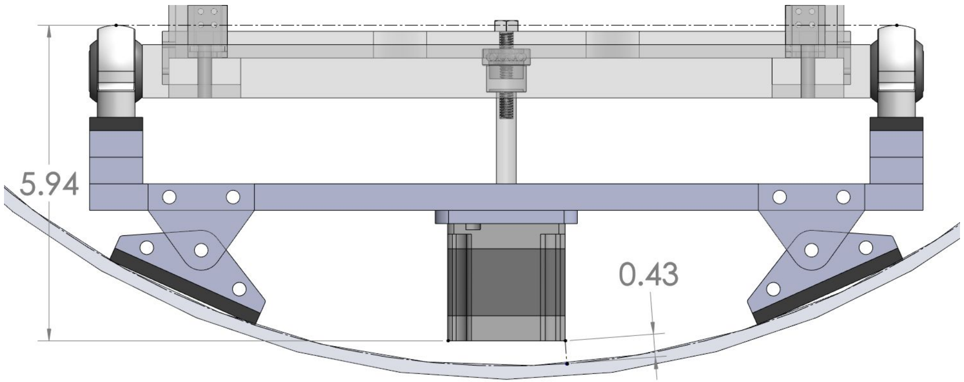
Chamber Interface: Structure

BF

Ci.1: Fit inside 15-18 in radius vacuum chambers



VC-01 Clearance



VC-02 Clearance

Chamber Interface: Structure

BF

Ci.2: Avoid scratching chamber walls

Vacuum Chamber Material Mohs Hardness:

- VC-01
  - Minimum: 5.0 (Lower end of stainless steel)
- VC-02
  - Minimum: 7.0 (Lower end of Silica)

Chamber Interface Material Hardness:

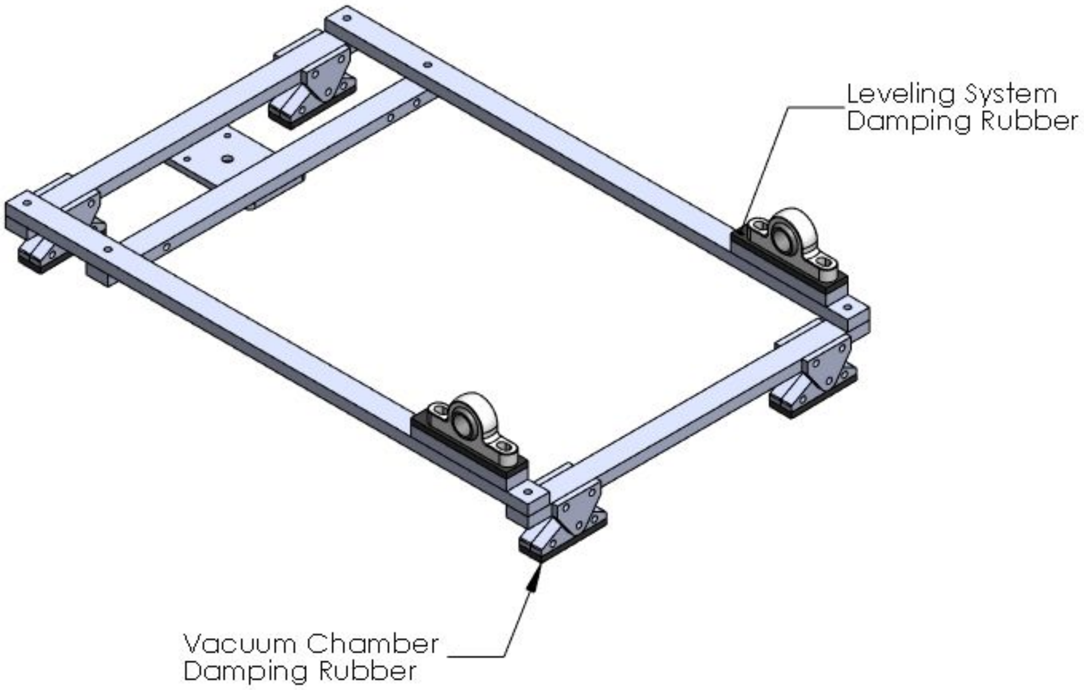
- Garolite (Epoxy)
  - Maximum: 3.0 (Upper end for epoxies)
  - 110 (Rockwell Hardness)
- Buna-N Rubber
  - 70-90 (Shore A)
  - Rubber will not scratch silica or stainless steel in this use case

Chamber Interface: Structure

BF

Ci.3: Isolated from vibrations from vacuum chamber walls

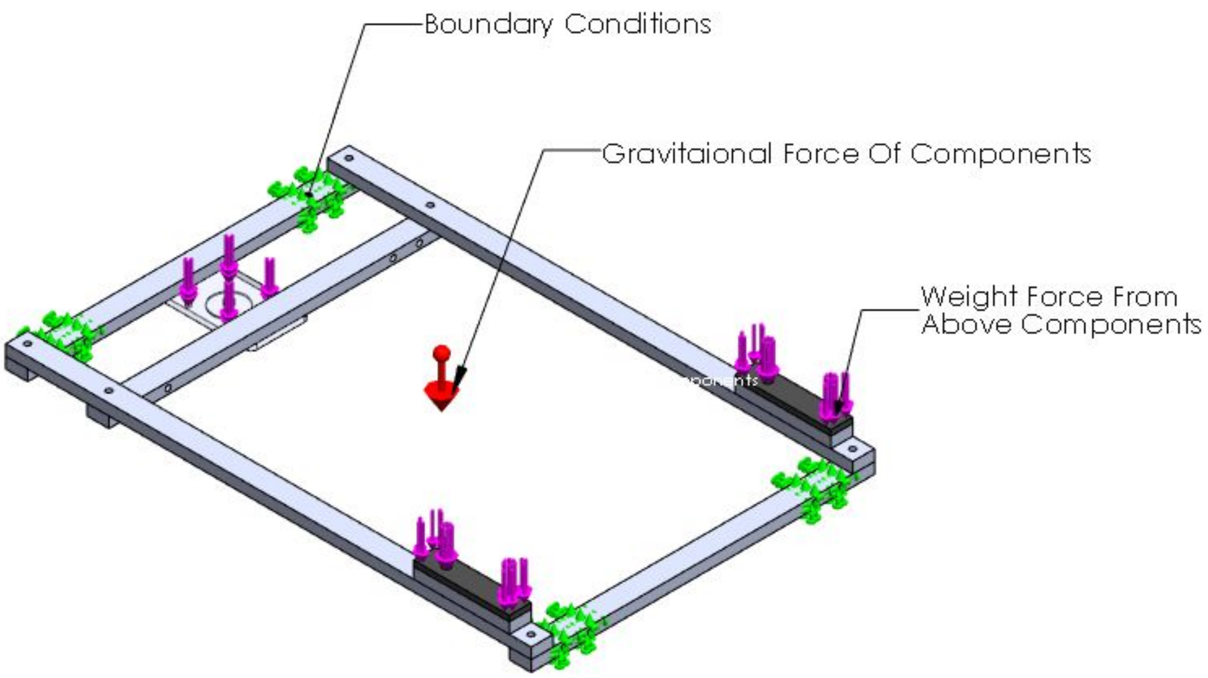
- Rubber between feet and chamber walls reduce noise due to outside vibrations
- Rubber between chamber interface and leveling system dampens oscillations caused by stepper motor
- 0.25 inch Buna-N rubber applied as shown in the figure deemed sufficient by SPACE Lab personnel.



Chamber Interface: Structure

Ci.4: Not exceed 0.04 inches of deflection

- Assumed maximum thruster weight of 17.6 lbf
- Omitted feet to increase simulation speed
- Assumed feet mounting points fixed
- Assumed weight of overlying components evenly distributed

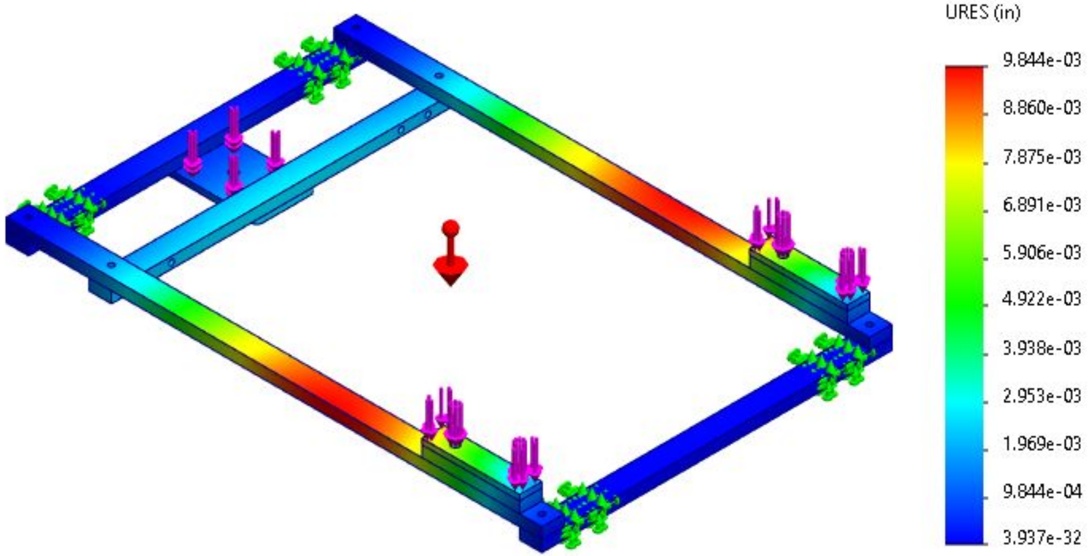


Chamber Interface: Structure

BF

Ci.4: Not exceed 0.04 inches of deflection

- Max Deflection of 0.009844in
- In the event of excessive deflection in production, a doubler can be added to sections shaded in red and orange

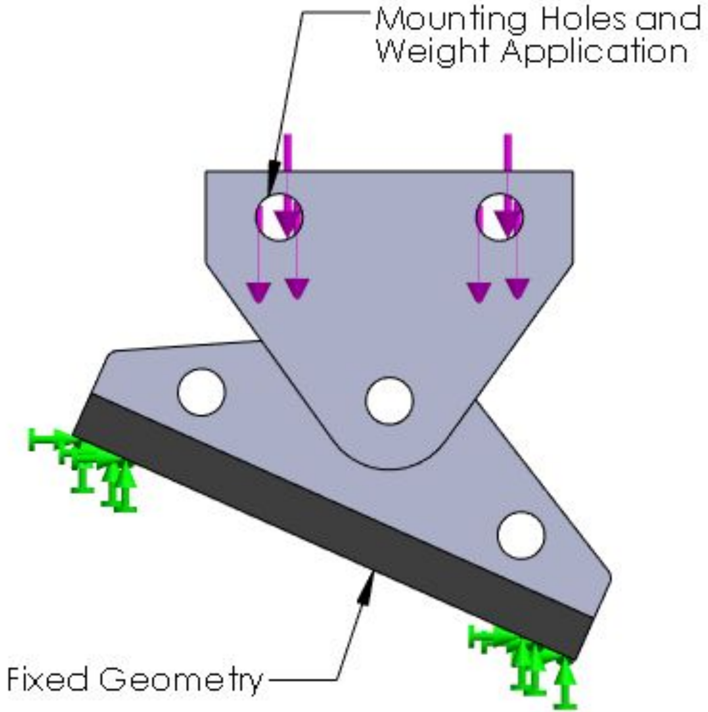


Chamber Interface: Structure

BF

Ci.4: Not exceed 0.04 inches of deflection

- Assumed maximum thruster weight of 17.6 lbs .
- Assume mounting holes are medium of weight transfer.
- Assumes equal weight distribution across all 4 feet.
- Self weight of components also considered.

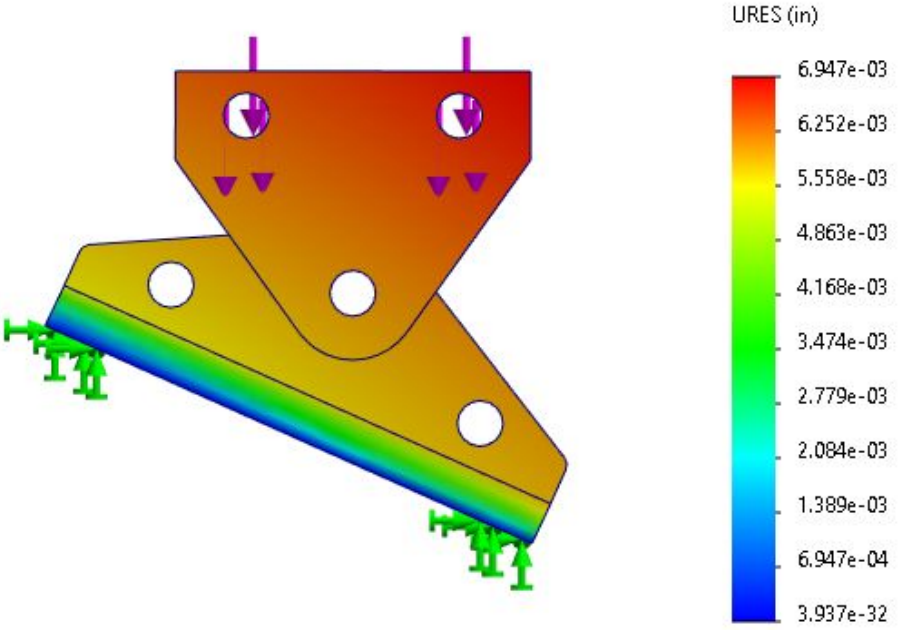


Chamber Interface: Structure

BF

Ci.4: Not exceed 0.04 inches of deflection

- Maximum deflection of 0.006947 in
- An estimated net deflection of 0.01654 in across the chamber interface remains under 0.04 in



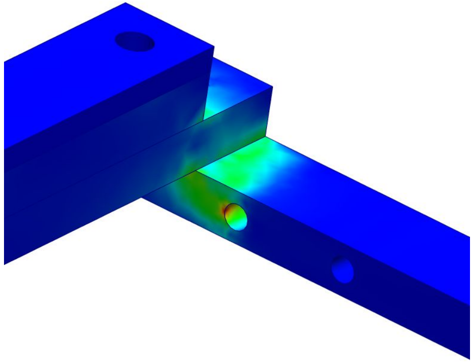
Chamber Interface: Structure

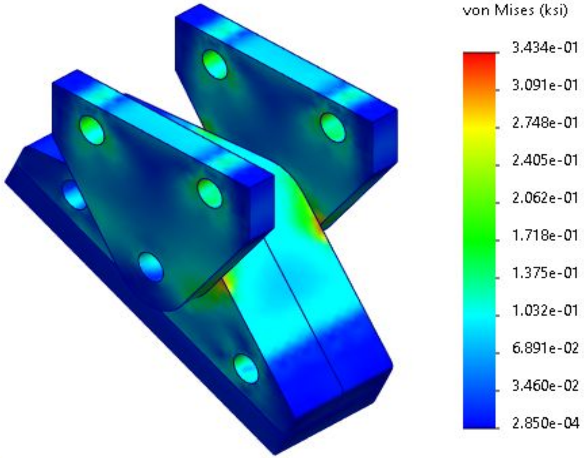
BF

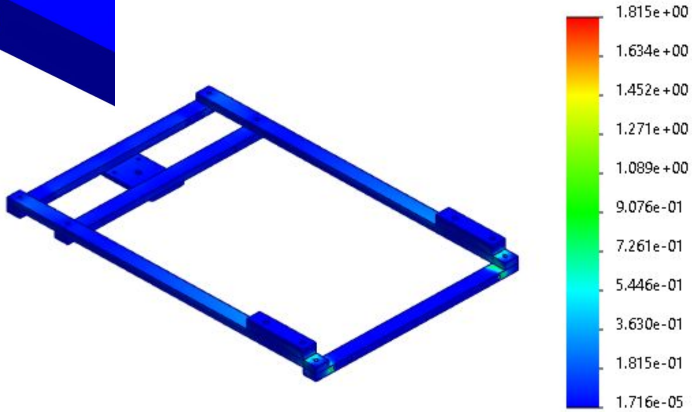
Ci.5: Minimum safety factor of 2.5

Chamber Interface Feet
- Max stress on G10 of 0.3434 ksi
- FoS = 120

Chamber Interface Struts
- Max stress on G10 of 1.815 ksi
- FoS = 22.6







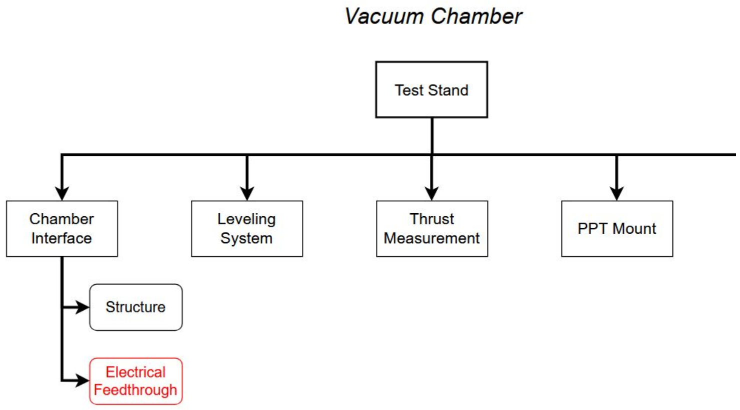
Chamber Interface: Structure

Requirements Review

ID	Requirement	Satisfied via:	Sys. req. met:
Ci.1	Test stand must **fit inside** vacuum chamber with **18 inch** radius of curvature, and be able to adapt to a minimum radius of curvature of **15 inches**	Chamber interface feet accomodate 15 -18” radius of curvature	N/A
Ci.2	Stand-chamber physical interface must **avoid scratching** to **chamber walls**	Chamber interface materials are not as hard as interface materials	**Sys. 9**
Ci.3	Chamber interface must be **isolated from vibrations from vacuum chamber walls** in accordance to SPACE Lab standards	Application of rubber in test stand approved by P. Thoreau	N/A
Ci.4	Chamber interface must **not exceed 0.04 inches of deflection** under the weight of overlying subsystems.	FEA results indicate a net deflection of 0.01654 in	N/A
Ci.5	Chamber interface assembly must have a **minimum safety factor of 2.5**	FEA results indicate a minimum FOS of 22.6	N/A

Chamber Interface: Electrical Feedthrough

System Architecture



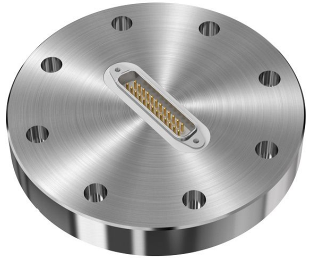
Driving Requirements

ID	Requirement	Verification Method
Ci.6	Have **sufficient number of connection** inputs to support test stand and PPT	*Inspect*
Ci.7	Electrical feedthroughs shall be able to **interface with the flanges provided by the SPACE lab**	*Inspect*
Ci.8	Ground sources shall **comply with SPACE lab standards on grounding**	*Test*

Chamber Interface: Electrical Feedthrough

- Flange usage **requires 14 ports**:
  - IL-030 **requires 4 cables**
    - Power
    - Reference GND
    - Digital I/O
    - Analog output
  - Nema-23 **requires 4 connections**
    - Power
    - Digital I/O
    - Analog Output
    - Reference GND
  - PPT **requires 4 connections**
    - 3 power inputs
    - Analog output
  - Electrostatic comb **requires 2 connections**
    - 2 power inputs
- **Feedthrough shall utilize BD-25 connectors**

- Flanges provided by SPACE lab **BD-25 compatible**
  - **BD-25 provides 25 connections per flange**
  - **Satisfies requirement Ci.6 & Ci.7**
- Standardized ConFlat flanges **provide reference GND**
  - **Compliant with SPACE lab standards**
  - **Satisfies Ci.9**



[i17]

[i16]

Chamber Interface: Electrical Feedthrough

KLV

Requirements Review

ID	Requirement	Satisfied via:	Sys. req. met:
Ci.9	Have **sufficient number of connection** inputs to support test stand and PPT	Utilize **BD-25 style connectors**	N/A
Ci.10	Electrical feedthroughs shall be able to **interface with the flanges provided by the SPACE lab**	**BD-25 female connectors** interface with **BD-25 flanges**	N/A
Ci.11	Ground sources shall **comply with SPACE lab standards on grounding**	Flanges provide **ground reference**	N/A

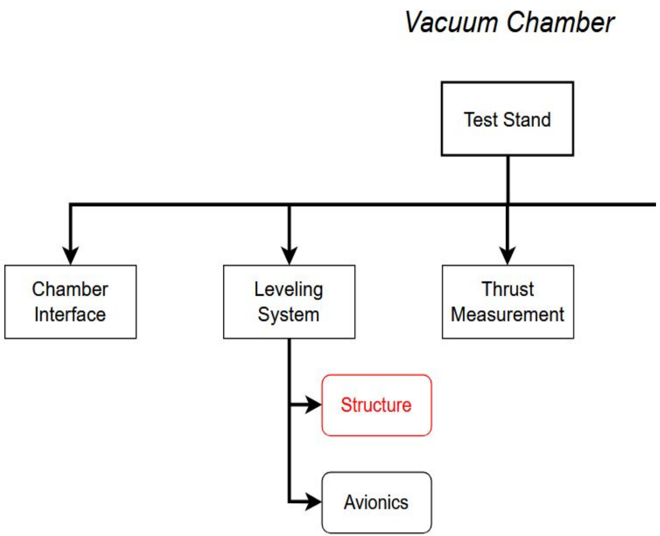
Chamber Interface: Budget Summary

Category	**Item**	**Cost**	**Total**
Structure			
Avionics	DB 25 Connector	$ 22.82	$ 44.08
	High Temperature Stranded Wire	$ 21.26	
Software			
Other			
			$ 44.08

Leveling System: Structure

WW, BF

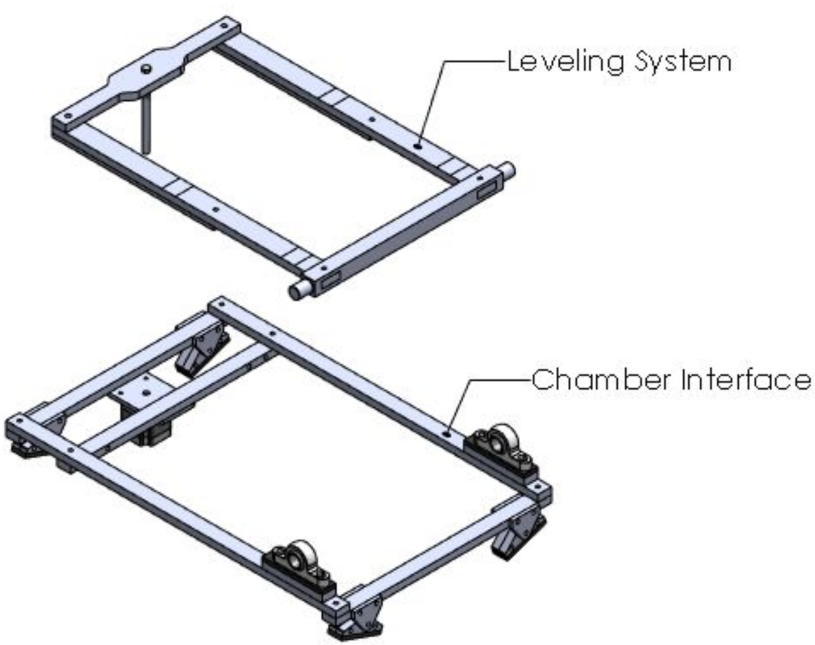
System Architecture

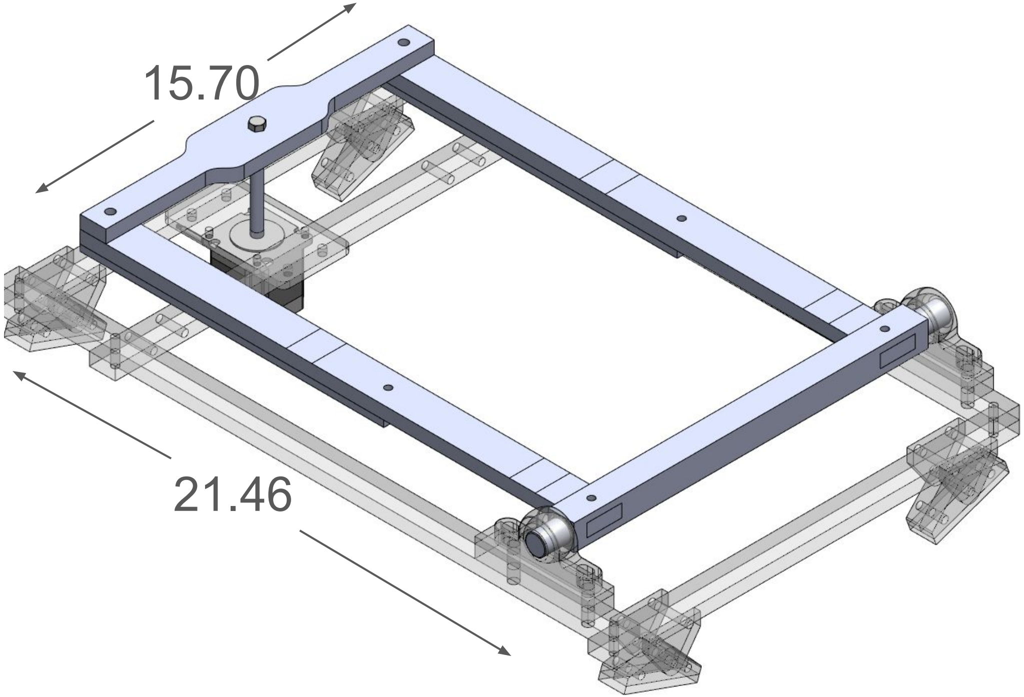


Driving Requirements

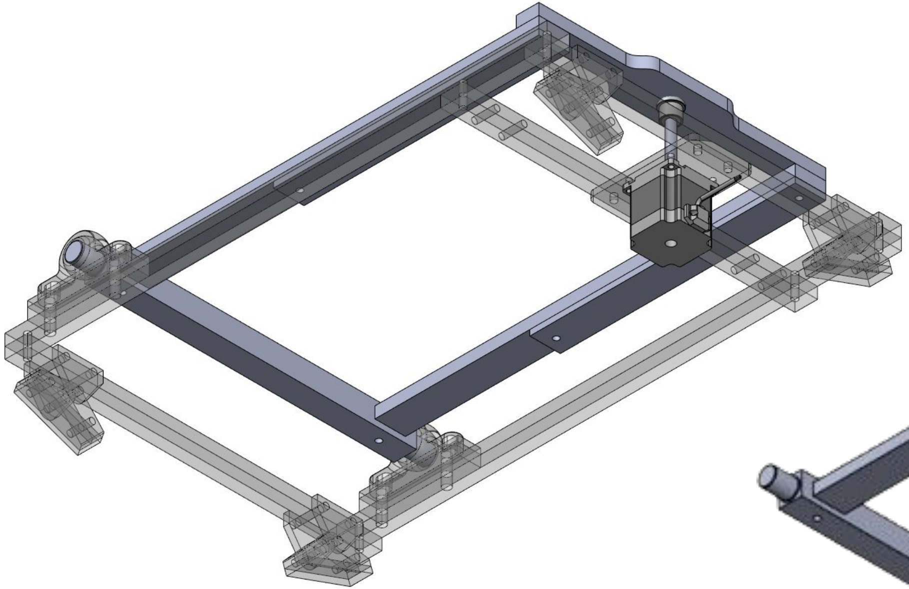
ID	Requirement	Verification Method
Ls.1	Leveling system must be **able to pitch** across bearing axis within a range of **±3 degrees**	*Inspection*
Ls.2	Leveling system must not exceed **0.04 inches of deflection** due to the weight of overlying subsystems.	*Analysis*
Ls.3	Leveling system assembly must have a **minimum safety factor of 2.5**	*Analysis*

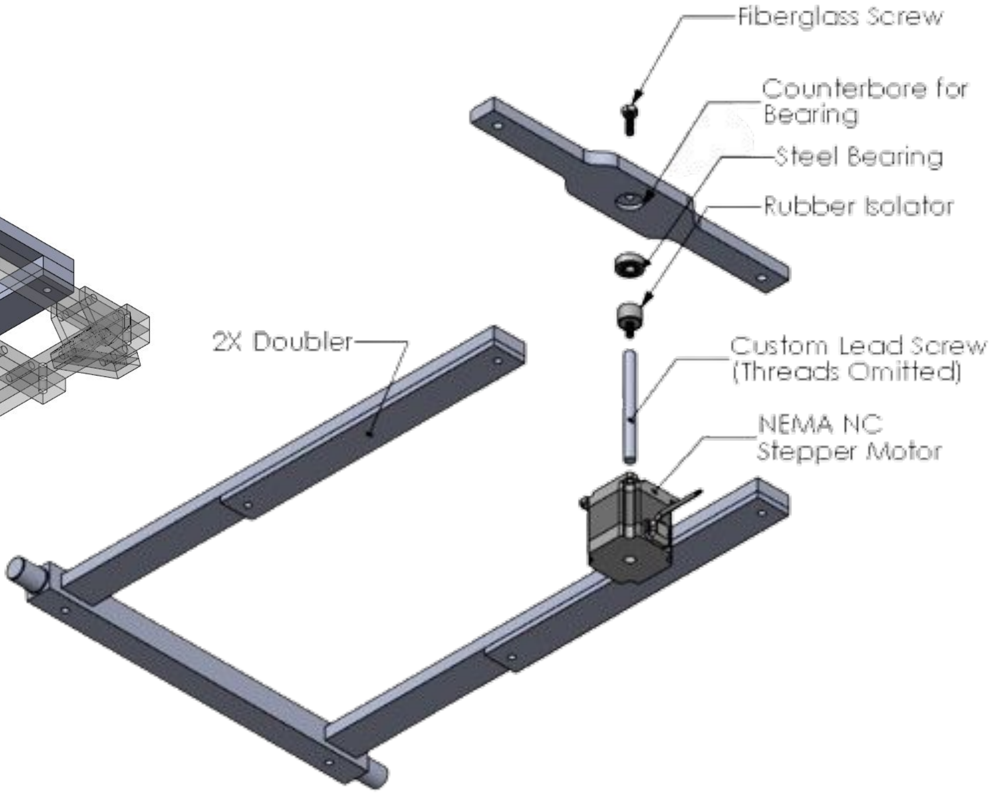
Leveling System: Structure Overview





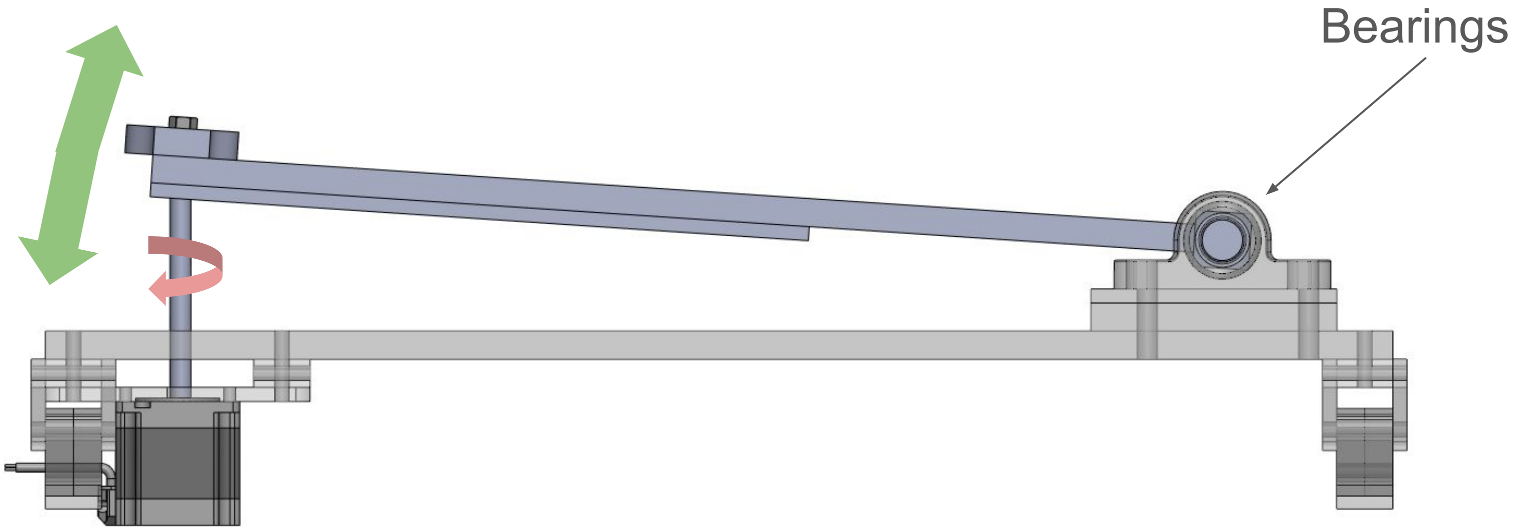
Leveling System: Structure Overview





Leveling System: Structure Overview

- After the thruster fires and oscillates, it is possible that the test stand could become misaligned
  - Plastic deformation, shifting due to tolerance limitations, etc
- The NEMA NC Stepper motor actuates a lead screw to adjust the stand up and down along the axis of the bearings

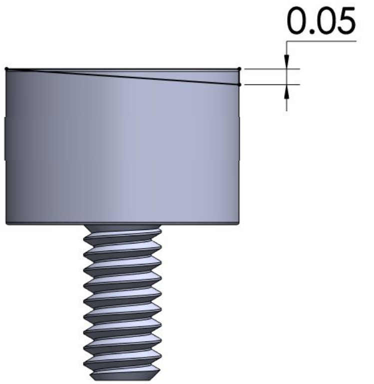


Leveling System: Structure

Ls.1: Able to pitch ±3 degrees

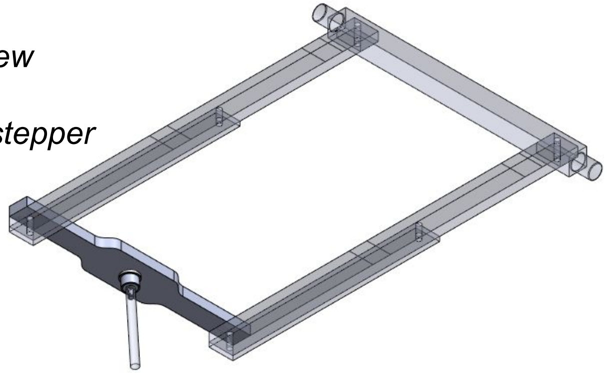
BF

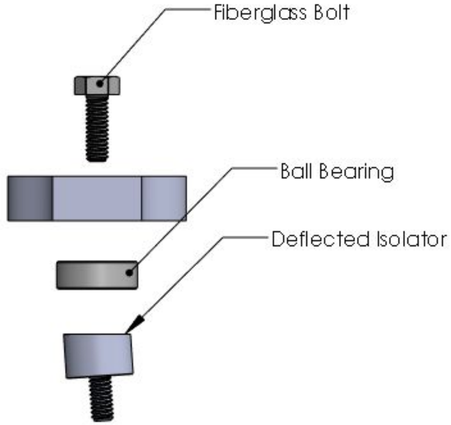
- Rubber isolator has a maximum deflection of 0.05 inches
- Alleviates shear and moments due to rotation of leveling system



Top: Rubber isolator and cross sectional view

Bottom: Reference view and exploded view of stepper motor stress relief assembly

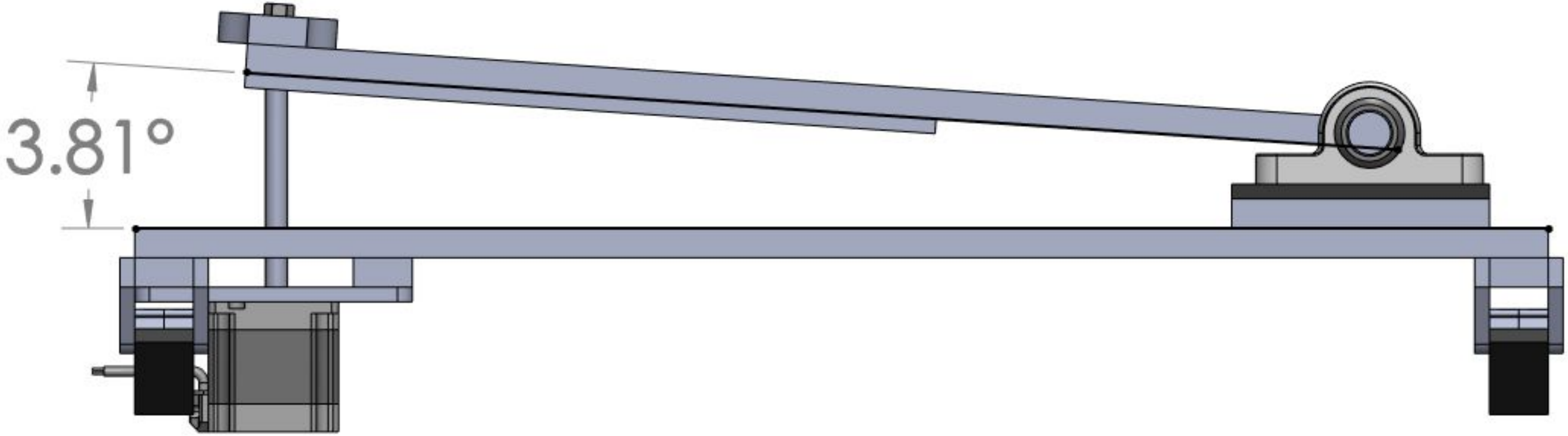




Leveling System: Structure

BF

Ls.1: Able to pitch ±3 degrees

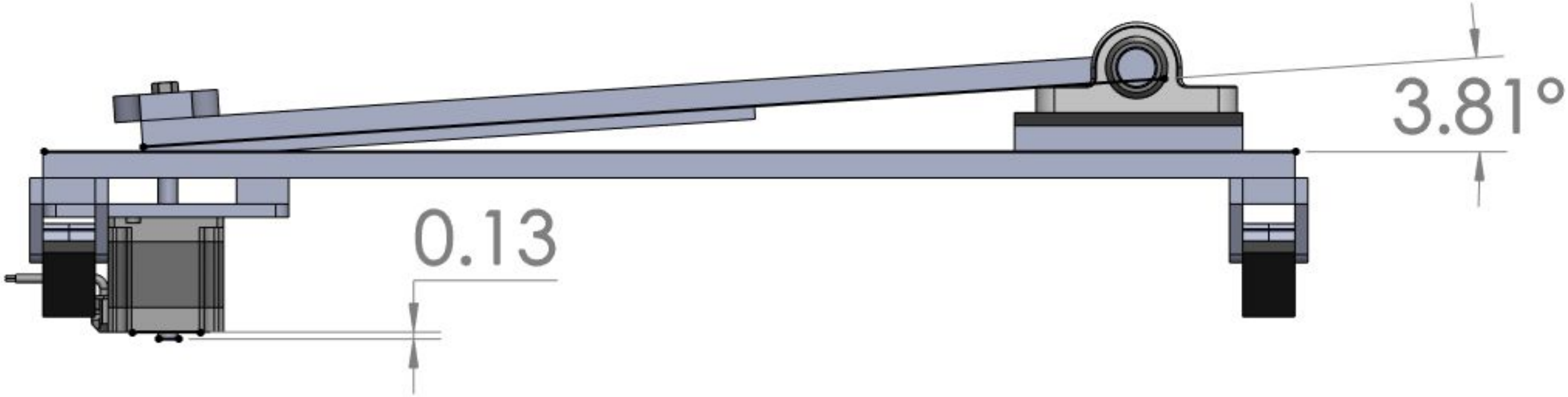


Demonstration of leveling system pitching up

Leveling System: Structure

BF

Ls.1: Able to pitch ±3 degrees

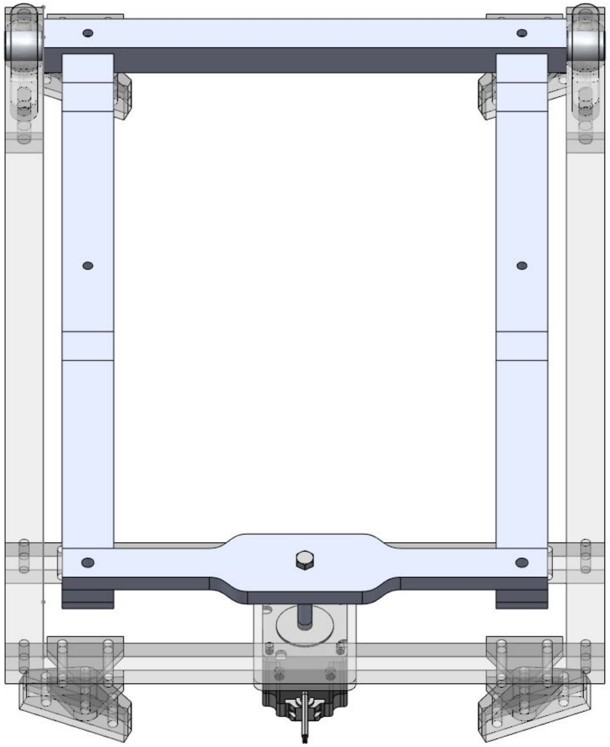


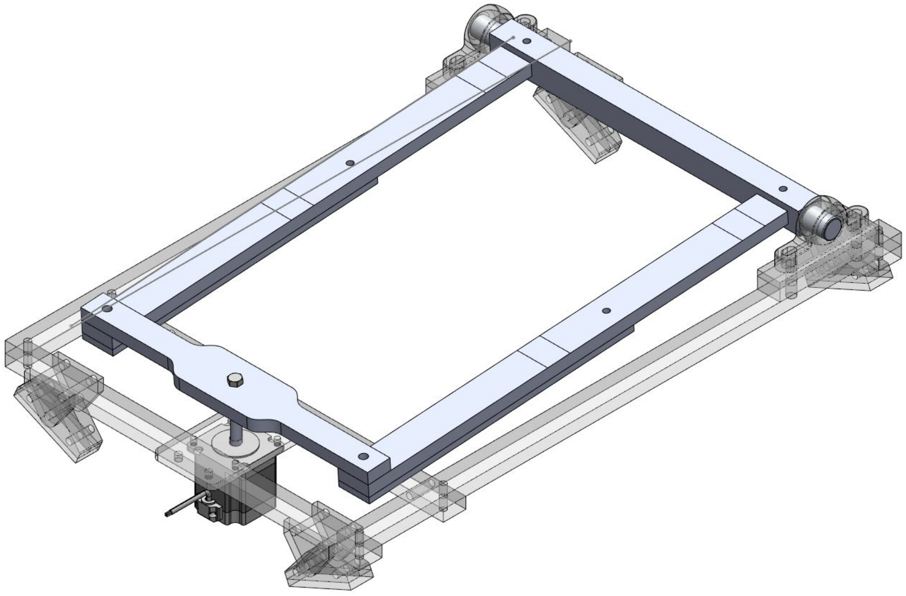
Demonstration of leveling system pitching down

Leveling System: Structure

BF

Ls.1: Able to pitch ±3 degrees





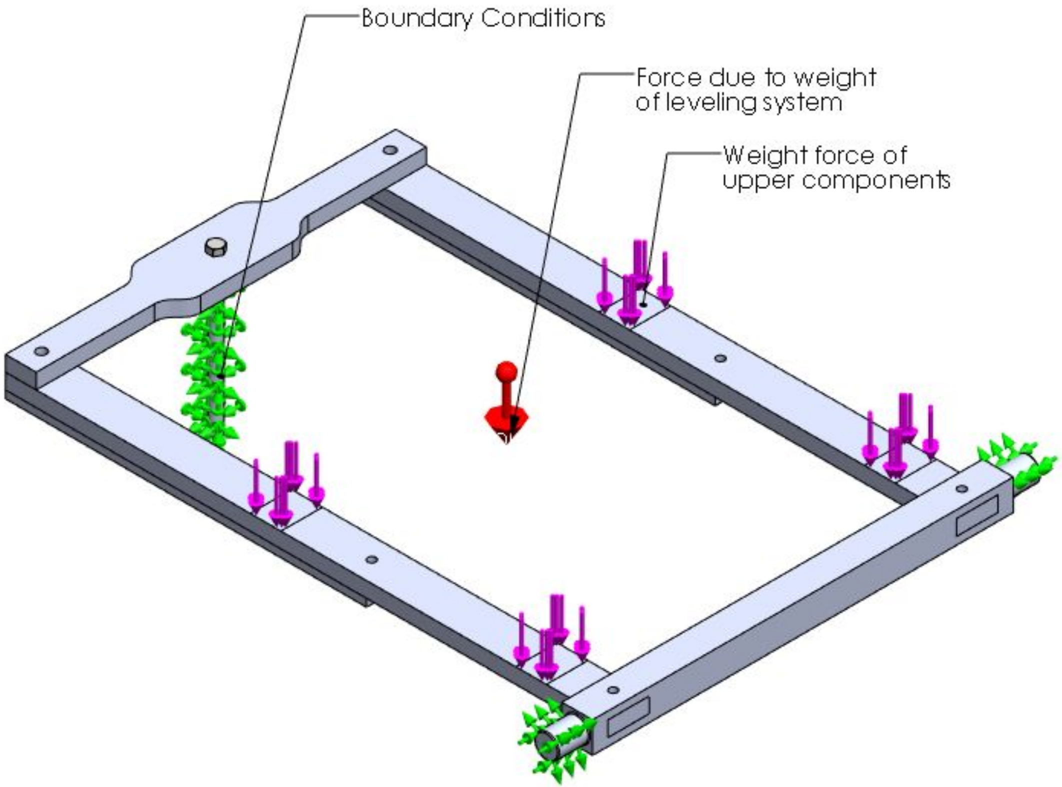
Clearance check for pitch-down state

Leveling System: Structure

BF

Ls.2: Not exceed 0.04 inches of deflection

- Assumed maximum thruster weight of 17.6 lbf
- Assumed pin condition at bearings and collar condition for lead screw
- Weight of upper components considered to be evenly distributed

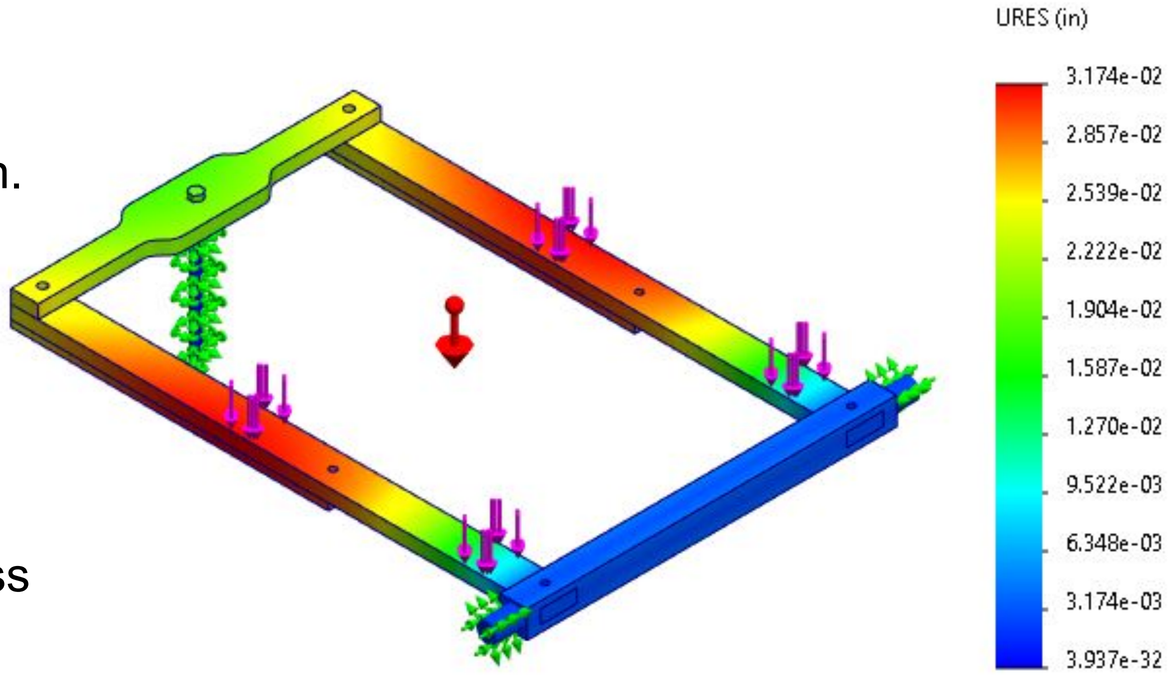


Leveling System: Structure

BF

Ls.2: Not exceed 0.04 inches of deflection

- Maximum deflection determined to be 0.03174 in.
- "Half-doubler" added to reduce deflection
  - If deflection of production model exceeds 0.04, a full doubler is budgeted to further increase stiffness

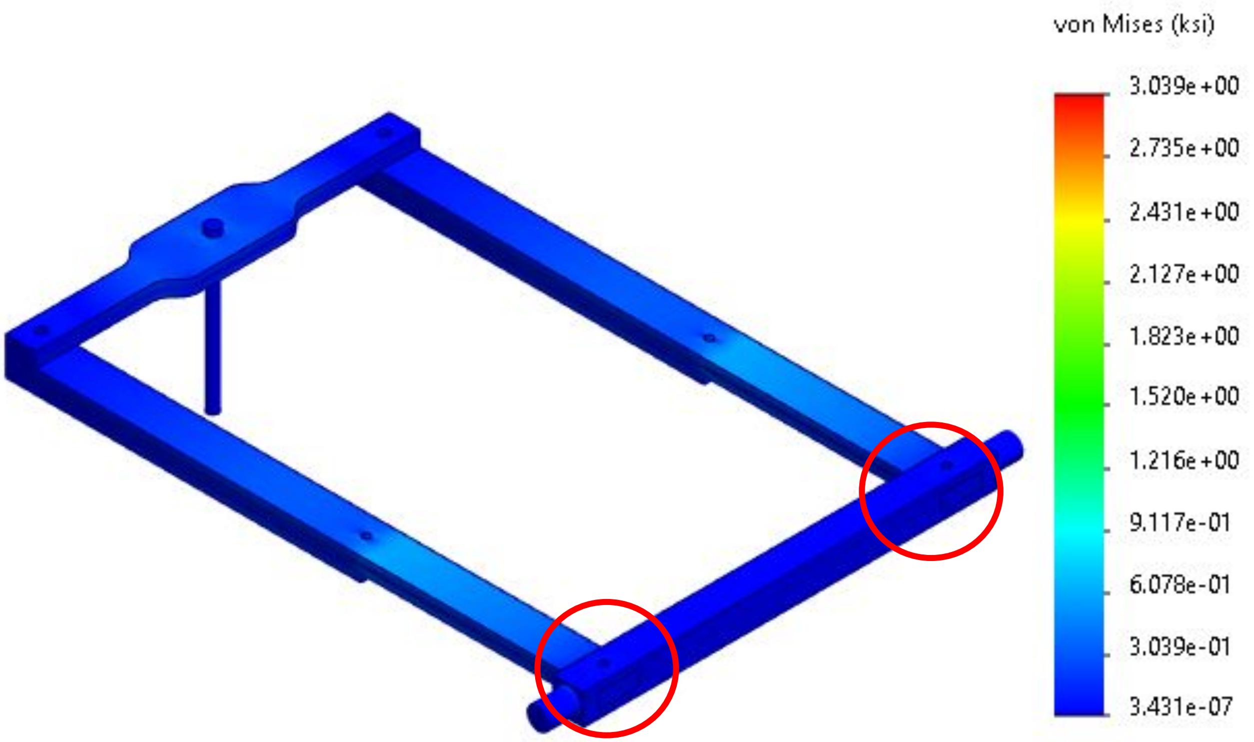


Leveling System: Structure

Ls.3: Minimum safety factor of 2.5

BF

- Maximum stress occurred on G10 pieces (red circles) and was determined to be 3.039 ksi.
- FoS = 13.7



Leveling System: Structure

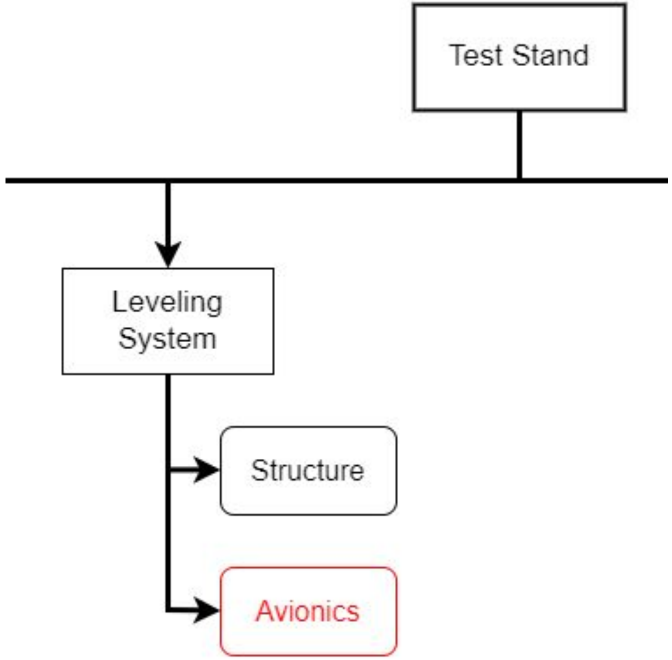
KLV, BF, LL

Requirements Review

ID	Requirement	Satisfied via:	Sys. req. met:
Ls.1	Leveling system must be **able to pitch** within a range of **± 3°**	Nylon bushings and flexible rubber isolator	**Sys. 2**
Ls.2	Leveling system must **not exceed 0.04 inches of deflection** due to the weight of overlying subsystems.	FEA modeling of leveling system weight and force due to weight of upper components.	**N/A**
Ls.3	Leveling system assembly must have a **minimum safety factor of 2.5**	FEA modeling of leveling system weight and force due to weight of upper components.	**N/A**

Leveling System: Avionics

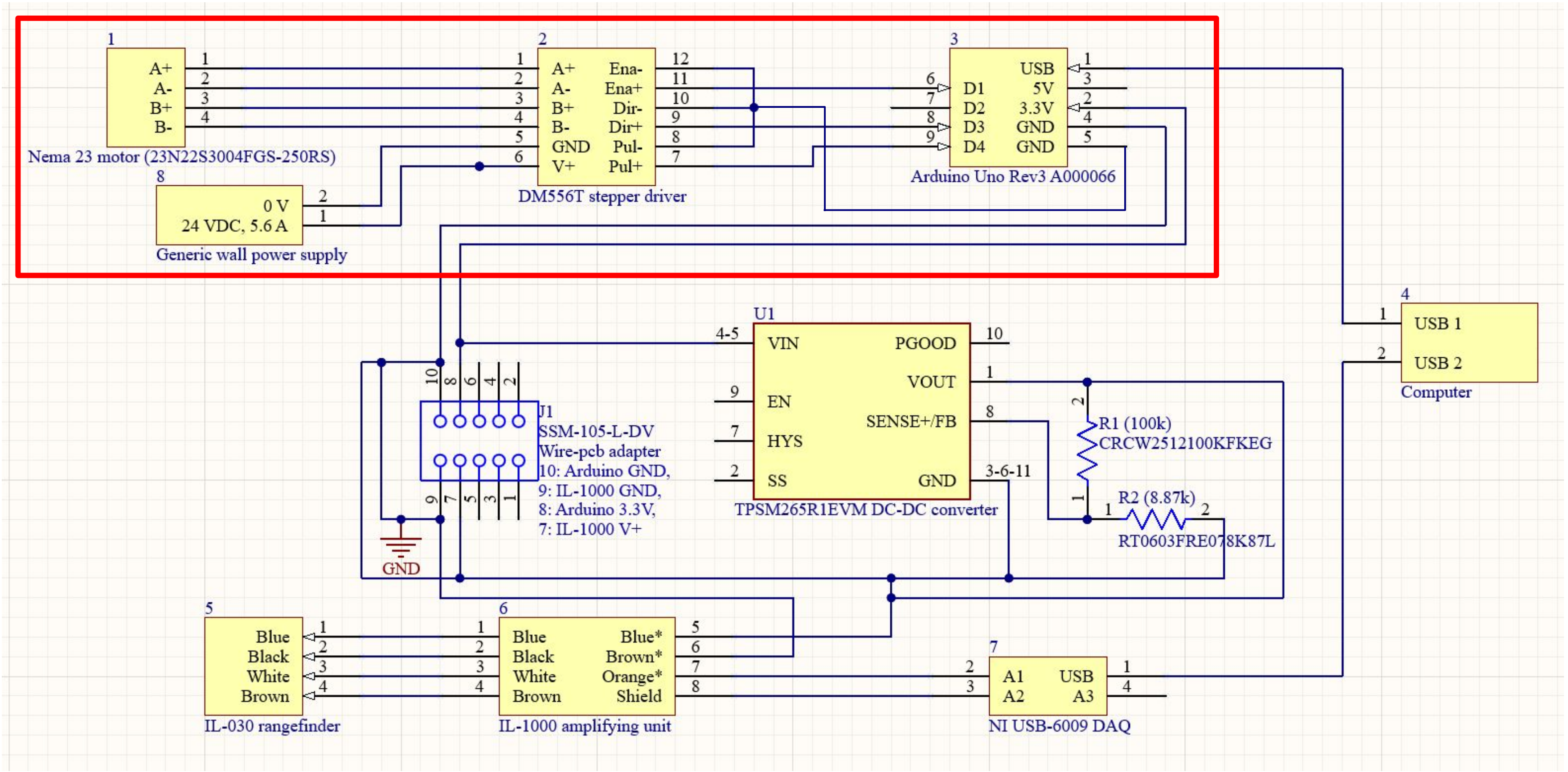
System Architecture



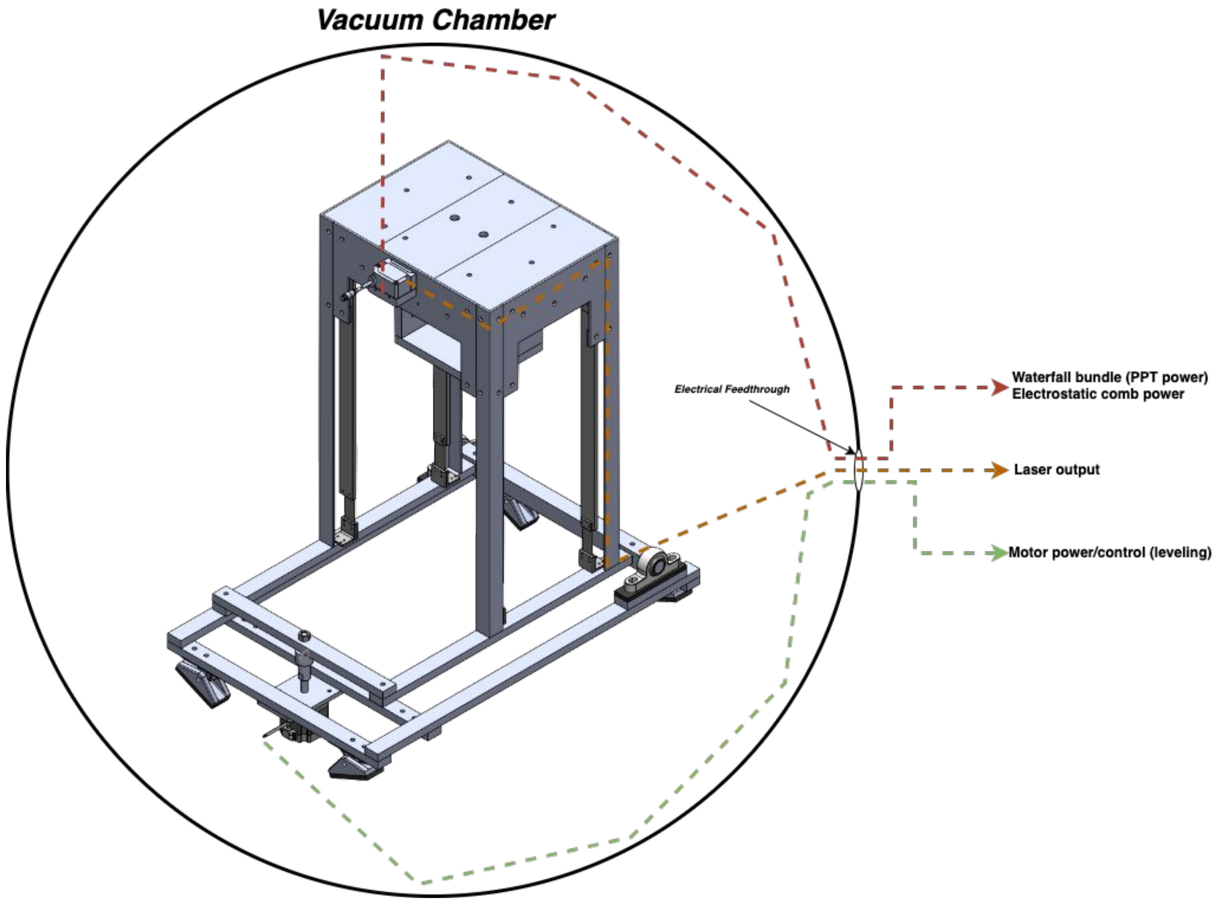
Driving Requirements

ID	Requirement	Verification Method
Ls.4	Electronics/hardware must have **minimal conductive components**	*Inspection*
Ls.5	Stepper must be able to actuate so that leveling system may **pitch between ±3 degrees**	*Test*
Ls.6	Stepper must be able to actuate so that leveling system has **minimum resolution of 0.001 degrees**	*Test*

Leveling System: Avionics Overview

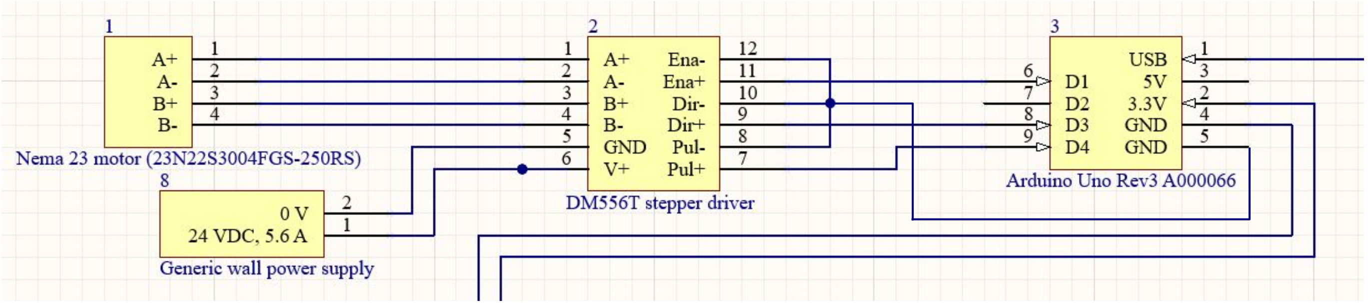


Leveling System: Avionics Overview



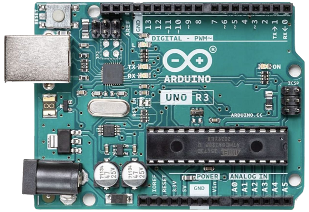
Leveling System: Avionics

Ls.4: minimal conductive components



Power supply [i19]

DM556T [i5]



Arduino Uno [i6]

Nema 23 non-captive motor [i4]

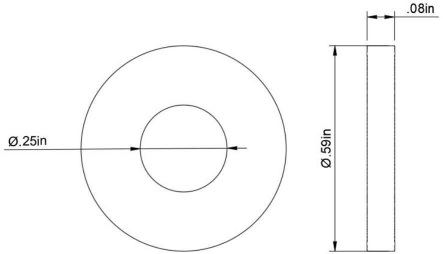
- Non-captive actuator model chosen for smaller footprint compared to other design options
- Nema 23 metal actuator rod converted to 3D printed part
  - Custom design allows for more flexibility
  - **Satisfies Ls.4** by reducing conductive material
- DM556T chosen for high compatibility with Arduino Uno and Nema 23 motors

Leveling System: Avionics

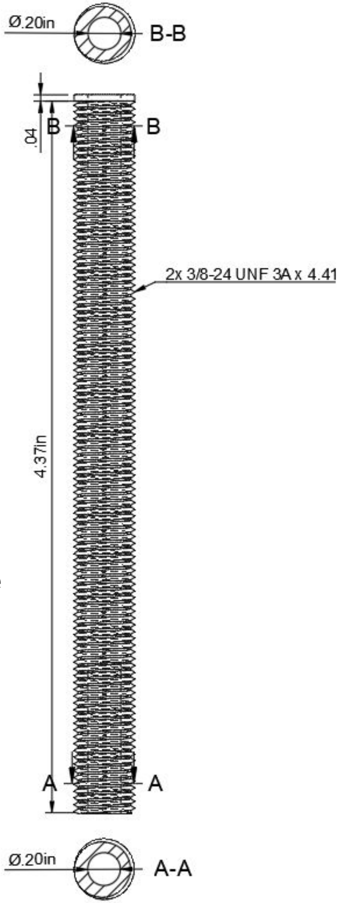
Ls.5: pitch between ± 3°

Nema-23 Actuator Rod

- A custom actuator rod will be 3D printed with ⅜” ACME threads and smoothbore holes on either end designed to fit 1/4-20 threads using PETG filament
    - Holes are printed undersized to be threaded by hand
    - First attempt at printing yielded scaffolding bonding
    - Second attempt at printing without scaffolding was with incorrect thread, print quality was passable
- A circular stopper is attached to the screw by a bolt through the hole shown in the A-A section view. A leveling adapter is threaded in the hole shown in the B-B section view



Circular stopper



Actuator screw


PLA Threaded Prototype

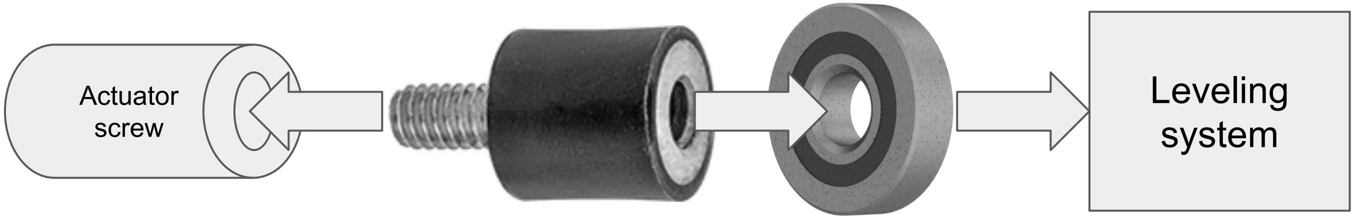
Leveling System: Avionics

WW, BF

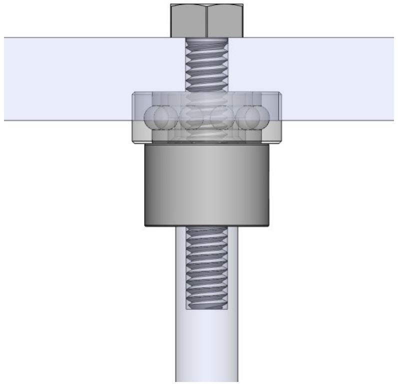
Ls.5: pitch between ± 3°

Leveling adapter

- A custom adapter made of a metal bearing and isolator mount will integrate the actuator screw and leveling system
- Isolator has 1/4-20 threads
- Isolator is flexible to allow system dynamics to function properly
  - Rated at ±7.5 degree max bending based on max shear load
- Bearing rotates to allow actuator screw motion
- Bearing is held in place by a combination of friction fit and gravitational force in a counterbored hole



Isolator mount [i23] *Metal bearing [i22]*

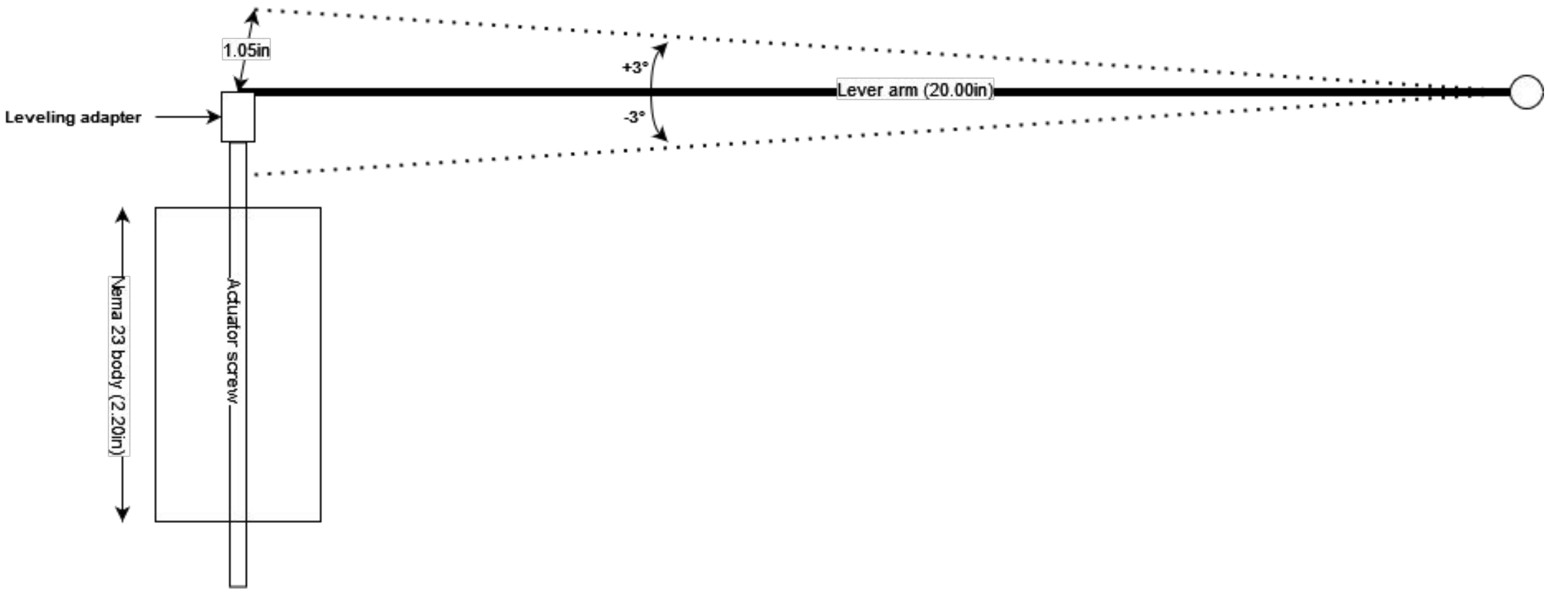


Leveling adapter CAD

Leveling System: Avionics

WW

Ls.5. pitch between ± 3°, Ls.6: minimum resolution 0.001 degrees



- Nema 23 applies 0.05 in axial displacement per revolution → stand angle can be adjusted with a resolution of 4.41E-5 degrees per revolution
    - **Satisfies Ls.6** requiring resolution of 0.001 degrees
- Actuator screw length must be at least *2.20 in*+*(2*1.05 in)*=*4.30 in* to satisfy ±3 degree adjustment range **required by Ls.5**

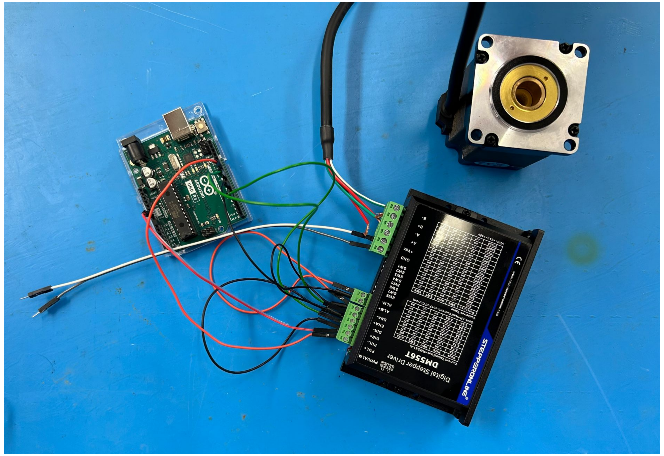
Leveling System: Avionics

WW

Subsystem Testing

Stepper Motor Verification Plan

- Confirm rated axial displacement of screw per revolution
- Confirm intended displacement range of custom screw
  - Determine print settings to optimize screw functionality
- Determine minimum step size
  - Note motor current draw requirement



Arduino Uno, Stepper Driver, and Stepper Motor

Leveling System: Avionics

Requirements Review

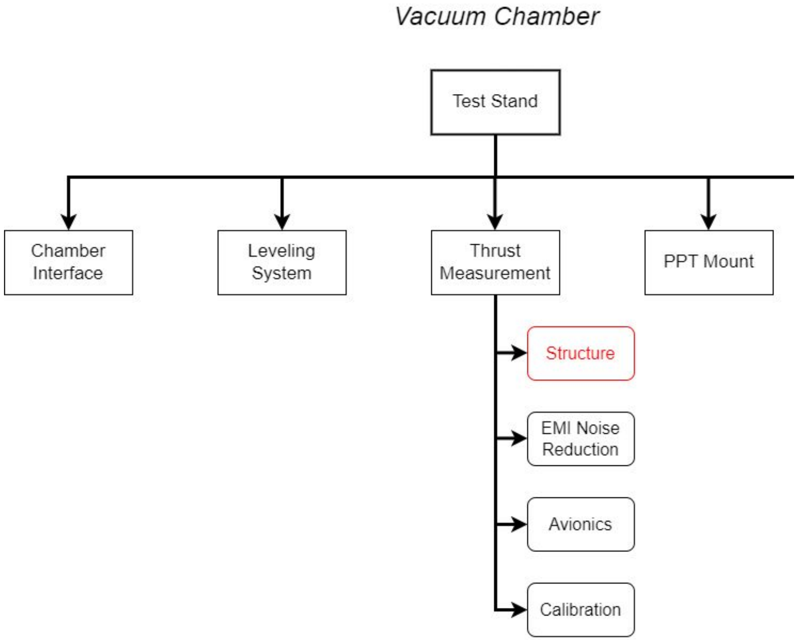
ID	Requirement	Satisfied via:	Sys. req. met:
Ls.4	Electronics/hardware must have **minimal conductive components**	Custom actuator rod printed with PETG	**Sys.2**
Ls.5	Stepper must be able to actuate so that leveling system may **pitch between ±3 degrees**	Nema-23 motor with custom length screw and leveling adapter	**N/A**
Ls.6	Stepper must be able to actuate so that leveling system has **minimum resolution of 0.001 degrees**	Nema-23 axial displacement per revolution of 0.05 in	**Sys.8**

Leveling System: Budget Summary

Category	Item	Cost	Total
Structure	Ball bearing	$ 20.47	$ 27.47
	Vibration damping sandwich mount	$ 7.00	
Avionics	Linear Stepper Motor	$ 51.19	$ 96.02
	Digital Stepper Driver	$ 20.86	
	24 V Power Supply	$ 16.99	
	Multicolored Dupont Wire	$ 6.98	
Software			
Other			
			$ 123.49

Thrust Measurement: Structure

System Architecture



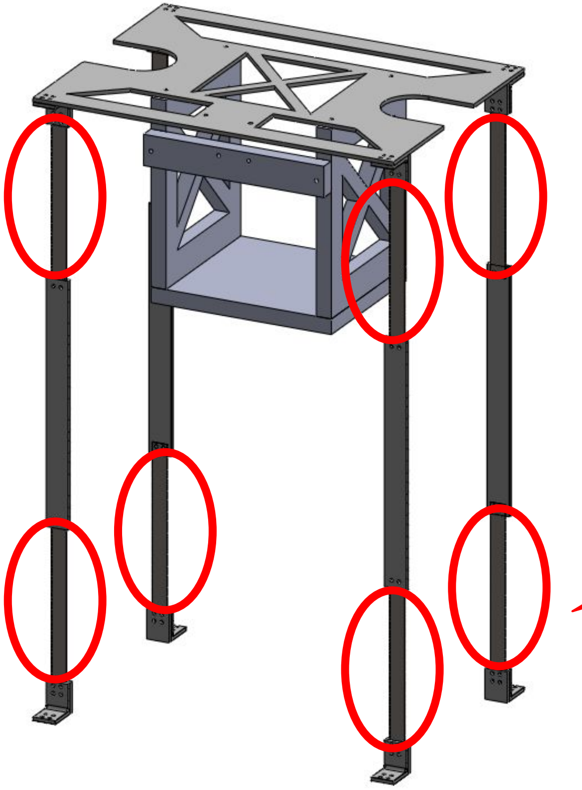
Driving Requirements

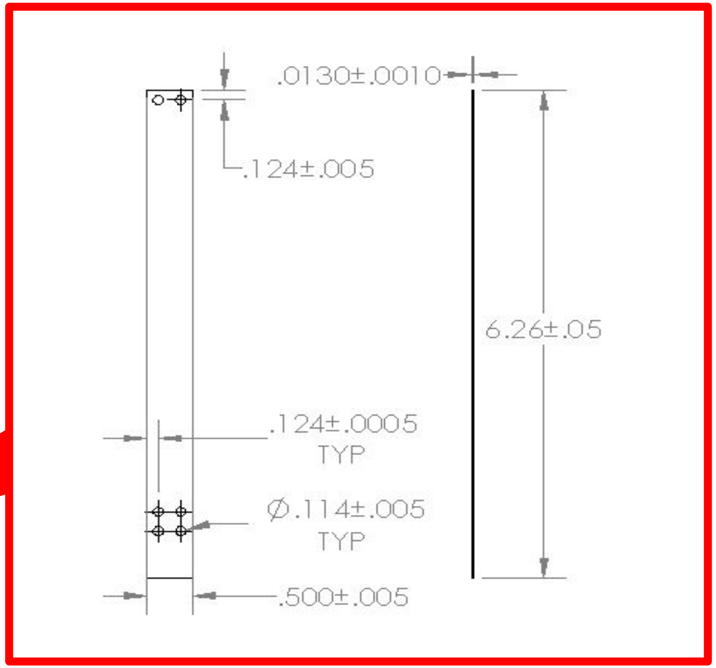
ID	Requirement	Verification Method
Tm.1	Flexure spring constants must allow for **2.25 μlbf*s to 22.5 mlbf*s** (10 μN*s to 100 mN*s) **impulses** and **22.5 μlbf to 22.5 mlbf** (0.1 mN to 0.1 N) **steady-state forces** to be resolved	*Analysis*
Tm.2	Flexures must be replaceable/interchangeable	*Inspection*

Thrust Measurement: Structure

LL, AD

*Tm.1: 2.25 µlbf*s to 22.5 mlbf*s impulses and 22.5 µlbf to 22.5 mlbf steady-state forces*





**All units in inches unless otherwise specified*

Thrust Pendulum Assembly with 8 Flexures Highlighted

Thrust Measurement: Structure

WW, LL

*Tm.1: 2.25 µlbf*s to 22.5 mlbf*s impulses and 22.5 µlbf to 22.5 mlbf steady-state forces*

- Angular equation of motion iterated through **ode89** to solve for dynamic response
  - Peak deflection predicted by the **solved angular equation of motion** and compared to ode89 results
- The pendulum's **8 flexures** are modeled as a single effective spring
  - Collinear flexures on each arm are modeled in series
  - The four arms together are modeled in parallel

$$I_p\ddot{\theta} + c\dot{\theta} + k_{rad}\theta = \tau$$

$$k = \frac{3EI}{l^3}$$

$$k_{eff} = 4 * (\frac{1}{k} + \frac{1}{k})^{-1}$$

$$k_{rad} = k_{eff}L^2 - mgL_{cg}$$

$$c = 2\zeta\sqrt{I_p k_{rad}}$$

$$\theta(t) = \frac{I_b L}{I_p \omega_n}[\frac{1}{\sqrt{1-\zeta^2}}e^{-\zeta\omega_n t}\sin(\omega_d t)]$$

$$\dot{\theta(t)} = \omega_d e^{-\zeta\omega_n t}\cos\omega_d t - \zeta\omega_n e^{-\zeta\omega_n}\sin\omega_d t$$

$$t_{peak} = \frac{\pi}{2\omega_d}$$

$$\omega_n = \sqrt{\frac{k_{rad}}{I_p}}$$

$$\omega_d = \omega_n\sqrt{(1-\zeta^2)}$$

Equations of Motion for an Inverted Pendulum from Polk [7]

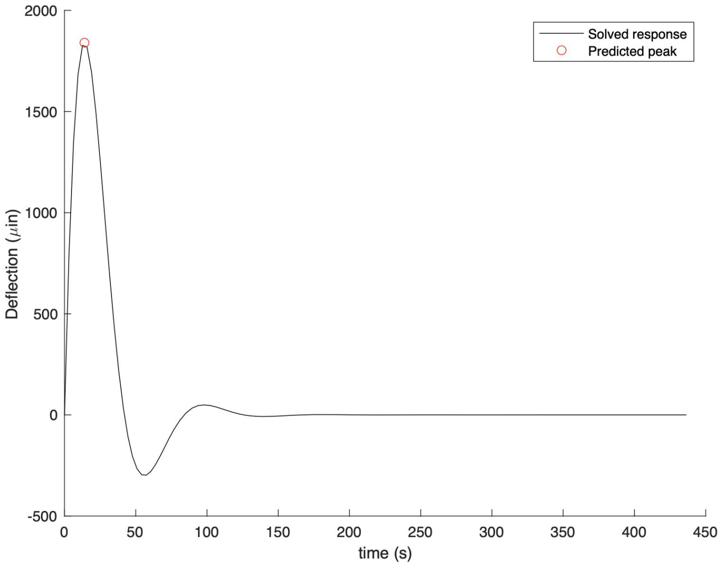
Thrust Measurement: Structure

WW, LL

*Tm.1: 2.25 μlbf*s to 22.5 mlbf*s impulses and 22.5 μlbf to 22.5 mlbf steady-state forces*

Design - Flexures

- Iterating through flexure dimensions between widths of 0.2-3”, lengths of 1-6” to solve for required thicknesses
- For the flexure thicknesses that did satisfy buckling requirements:
  - thruster masses and impulse bit were varied incrementally within an impulse response Matlab script
- This yielded results that were used to generate a flexure selection chart



*Sample deflection plot for 0.22 lbf thruster with 2.25 μlbf*s impulse bit using flexure set 1 and zeta=0.3*

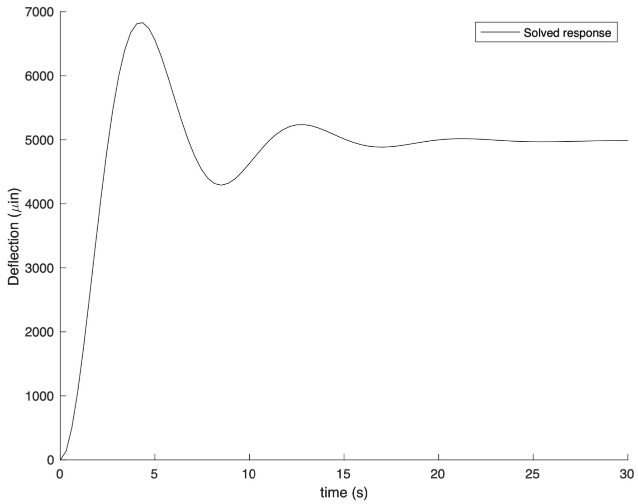
Thrust Measurement: Structure

WW, LL

*Tm.1: 2.25 μlbf*s to 22.5 mlbf*s impulses and 22.5 μlbf to 22.5 mlbf steady-state forces*

Design - Flexures

- At low impulses, extremely low k values could yield higher displacements
- A minimum k value of 2.25E-4 mlbf*s/rad was set to balance between resolvable deflection and system interference (i.e. waterfall)
- All solution outputs require that flexure loading be less than critical buckling loading by FoS>=2
- Ideal settling times are on the order of 10 s, extremely low k required to resolve low impulses results in high settling time
    - Acceptable for fringe case testing



*Sample deflection plot for 0.13 lbf thruster with 22.5 lbf*s steady-state thrust using flexure set 1 and zeta=0.3*

Thrust Measurement: Structure

*Tm.1: 2.25 μlbf*s to 22.5 mlbf*s impulses and 22.5 μlbf to 22.5 mlbf steady-state forces*

Flexure Selection Chart

		Impulse Bit (lbf*s)				
		2.25E-07	2.25E-06	2.25E-05	2.25E-04	2.25E-03
Thruster Weight (lbf)	0.220	0.84, 0.01	0.84, 0.01	0.9, 0.01	0.82, 0.02	1, 0.1
	0.441	0.9, 0.01	0.9, 0.01	0.96, 0.01	0.82, 0.02	1, 0.1
	0.661		0.96, 0.01	0.96, 0.01	0.82, 0.02	1, 0.1
	0.881			0.98, 0.015	0.82, 0.02	1, 0.1
	1.10			0.98, 0.015	0.82, 0.02	1, 0.1
	1.32			0.98, 0.015	0.82, 0.02	1, 0.1
	1.54			0.98, 0.015	0.82, 0.02	1, 0.1
	1.76			0.98, 0.015	0.82, 0.02	1, 0.1
	1.98			0.98, 0.015	0.82, 0.02	1, 0.1
	2.20			0.98, 0.015	0.82, 0.02	1, 0.1
	3.31			0.98, 0.015	0.82, 0.02	1, 0.1
	4.41			0.98, 0.015	0.82, 0.02	1, 0.1
	5.51			0.98, 0.015	0.82, 0.02	1, 0.1
	6.61			0.98, 0.015	0.82, 0.02	1, 0.1
	7.72			0.98, 0.015	0.82, 0.02	1, 0.1
	8.82			0.98, 0.015	0.82, 0.02	1, 0.1
	9.92			0.6, 0.02	0.82, 0.02	1, 0.1
	11.0			0.6, 0.02	0.82, 0.02	1, 0.1
	12.3			0.6, 0.02	0.82, 0.02	1, 0.1
	13.2			0.6, 0.02	0.82, 0.02	1, 0.1
	14.3			0.6, 0.02	0.82, 0.02	1, 0.1
	15.4			0.7, 0.2	0.82, 0.02	1, 0.1
	16.5			0.7, 0.2	0.82, 0.02	1, 0.1
	17.6			0.7, 0.2	0.82, 0.02	1, 0.05
	18.7			0.7, 0.2	0.82, 0.02	1, 0.05
	19.8			0.82, 0.02	0.82, 0.02	1, 0.05
	20.9			0.82, 0.02	0.82, 0.02	1, 0.05
	22.0			0.82, 0.02	0.82, 0.02	1, 0.05

Thrust Measurement: Structure

WW, LL

*Tm.1: 2.25 μlbf*s to 22.5 mlbf*s impulses and 22.5 μlbf to 22.5 mlbf steady-state forces*

Design - Flexures

From the Matlab script, 8 flexure sets were defined for a constant length of 0.105”:

- **Set 1:**
  Thickness: 0.01”
  Width: 0.84”
- **Set 2:**
  Thickness: 0.9”
  Width: 0.01:
- **Set 3:**
  Thickness: 0.96”
  Width: 0.01”
- **Set 4:**
  Thickness: 0.98”
  Width: 0.015”
- **Set 5:**
  Thickness: 0.6”
  Width: 0.02”
- **Set 6:**
  Thickness: 0.7”
  Width: 0.2”
- **Set 7:**
  Thickness: 0.82”
  Width: 0.02”
- **Set 8:**
  Thickness: 1”
  Width: 0.1”
- **Set 9:**
  Thickness: 1”
  Width: 0.05”

Thrust Measurement: Structure

WW, LL

*Tm.1: 2.25 μlbf*s to 22.5 mlbf*s impulses and 22.5 μlbf to 22.5 mlbf steady-state forces*

Design - Ballasts

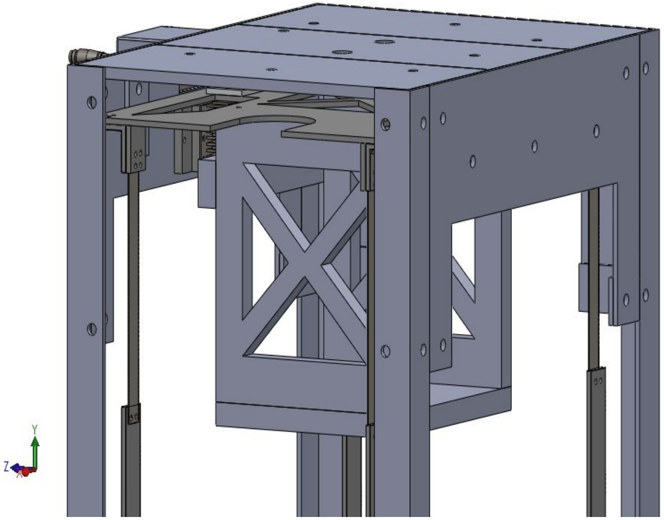
- Response are **extremely sensitive**, so ballasts should be used to attain rated thruster mass per flexure set
  - Ballasts must be **non-conductive, vacuum safe, and relatively dense**
- 0.5” Garolite sheets blocks are recommended and will be provided to SPACE lab in increments of **0.22, 0.11, and 0.02 lbf**
  - Sheets will be cut down into blocks are desired weights

Garolite sheet [i27]

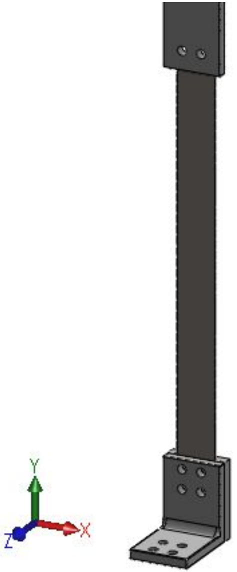
Thrust Measurement: Structure

AD

Tm.2: Flexures must be replaceable/interchangeable



***Flexures accessible under frame**. Side of frame removed for clarity*



*Flexures held in place with 6 through bolts and nuts. **Effective flexure length** is **4.9 inches**. Bottom shown, top similar*

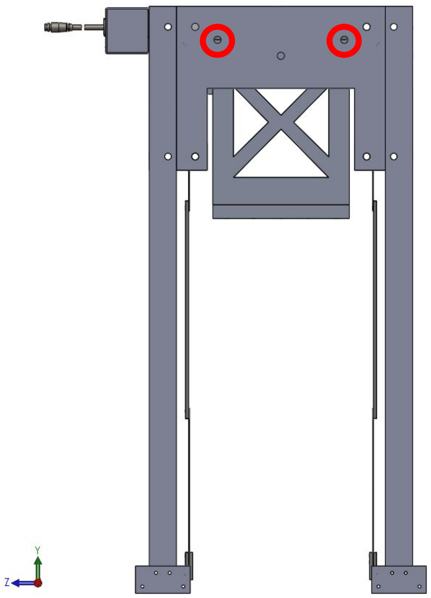
*Fully removed flexure. **Overall length** of **6.26 inches**, **overall width** of **0.5 inches***

Tm.2 Replaceable/Interchangeable satisfied by this design strategy

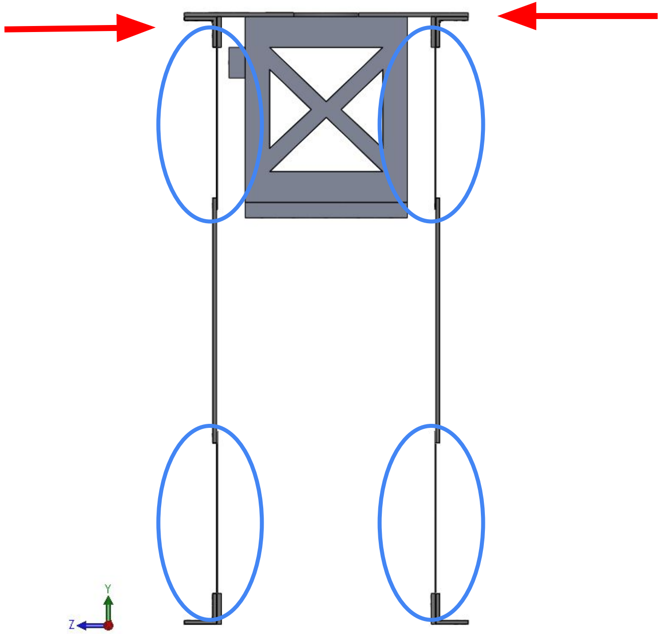
Thrust Measurement: Structure

AD

Tm.2: Flexures must be replaceable/interchangeable



*¼” **pins or bolts** can be inserted in these holes to **hold top of pendulum during flexure change**. Left side shown, right side similar*



Top** (highlighted in red) **held by pins** while **flexures** (circled in blue) are **changed**. Flexures accessible under frame for **ease of removal

Thrust Measurement: Structure

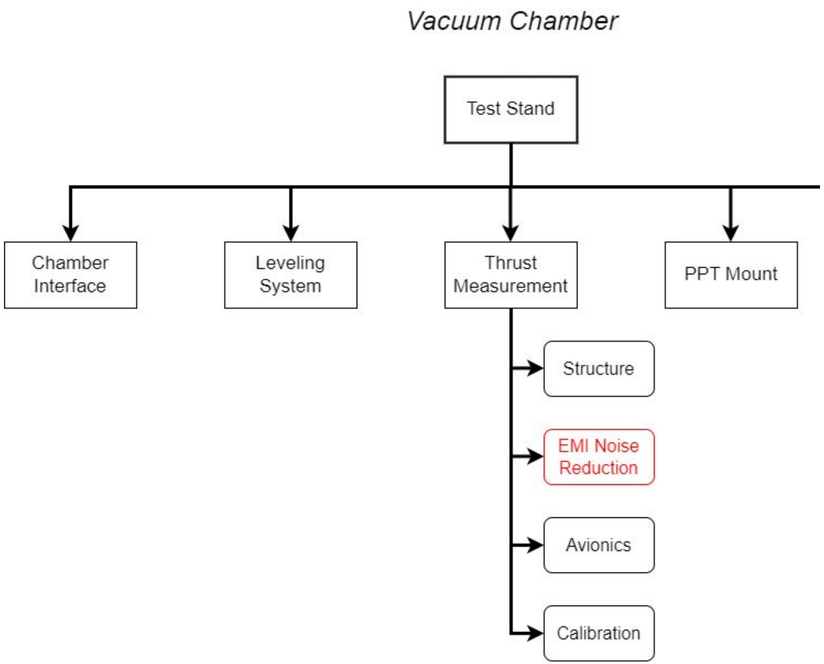
Requirements Review

ID	Requirement	Satisfied via:	Sys. req. met:
Tm.1	Flexure spring constants must allow for **2.25 μlbf*s to 22.5 mlbf*s** (10 μN*s to 100 mN*s) **impulses** to be tested	Use of 9 sets of flexures	**Sys.3** **Sys.4**
Tm.2	Flexures must be **replaceable/interchangeable**	Removable flexure fasteners & ergonomic structure	

Thrust Measurement: EMI Shielding

KLV

System Architecture



Driving Requirements

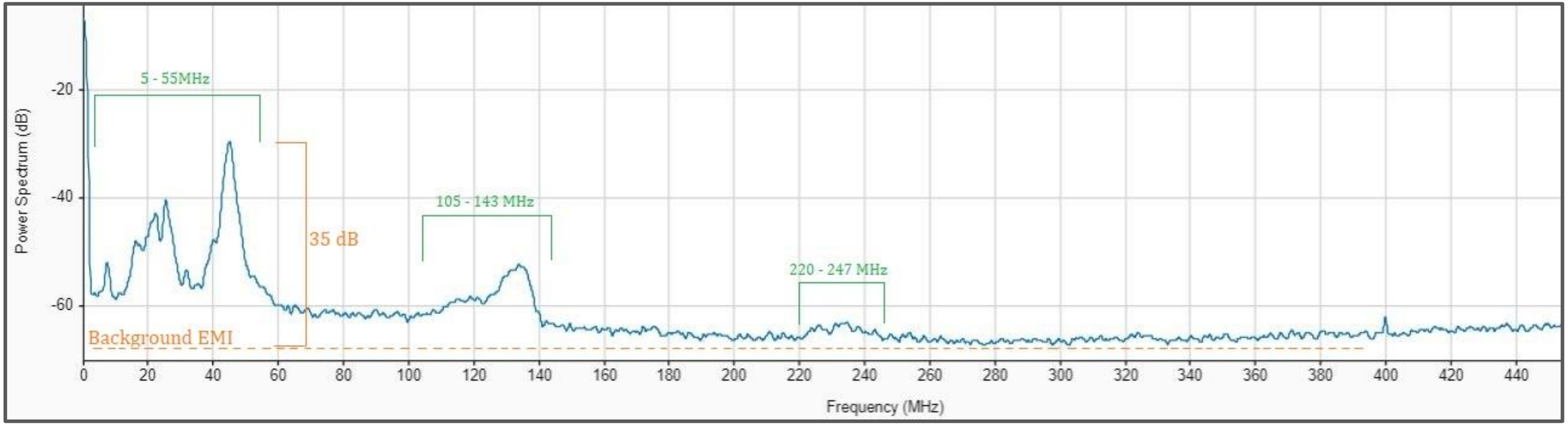
ID	Requirement	Verification Method
Tm.3	Provide **35 dB of attenuation** to for signal frequencies **between 5 MHz to 250 MHz**	*Test*

Thrust Measurement: EMI Shielding

Tm.3: 35 dB of attenuation, between 5 MHz to 250 MHz

- Collected EMI attenuation data from Dawgstar and applied a FFT to determine peak frequency intensities
- Notable frequency peaks:
  - **5 - 247 MHz range**
- **Minimum shielding attenuation required:**
  - **35 dB**
- **Thickness copper needed:**
  - **0.0024”**

Noise Power Spectrum from 0-450 MHz



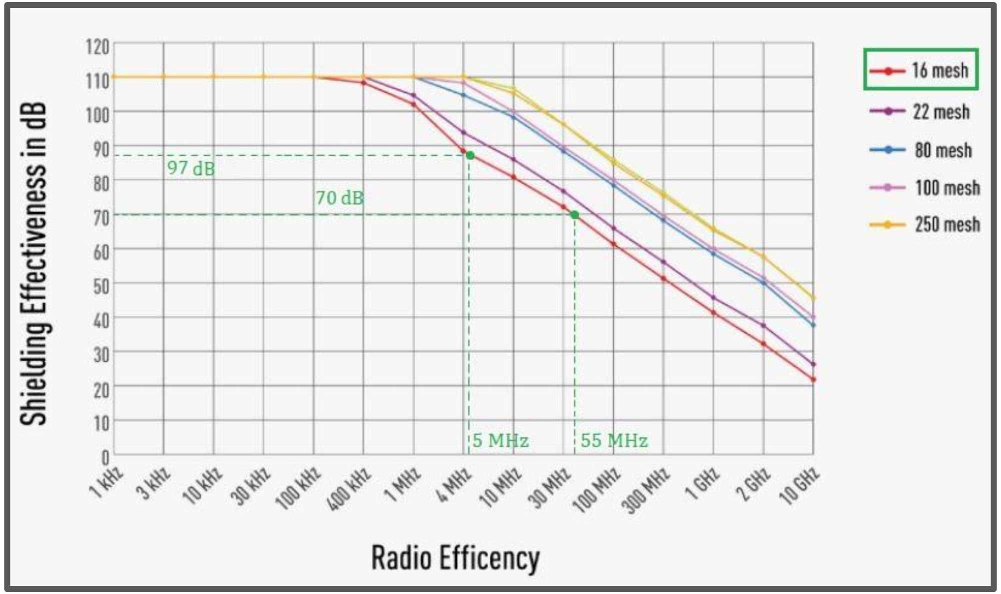
Thrust Measurement: EMI Shielding

KLV

Tm.3: 35 dB of attenuation, between 5 MHz to 250 MHz

- Tinned copper braiding sheath
  - Wire protection
  - Thickness: **0.013”**
  - Provides **132 - 356 dB** shielding attenuation
  - **Satisfies Tm. 3**
- Copper mesh faraday shield
  - Mesh # 16
  - Wire diameter: **0.011”**
  - Mesh size: **0.0515”**
  - Provides **70 - 97 dB** shielding attenuation
  - **Satisfies Tm. 3**

Mesh Shielding vs EMI frequency



[i26]

Thrust Measurement: EMI Shielding

WW

Tm.3: 35 dB of attenuation, between 5 MHz to 250 MHz

Rangefinder hardware shielding

- IL-1000 and USB-6009 will be contained in an aluminum box to protect against external EM waves
  - External grounding is not required
- A box will be chosen once hardware order has arrived so an optimal configuration for ease of use can be determined
  - Wire throughput holes will be drilled
- IL-1000 and USB-6009 have an approximate combined footprint of 6.3 in x 4.2 in

Electronics box example [i20]

Thrust Measurement: EMI Shielding

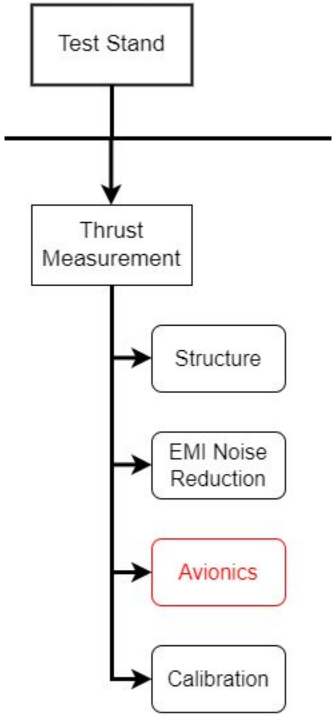
Requirements Review

ID	Requirement	Satisfied via:	Sys. req. met:
Tm.3	Provide **35 dB of attenuation** to for signal frequencies **between 5 MHz to 250 MHz**	Copper braid & mesh shielding	**Sys.3**

Thrust Measurement: Avionics

WW

System Architecture

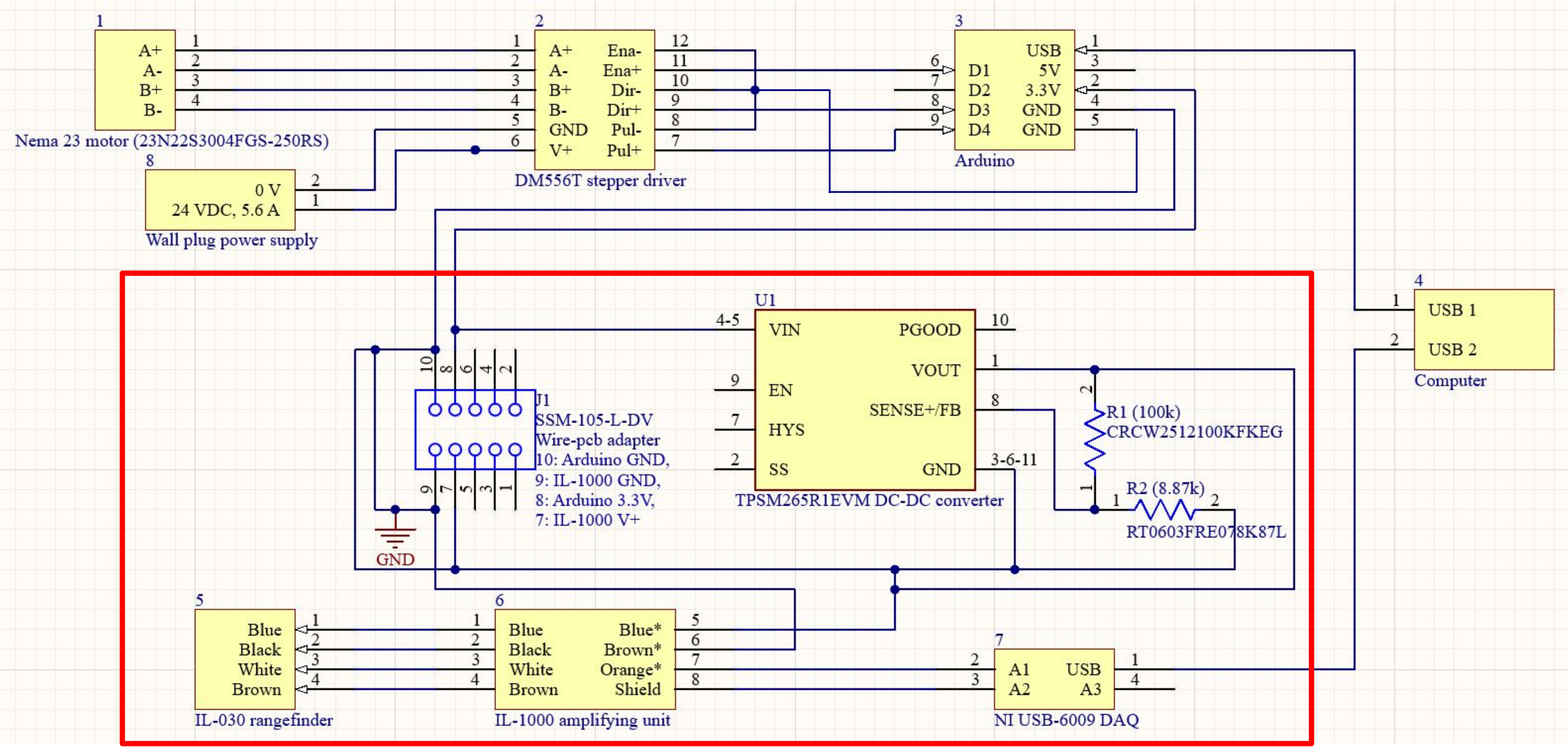


Driving Requirements

ID	Requirement	Verification Method
Tm.4	DAQ must be capable of sampling at least **40x the natural frequency** of the test stand	*Demonstration*
Tm.5	DAQ must have sufficient memory to collect data for a timescale **10x the period** of the test stand	*Test*
Tm.6	Rangefinder must have **minimum resolution of half the minimum stand deflection**	*Test*

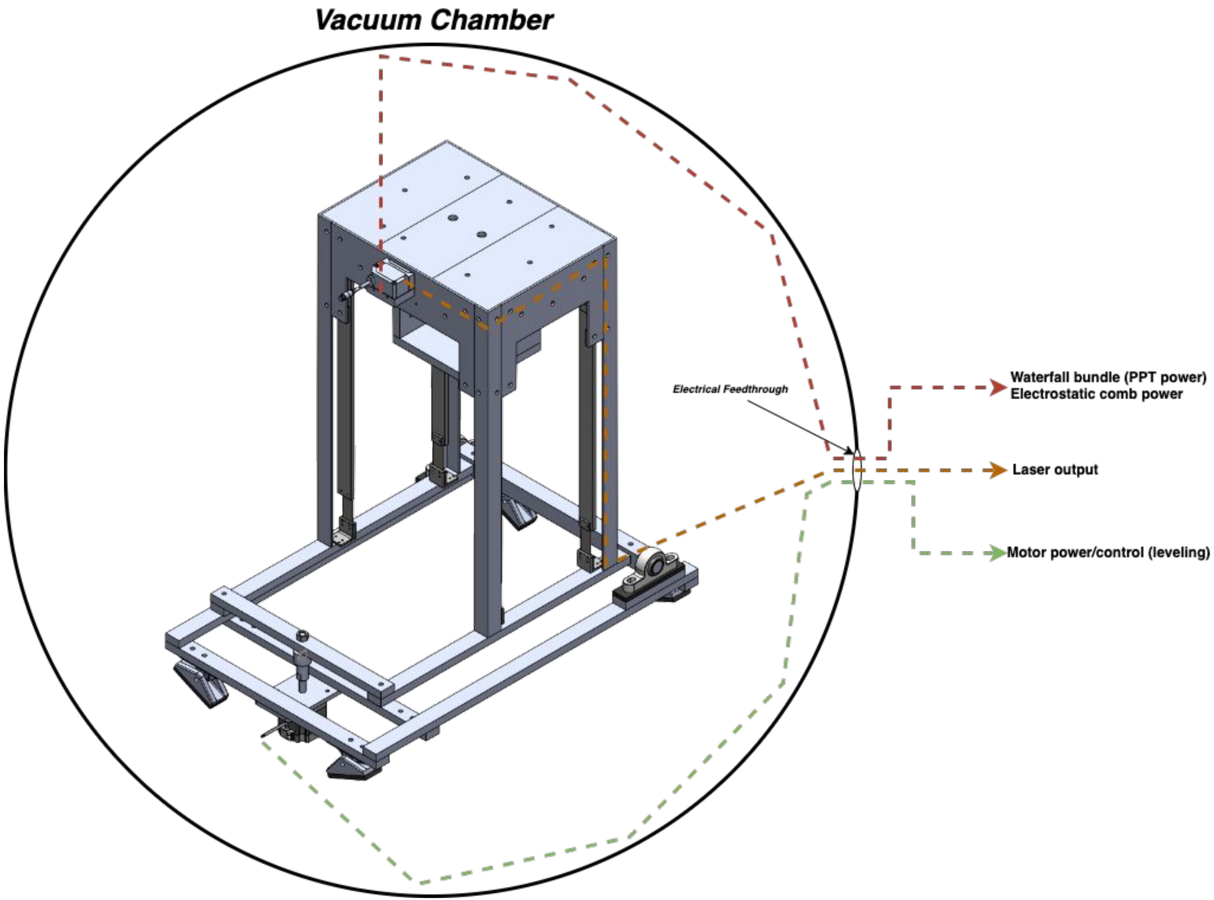
Thrust Measurement: Avionics Overview

WW



Thrust Measurement: Avionics Overview

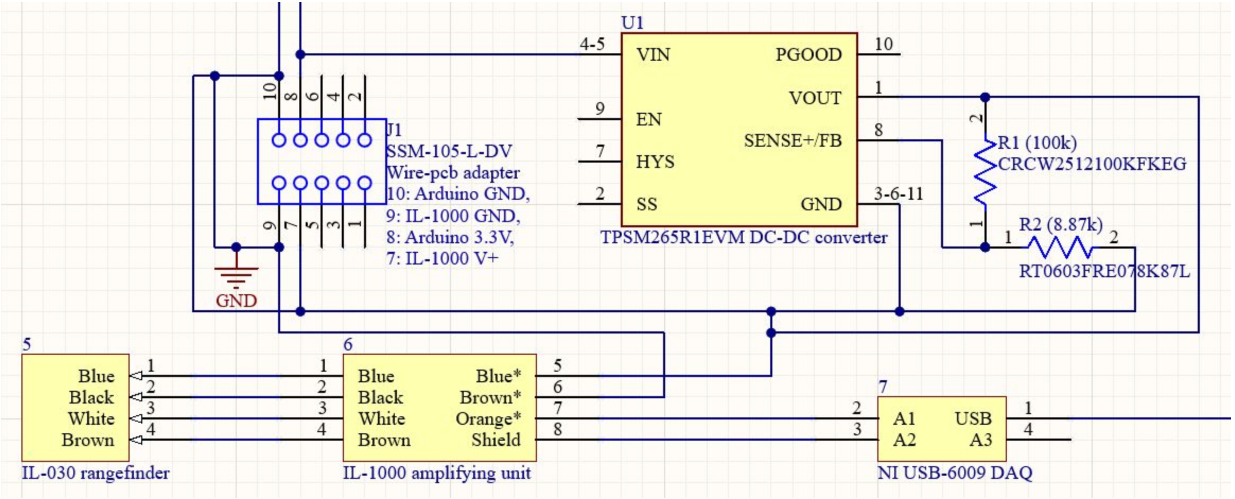
WW



Thrust Measurement: Avionics

WW

Tm.4: 40x the natural frequency of the test stand Tm.5: 10x the period



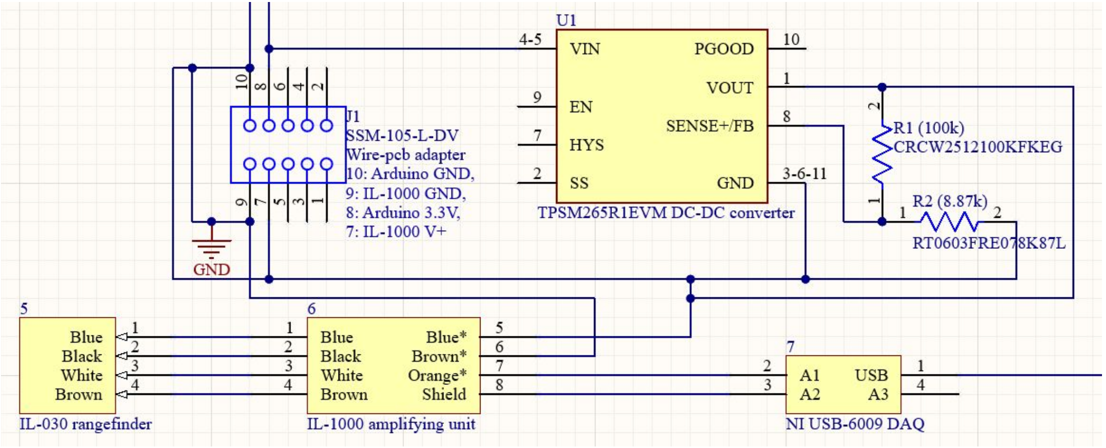
USB-6009 [i3]

- NI USB-6009 chosen for sampling rate capabilities, compatibility with NIDAQmx, and price point
  - Programmable sampling rate with maximum of 48 kHz **satisfies Tm.4** of data collection resolution based on expected test stand natural frequency of 1 - 10 Hz
- NI USB-6009 has 512 byte FIFO buffer for data transferred to the computer
  - **Satisfies Tm.5 of** sufficient DAQ memory size

Thrust Measurement: Avionics

WW

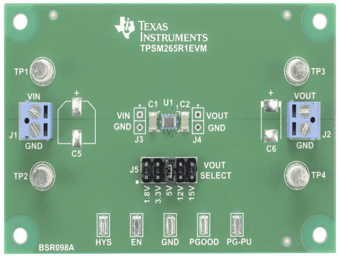
Tm.6: minimum resolution of half the minimum stand deflection



- IL-030 has a rated resolution of 788 μin (20 μm, to be verified) and programmable 1 - 3 kHz output frequency
  - **Satisfies Tm.6** of minimum resolvable deflection
- IL-1000 compatible with IL-030 for signal amplification prior to digitization
- TPSM265R1EVM receives 3.3V power source from Arduino and boosts it to 15V with 100mA to power IL-1000
  - Within maximum power limit for IL-1000 of 2300mW

IL-030 [i1]

IL-1000 [i2]



TPSM265R1EVM [i21]

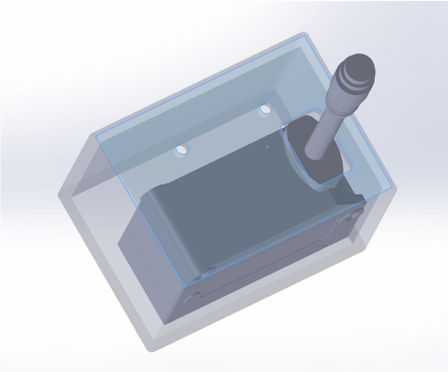
Thrust Measurement: Avionics

WW, AD, LL

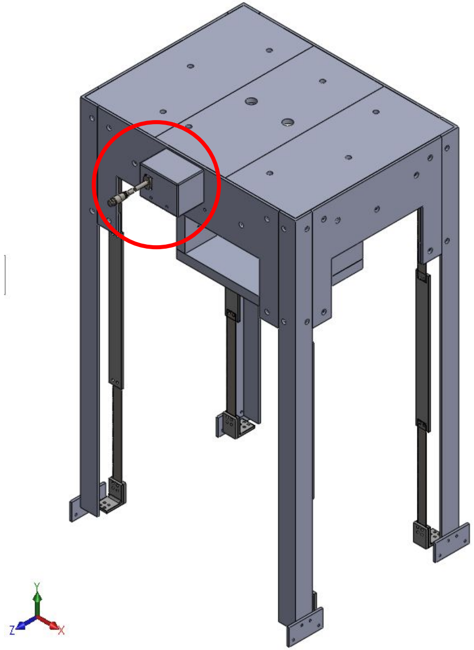
Tm.6: minimum resolution of half the minimum stand deflection

Rangefinder CAD

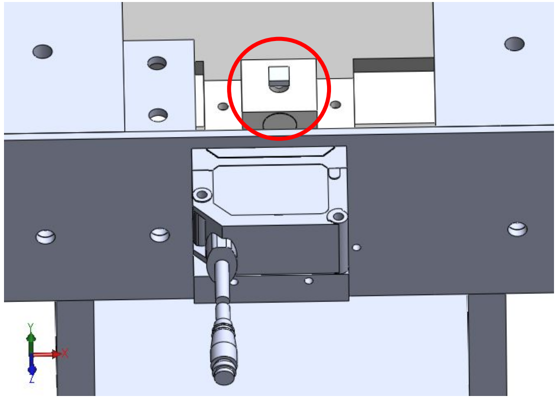
- Laser body sits on top of custom printed mount
- Laser housing covered by copper mesh for EMI shielding
- Hole in garolite structure allows for laser to see target on pendulum



Laser rangefinder housing



Laser and housing mounted on test stand



Magnetic damper with laser target on the side

Thrust Measurement: Avionics

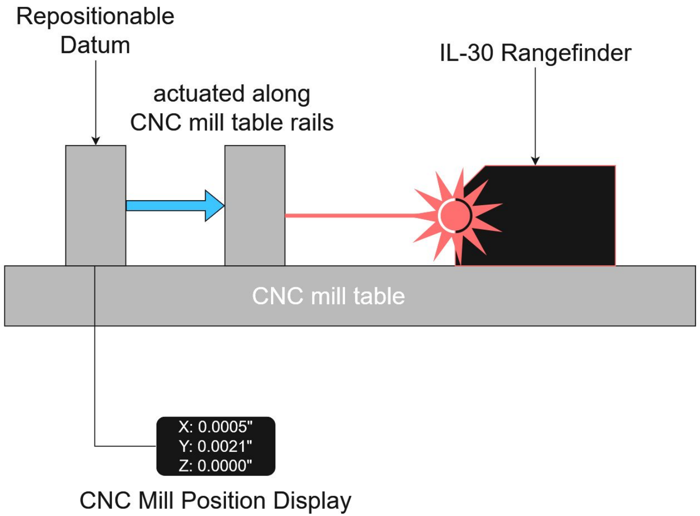
WW, LL

Subsystem Testing

Rangefinder Verification Plan

To be completed upon the arrival of relevant IL-series hardware

- SPACE Lab's IL-100 rangefinder is not available for testing
- Use ME CNC mill table to move a target in 500 μin (12.7 μm) increments
  - ME shop has confirmed available use for this test
- Determine the minimum displacement of the target for the IL-030 to resolve a difference in distance from a target



Rangefinder resolution test setup

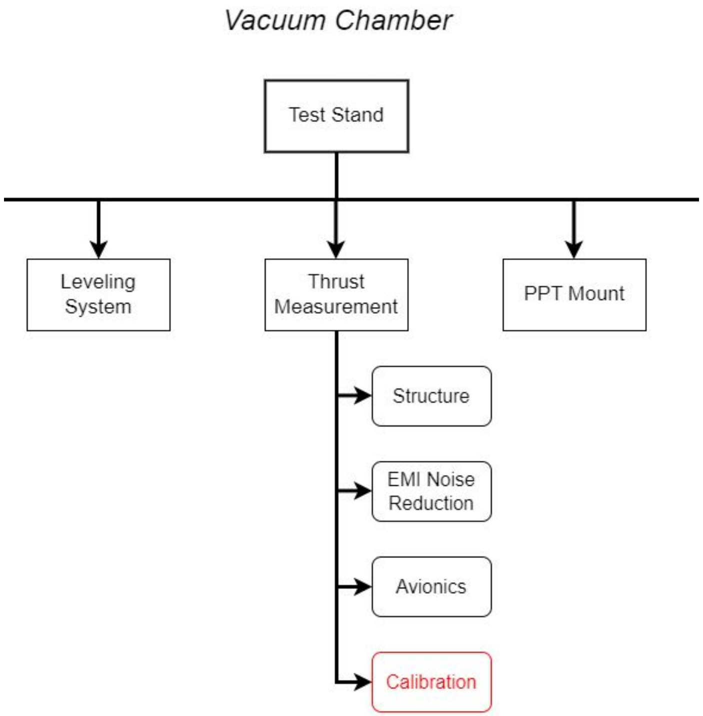
Thrust Measurement: Avionics

Requirements Review

ID	Requirement	Satisfied via:	Sys. req. met:
Tm.4	DAQ must be capable of sampling at least **40x the natural frequency** of the test stand	NI USB-6009 48 kHz maximum sampling rate	**N/A**
Tm.5	DAQ must have sufficient memory to collect data for a timescale **10x the period** of the test stand	NI USB-6009 512 byte FIFO buffer	**N/A**
Tm.6	Rangefinder must have **minimum resolution of half the minimum stand deflection**	Rangefinder rated resolution of 788 μin	**Sys.3** **Sys.4**

Thrust Measurement: Calibration

System Architecture



Driving Requirements

ID	Requirement	Verification Method
Tm.7	Calibration procedure must be completable **under vacuum**	*Demonstration*
Tm.8	**Stand configuration must not change** between calibration and testing	*Demonstration*

Thrust Measurement: Calibration

AD

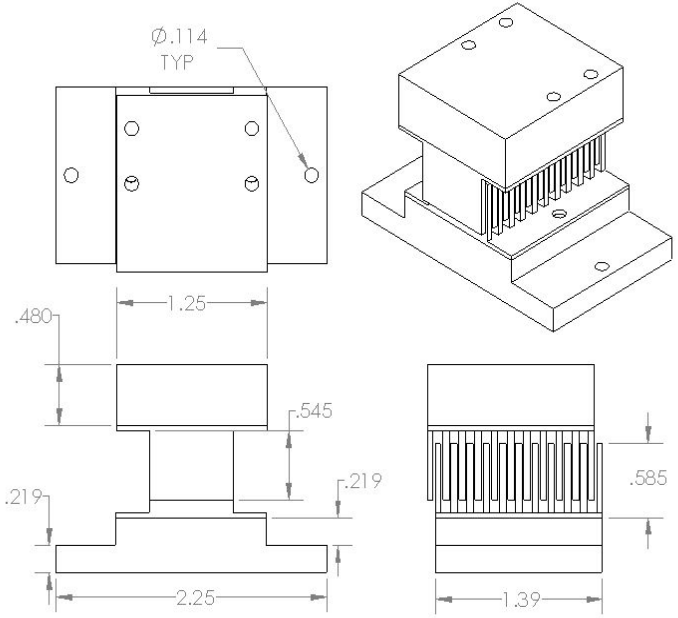
Tm.7: Calibration procedure must be completable under vacuum

Design - Additional Considerations

- Successful operation of the test stand requires a known impulse to calibrate the displacement of the sensor relative to the force

Calibration Approach

- An electrostatic comb array designed by Curtis Promislow, a SPACE Lab PhD candidate, shall be used to generate a known impulse to calibrate the deflection of the pendulum
- Stand is able to be calibrated while under vacuum



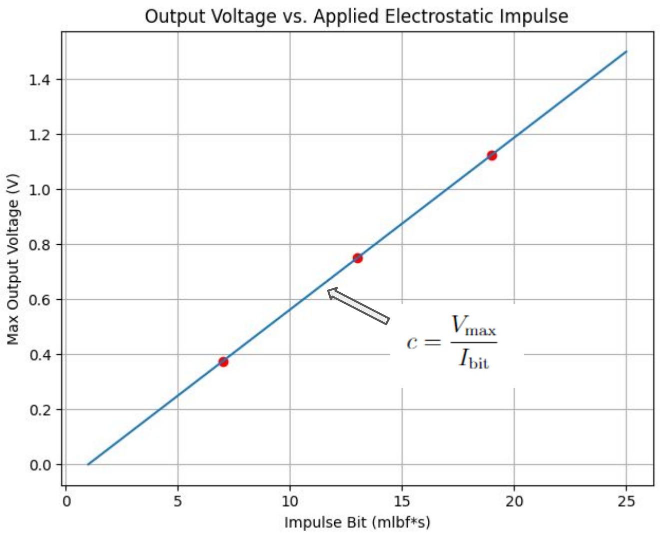
Electrostatic Comb CAD

Thrust Measurement: Calibration

Tm.7: Calibration procedure must be completable under vacuum

Electrostatic Fin Calibration - Impulse

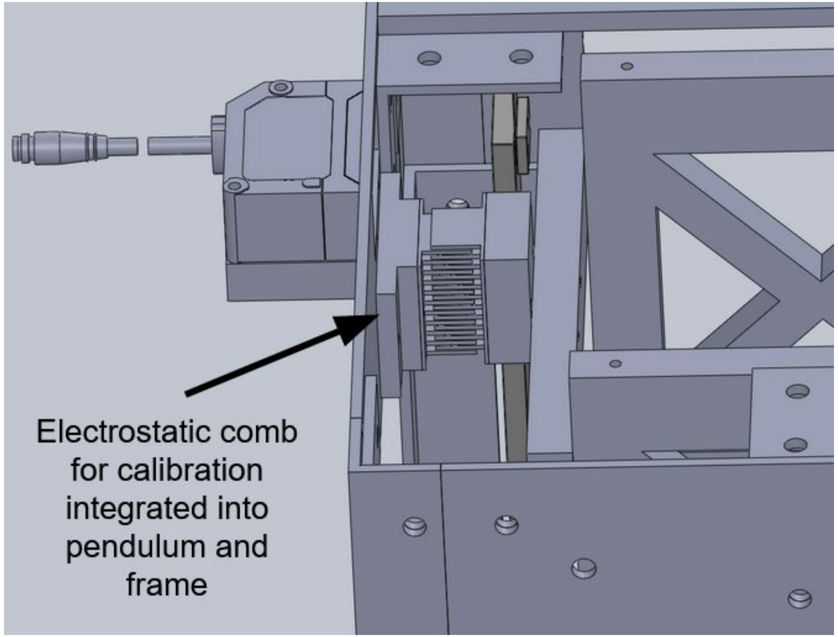
- A plot of Linear Impulse is generated to determine the slope *c*, which represents the calibration constant of the system for the duration of testing for that day.
- This determination of the slope *c* ensures that the system's response is accurately calibrated for the specific testing conditions.
- The calibration process should be repeated before and after testing to ensure consistency and accuracy in the system's performance across different operating conditions.
- Data collection system discussed in further detail in *Data Analysis*
  - Calibration procedure **satisfies Tm.7**



$$V_{max} = c \times I_{bit} \Rightarrow c = \frac{V_{max}}{I_{bit}}$$

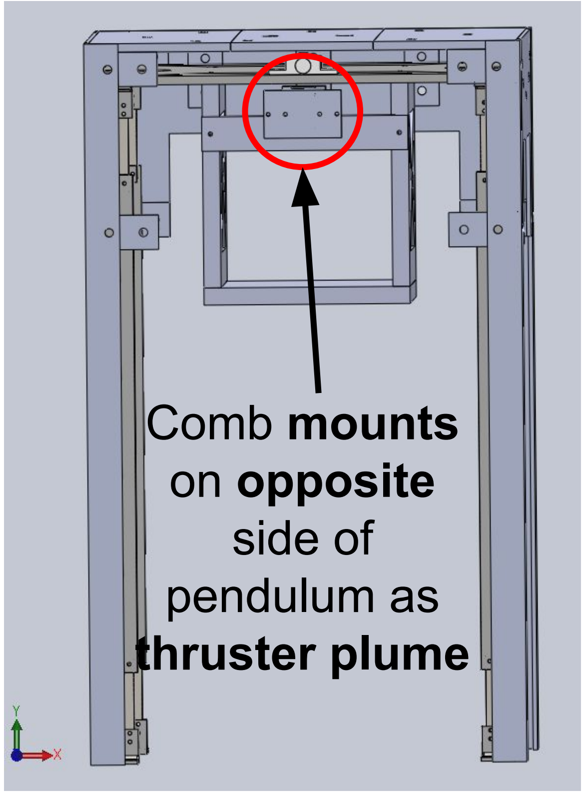
Thrust Measurement: Calibration

Tm.8: Stand configuration must not change



*One half of comb **mounts to stationary frame**, the other **mounts to shelf** for thruster mounting*

Satisfies Tm.8 for installation without configuration change



Comb mounts in center of frame to ensure no torquing of pendulum

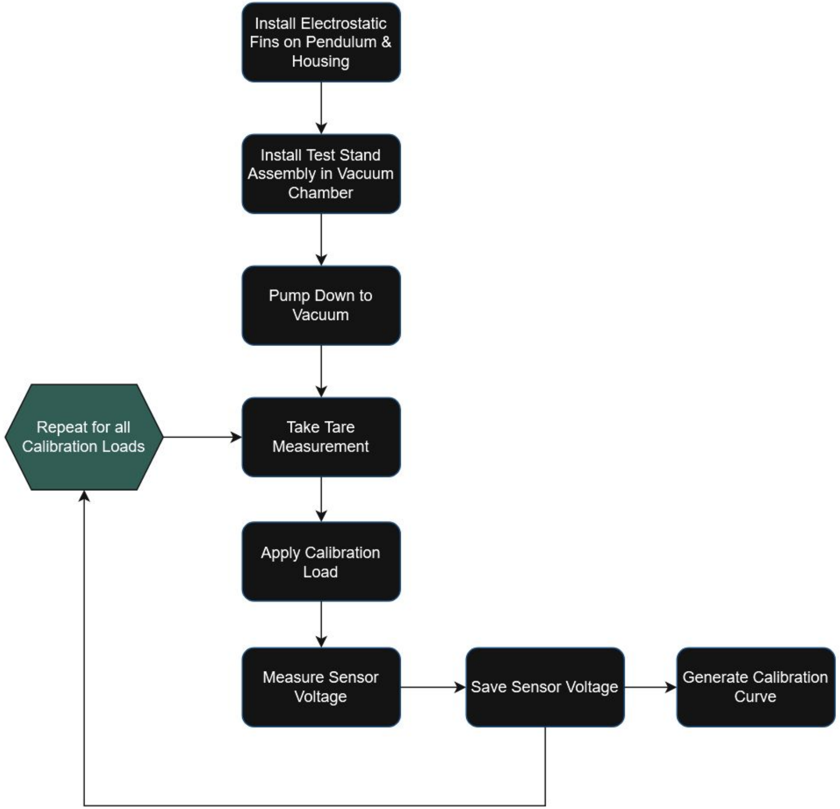
Thrust Measurement: Calibration

FC, LL

Tm.8: Stand configuration must not change

Calibration - Impulse

- In the range of the stand's operation, we expect a linear correlation between impulse bit and deflection
  - A linear regression can be applied, given several known calibration values, to determine impulse bits associated with any deflections generated throughout thruster testing.
- The process begins by running the electrostatic combs three times under different voltages to build up a calibration curve regression, with various given impulse bit values provided.
- The V_{max} associated with each impulse is then determined for each impulse bit.



Calibration Procedure Outline Derived from [1]

Thrust Measurement: Calibration

Requirements Review

ID	Requirement	Satisfied via:	Sys. req. met:
Tm.7	Calibration procedure must be completable **under vacuum**	External control and data collection system	**N/A**
Tm.8	**Stand configuration must not change** between calibration and testing	Design of pendulum and housing mounting points	**N/A**

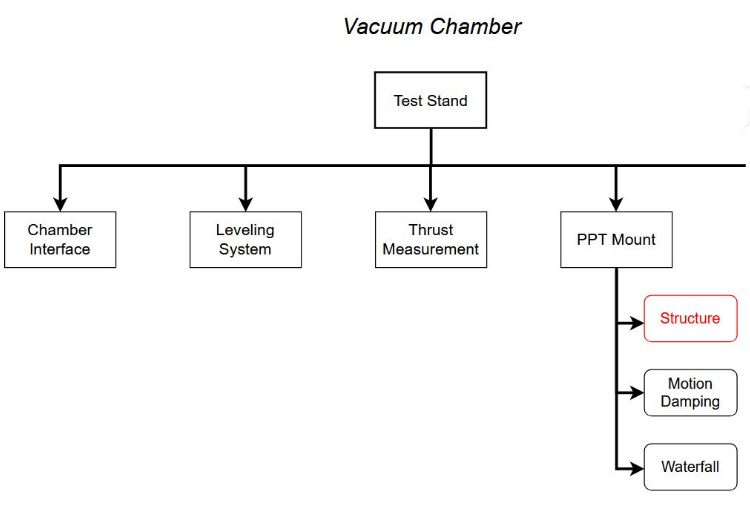
Thrust Measurement: Budget Summary

NC

Category	Item	Cost	Total
Structure	Spring Steel 0.01”	$ 45.20	$ 120.58
	Spring Steel 0.02”	$ 35.26	
	Spring Steel 0.005”	$ 40.12	
Avionics	IL - 30 Laser	$ 348.25	$ 732.75
	IL - 1000 Transducer	$ 238.00	
	DAQ	$ 62.00	
	Connectivity AMP Connectors	$ 22.60	
	Keyence Wire Adapter	$ 12.90	
	TI DC-DC Converter	$ 49.00	
Software			
Other			
			$ 853.33

PPT Mount: Structure

System Architecture



Driving Requirements

ID	Requirement	Verification Method
Pm.1	Structure must be able to **support** thrusters with mass between **2.2 lbs to 17.6 lbs**	*Analysis*
Pm.2	Test stand shelf must be wide enough to be able to **accommodate thrusters** up to **10 inches wide**	*Inspection*
Pm.3	Structure must be **non-conductive** and **outgas** in accordance with **NASA standards** for **ASTM E595** outgassing testing	*Test*
Pm.4	PPT mount structure must keep **thrusters centered to within 10% of vacuum chamber radii**	

PPT Mount: Structure

AD

Pm.1: Structure must be able to support thrusters with mass between 2.2 lbs to 17.6 lbs

Analysis - Buckling

- Only flexure buckling considered
  - Flexures are the weakest components
- Each leg of pendulum carries ¼ of the load of the thruster and stand
- **0.01 inch thick** flexures can support **2.2 lb** thruster and mass of test stand structure with a **factor of safety** of **3.13**
- **0.05 inch thick** flexures can support **17.6 lb** thruster and mass of test stand structure with a **factor of safety** of **4.32**
- As no buckling or permanent deformation occur during normal operation, after an impulse occurs, the pendulum returns to its zero point: **Pm.1 is satisfied**

$$P_{cr} = \frac{\pi^2 EI}{L^2}$$

$$P_{cr_{22}} = 4.88 lbf$$

$$P_{t_{22}} = 15.3 lbf$$

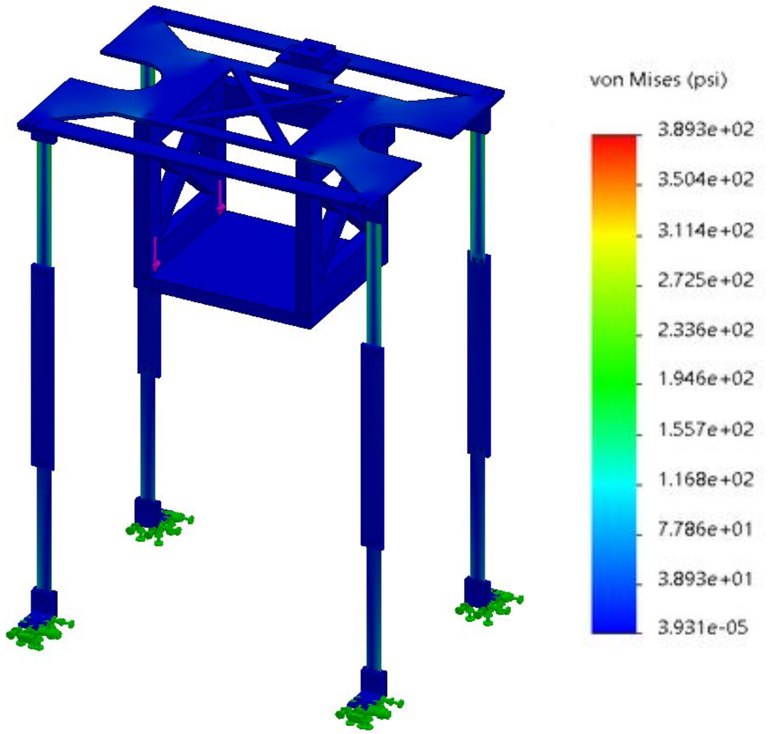
$$P_{cr_{17.6}} = 127 lbf$$

$$P_{t_{17.6}} = 29.4 lbf$$

PPT Mount: Structure

AD

Pm.1: Structure must be able to support thrusters with mass between 2.2 lbs to 17.6 lbs



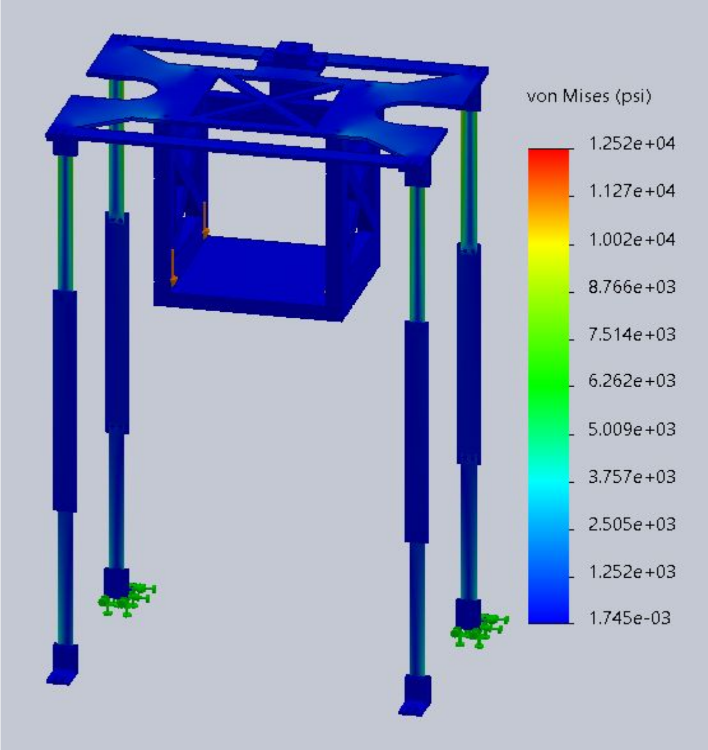
2.2 lb Thruster-Induced Pendulum Stress FEA

- Compressive stress in pendulum from 2.2 lb thruster on 0.01 inch flexure shown
- **Maximum equivalent stress** on all components other than flexures is **155.7 psi**
- **Compressive strength** of garolite is **65,000 psi**
- **Tensile strength** of Delrin is **6,300 psi**
- **Low risk of failure** of these materials from this loading configuration

PPT Mount: Structure

AD

Pm.1: Structure must be able to support thrusters with mass between 2.2 lbs to 17.6 lbs



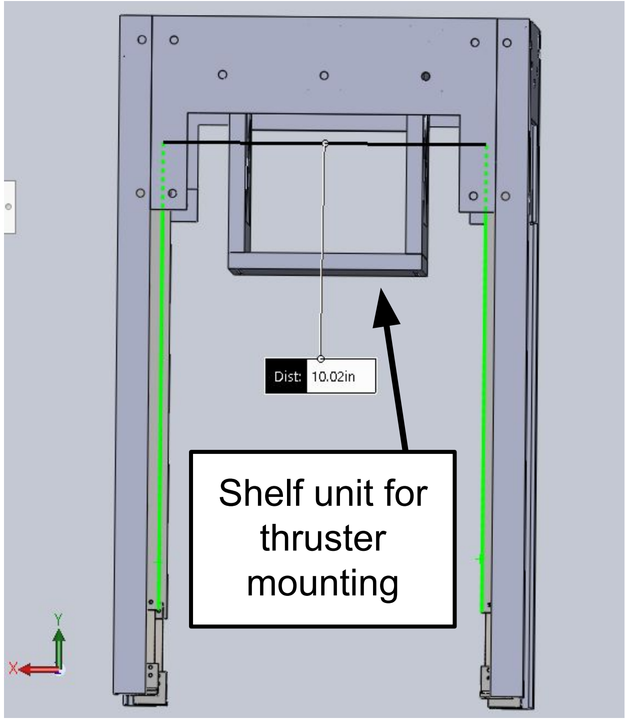
17.6 lb Thruster-Induced Pendulum Stress FEA

- Compressive stress in pendulum from 17.6 lb thruster on 0.05 inch flexure shown
- **Maximum equivalent stress** on all components other than flexures is **500.9 psi**
- **Low risk of failure** of these materials from this loading configuration

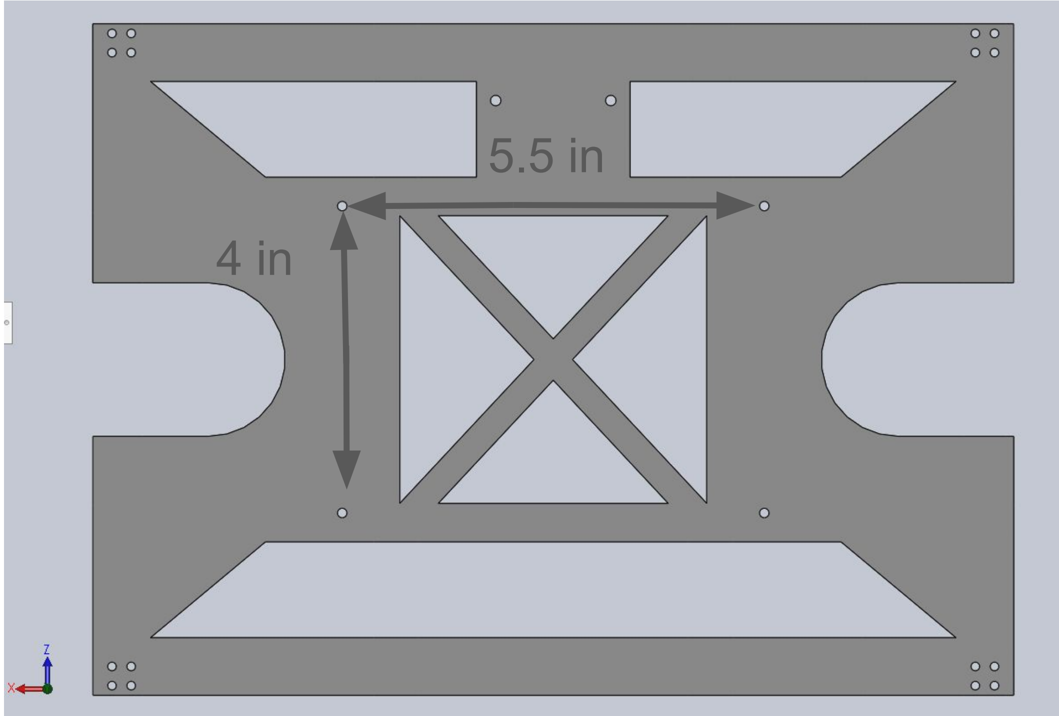
Pm.1 support 2.2 lbs to 17.6 lbs will be satisfied by using this test stand design and material choice

PPT Mount: Structure

Pm.2: Test stand shelf must be wide enough to be able to accommodate thrusters up to 10 inches wide



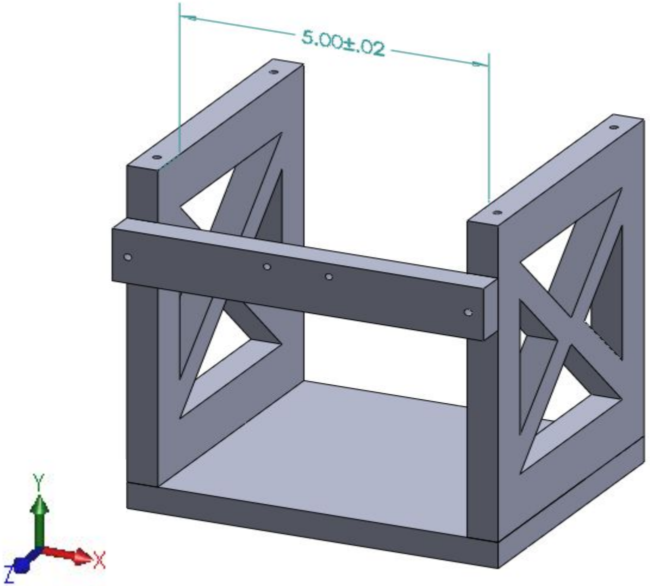
10 inches between pendulum legs



Standard bolt pattern for fitting different thruster mounts

PPT Mount: Structure

Pm.2: Test stand shelf must be wide enough to be able to accommodate thrusters up to 10 inches wide



Shelf for thruster mount designed to accommodate Dawgstar

- 5 inch wide shelf assembly designed to accommodate Dawgstar PPT
- Friction between thruster and shelf will be enough to keep low impulse PPT stationary
- Bolt pattern on top of pendulum allows for alternate mounting systems for larger thrusters, up to 10 inches
- Shelf made of vacuum-safe Delrin plastic for ease of manufacturing

Pm.2 *accommodate thrusters up to 10 inches wide* will be met with this mounting system

PPT Mount: Structure

LL, AD

Pm.3: non-conductive and outgas in accordance with NASA standards

Material Selection

- Non-conductive materials are
  - The introduction of conductive materials increases the probability of unwanted EM interference
- Nylon fasteners were purchased to test their feasibility for stand construction
  - Metal screws were purchased as back up
- Fiberglass and assorted polymer 3D printer filaments were assessed for their suitability as primary test stand structures
  - G10 Garolite sheet and angle stock were ultimately selected for primary structure
- 3D printed material was assessed for both its high modulus of elasticity and ease of manufacturing for prototyping

PPT Mount: Structure

LL

Pm.3: non-conductive and outgas in accordance with NASA standards

Material Inventory

	Component					
	Arms	**Shelf**	**Housing**	**Brackets**	**Fasteners**	**Prototype**
Material	G10 Garolite	Delrin	G10 Garolite Angle Stock & Sheet	G10 Garolite Angle Stock	Nylon	PETG
Manufacturing	Waterjet	Waterjet	Waterjet	Waterjet	N/A	3D Printed

PPT Mount: Structure

AD, LL

Pm.3: non-conductive and outgas in accordance with NASA standards

Material Outgassing:

- **CVCM:** collected volatile condensable material
- **TML:** total mass loss
- According to NASA Outgassing Data for Selecting Spacecraft Material:
  - A material **passes** if **CVCM<0.1%** and **TML<1%**
  - A material **fails** if **CVCM>0.1%** and **TML-WVR>1%**
- **No material** selected for the structure **exceeds CVCM of 0.09%**
- **No material** selected for the structure **exceeds TML of 0.71%**
- All materials selected for structure meet NASA standards on outgassing

PPT Mount: Structure

AD, LL

Pm.3: non-conductive and outgas in accordance with NASA standards

Material Outgassing:

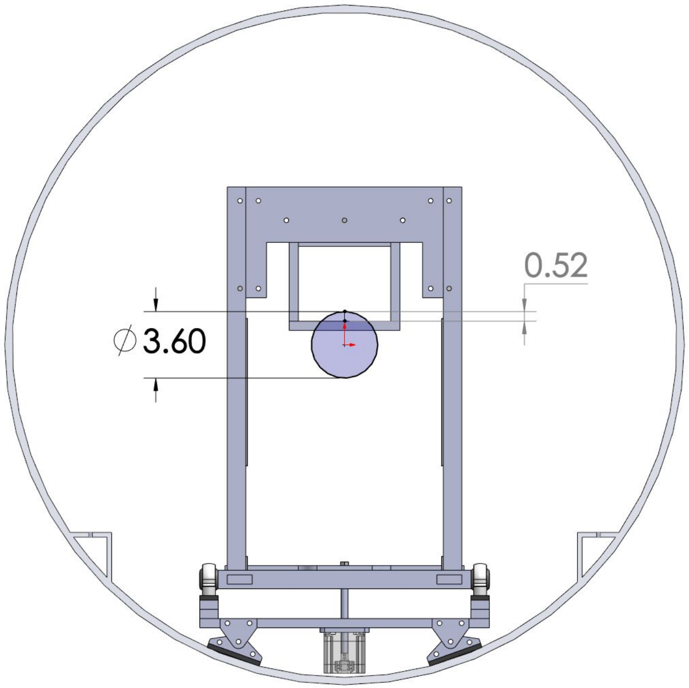
Material	Total Mass Loss (TML)	Collected Volatile Condensable Material (CVCM)	Water Vapor Retention (WVR)
Delrin Acetal Resin	0.39%	0.02%	0.15%
G10 Garolite, ⅛" thick	0.27%	0.00%	0.08%
Nylon (fasteners)	0.71%	0.09%	0.25%
PETG	0.35%	0.02%	0.18%

Pm.3 NASA Outgassing Standard ASTM E595 will be satisfied using the chosen structural materials

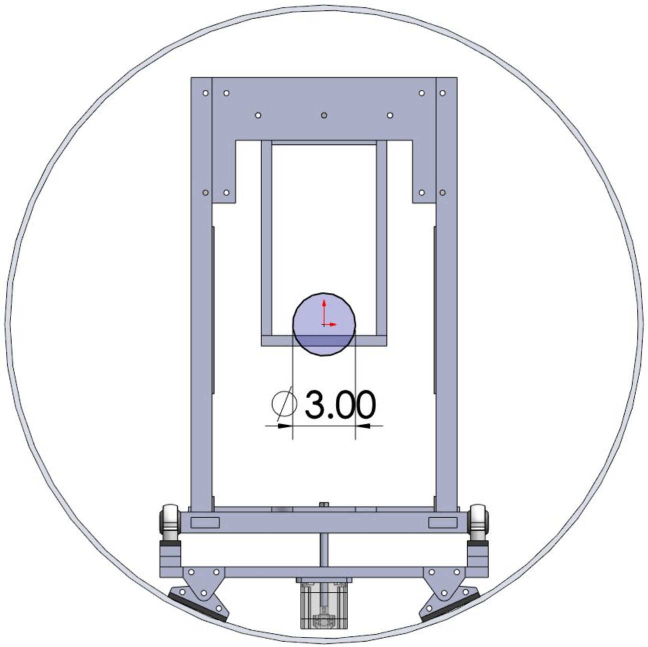
PPT Mount: Structure

BF

Pm.4: thrusters centered to within 10% of vacuum chamber radii



Test Stand in VC-01



Test Stand in VC-02

PPT Mount: Structure

Subsystem Testing

Material Tests: Nylon Bolt

- Test data obtained from DBF’s materials & test team’s assessments of M3, M4, and M5 nylon bolts under tensile and shear loading

	M4	M5	M6
Tensile Loading (ksi)	< 3.92	< 4.35	< 4.64
Shear Loading (ksi)	< 3.48	> 47.1	> 24.7

- All drawings currently use ¼” bolts (slightly larger than M6)
- From loads determined through FEA analysis, under maximum impulse and thruster mass conditions, ¼” bolts will sustain all expected tensile and shear loads

Pm.1 support 2.2 lbs to 17.6 lbs will be satisfied using ¼” nylon bolts

PPT Mount: Structure

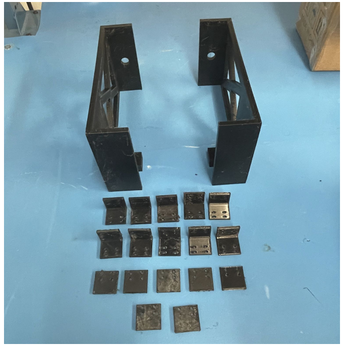
Subsystem Testing

Material Tests: Prototyping

Manufacturing has focused on assessing current designs' feasibility

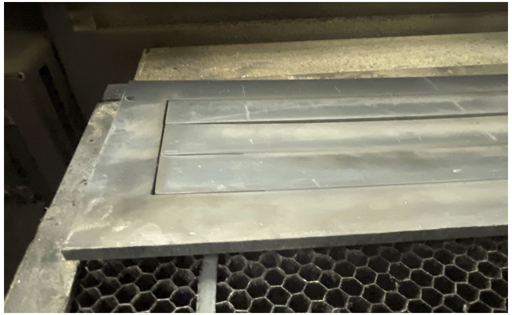
Pendulum prototype parts manufactured as of 3/13:

- **Pendulum Top** (laminate from A&A machine shop; laser cut)
- **Pendulum Arms** (ABS sheet; laser cut)
- **Pendulum Arm Brackets** (PLA filament; 3D printed)
- **Preliminary Clamping Mechanism** (PLA filament; 3D printed)



Pendulum Arm Brackets & Clamping Mechanism

Pendulum Top



Pendulum Arms (holes yet to be drilled)

PPT Mount: Structure

Subsystem Testing

Material Tests: Manufacturing Lessons Learned

- 3D printing tolerances do not have sufficient finish precision for components (like the stepper motor actuator rod)
  - Will need to cut down manufacturer provided metal rod and mitigate effects of introducing additional conductive components into the chamber
- Water jetting will be necessary for all garolite panel components
  - Need to complete training through chemistry department or ME shop
- ABS is not a suitable prototyping material for laser cutting
  - Fire and charring even at lowest laser cutter power (despite following all posted guidelines for cutting ABS)

PPT Mount: Structure

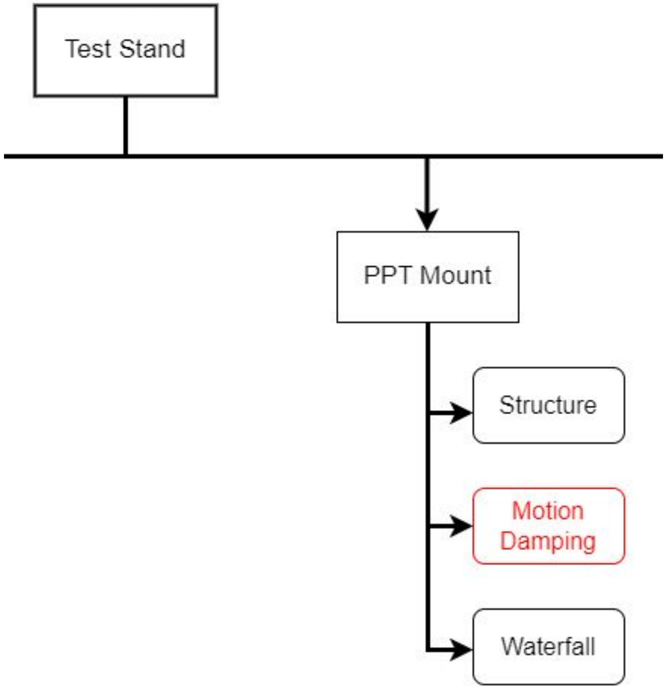
Requirements Review

ID	Requirement	Satisfied via:	Sys. req. met:
Pm.1	Structure must be able to **support** thrusters with mass between **2.2 lbs to 17.6 lbs**	FEA analysis	**Sys.5**
Pm.2	Test stand shelf must be wide enough to be able to **accommodate thrusters** up to **10 inches wide**	10 in shelf width	**Sys.6**
Pm.3	Structure must be **non-conductive** and **outgas** in accordance with **NASA standards** for **ASTM E595** outgassing testing	Assessment of current selected materials' properties	**N/A**
Pm.4	PPT mount structure must keep thrusters centered to within 10% of the radius	Interchangeable shelf system	**N/A**

NC

PPT Mount: Motion Damping

System Architecture



Driving Requirements

ID	Requirement	Verification Method
Pm.4	Damper system must **not affect stand equivalent spring constant.**	*Test*
Pm.5	Damper system must **provide a constant damping ratio** during the entire system response.	*Test*
Pm.6	Damper system must **settle stand motion to 2% within a timescale of 5x the period** of the test stand.	*Test*

PPT Mount: Motion Damping

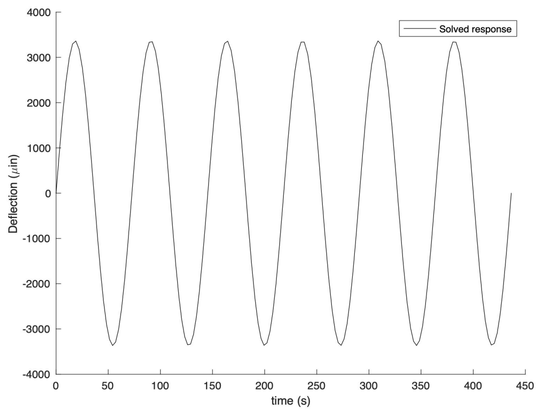
Pm.4: Not affect stand equivalent spring constant

NC, KLV

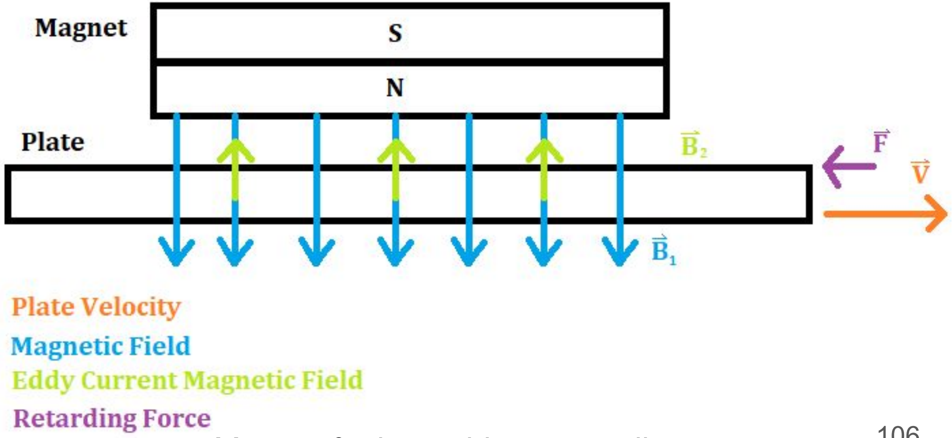
Deflecting pendulum in vacuum without damper elicits an unreasonable settling time of 15+ minutes [1]

An eddy current damper is required to reduce settling time without affecting spring constant [6]

- Made of a **magnet and a conductive plate**
- Passive system → minimal complexity
- Does not physically interfere with stand deflection, **Satisfying Pm.4**



Simulated undamped deflection impulse



Magnet & plate eddy current diagram

PPT Mount: Motion Damping

NC

Pm.4: Not affect stand equivalent spring constant

Installation:

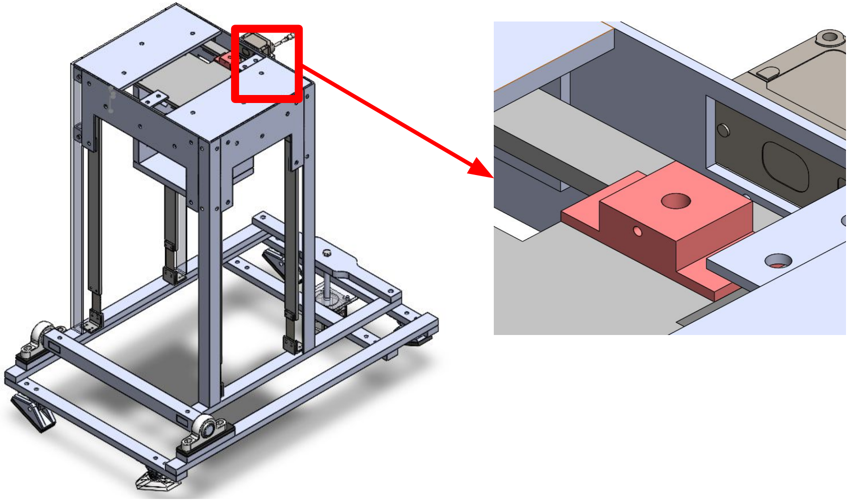
Magnet housing

- Bolted onto PPT mount

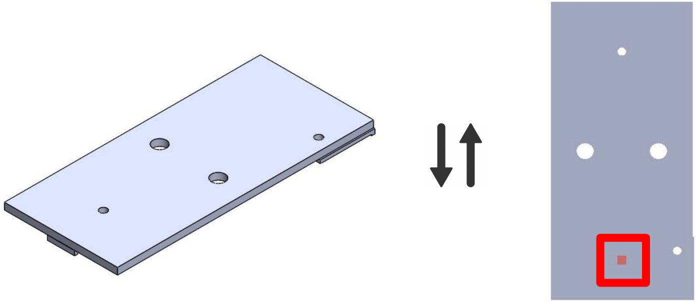
6061 Aluminum conductive plate

- Adhered with vacuum-rated adhesive onto upper rigid frame of stand

Distance of 0.2” between opposing parallel faces, **satisfying Pm.4**



Magnet housing relative to stand assembly



Aluminum damper plate relative to center of frame top

PPT Mount: Motion Damping

Pm.4: Not affect stand equivalent spring constant

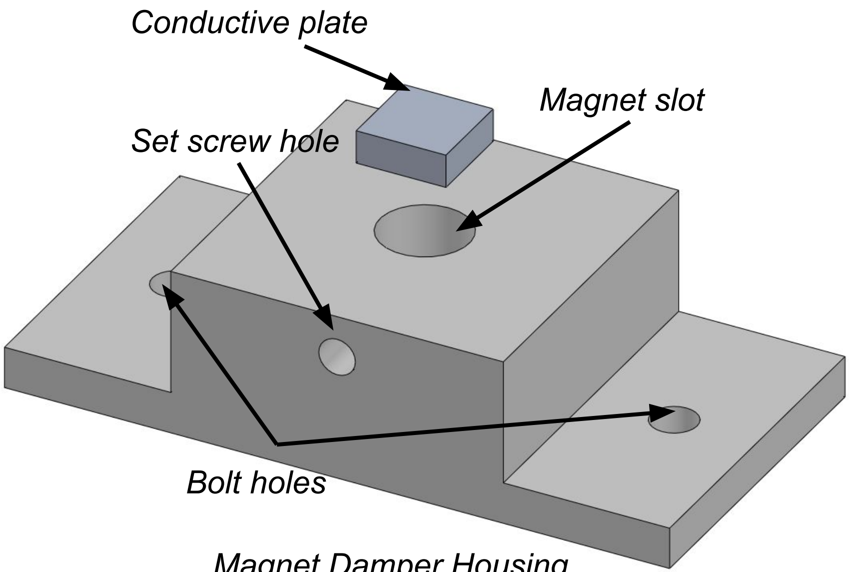
NC, AD

Magnet housing

- Magnet is held with #6 set screw
- Mounted to PPT Mount with bolt holes

6061 Aluminum conductive plate

- 0.5” square
- 0.04” thickness
- Adhered to removable top plate with vacuum adhesive



Magnet Damper Housing

PPT Mount: Motion Damping

NC

Pm.5: Provide a constant damping ratio

Magnet housing

- 14,800 G, 0.125” OD magnet
- 0.2” between magnet and plate

6061 Aluminum conductive plate

- 0.04” thickness
- 12.1 E-8 **Ω***ft resisstivity

The damper provides a constant damping ratio of

***ζ* = 0.47, satisfying Pm.5**

$$F_d = \frac{vB^2At}{\rho}$$

$$F_d = \zeta v$$

$$\zeta = \frac{B^2At}{\rho}$$

F_d = Damping force
v = Pendulum velocity
B = Magnetic field
A = Magnet face area
t = Plate thickness
ρ = Plate resistivity

Damping ratio equation derivation [6]

PPT Mount: Motion Damping

NC

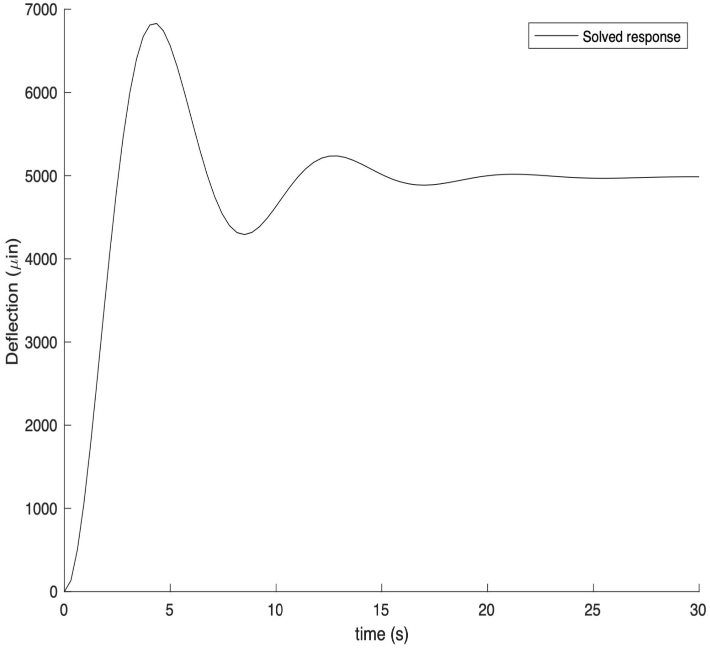
Pm.6: Settle stand motion to 2% within a timescale of 5x the period

Design:

Simulated a damped response with damping ratio of 0.47

Damping ratio settles motion by 5 periods (~60 s)

Satisfies Pm.6



Simulated damped deflection step response

PPT Mount: Motion Damping

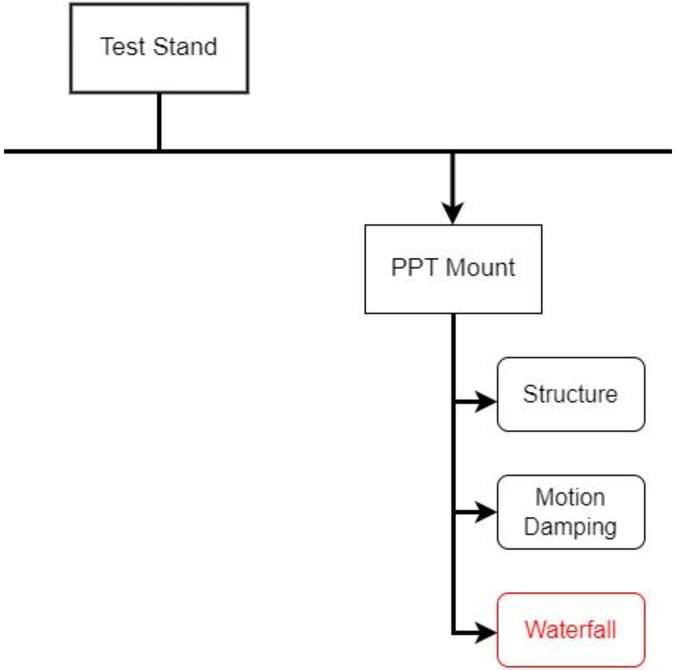
Requirements Review

ID	Requirement	Satisfied via:	Sys. req. met:
Pm.4	Damper system must **not affect stand equivalent spring constant.**	Eddy current damping has no physical contact with components	N/A
Pm.5	Damper system must **provide a constant damping factor** during the entire system response.	Use of permanent magnet	N/A
Pm.6	Damper system must settle stand motion to 2% within a timescale of **5x the period** of the test stand.	Matlab impulse response simulation	N/A

PPT Mount: Waterfall

KLV

System Architecture

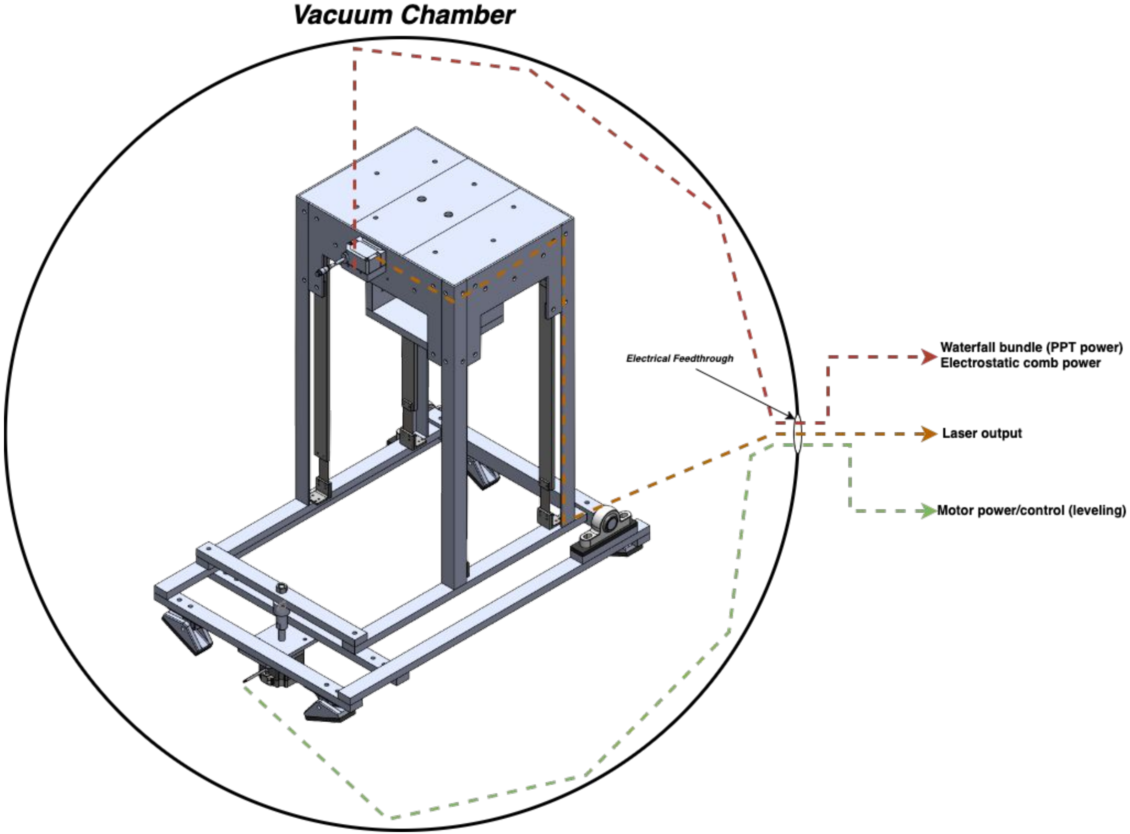


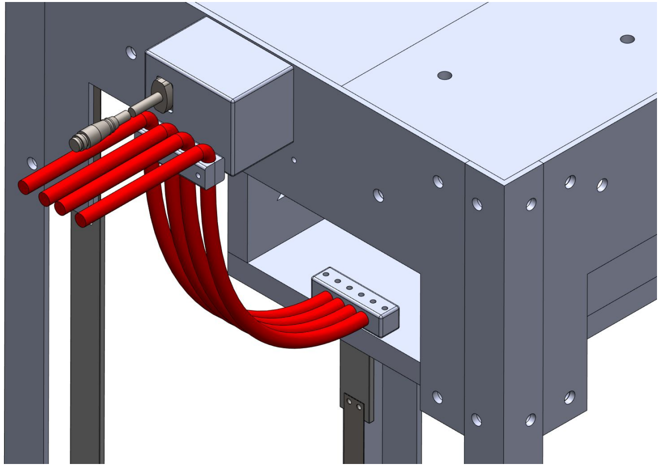
Driving Requirements

ID	Requirement	Verification Method
Pm.7	Waterfall shall **minimize effective spring constant of wires** connecting to pendulum.	**Testing**

PPT Mount: Waterfall

WW, KLV, BF





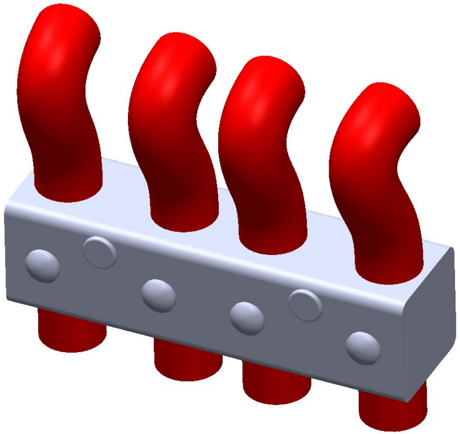
Waterfall system integration

PPT Mount: Waterfall

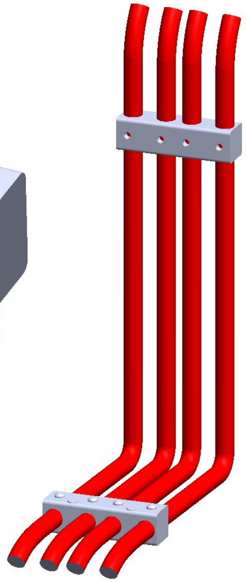
KLV, LL

Pm.7: minimize effective spring constant of wires

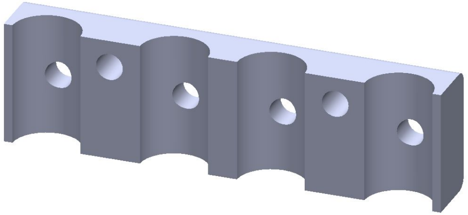
- Waterfall connects from rear of laser housing to rear edge of thruster platform
  - Estimated waterfall length clamp-to-clamp: **10 in**
- **Waterfall turns a net 90°**
  - Allows for thermal expansion perpendicular to pendulum motion
- **Waterfall spring constant contribution to be determined through testing**
- Waterfall held via screw-tightened clamps
  - Allows for waterfall adjustments as needed during testing
- **Waterfall carries 4 lines**
  - 3 power lines
  - 1 analog signal
- Largest gauge expected:
  - ¼ ” diameter
  - Waterfall **length 40x max wire thickness**



Clamp with fasteners



Clamp configuration with wires on pendulum



Half clamp detailed view

PPT Mount: Waterfall

Requirements Review

ID	Requirement	Satisfied via:	Sys. req. met:
Pm.7	Waterfall shall **minimize effective spring constant** of wires connecting to pendulum.	Waterfall **completes 90° turn**, and is has length **40x maximum wire thickness**	N/A

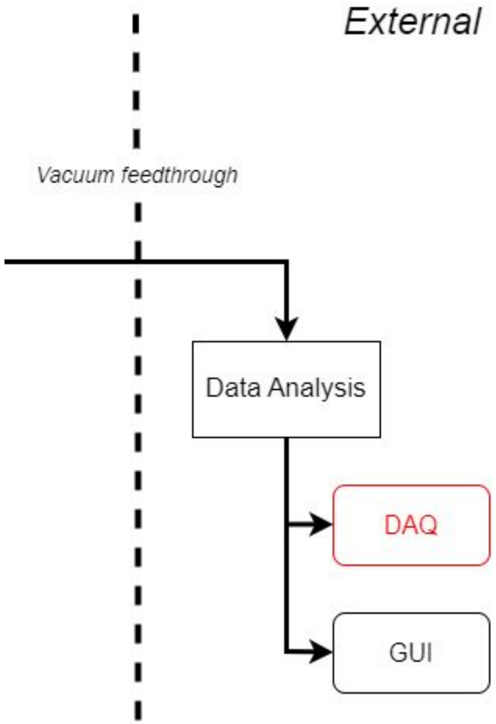
PPT Mount: Budget Summary

Category	Item	Cost	Total
Structure	Magnet	$ 0.58	$ 7.66
	Aluminum plate	$ 7.08	
Avionics	4 Pin Connector kit	$ 7.35	$ 7.35
Software			
Other			
			$15.01

Data Analysis: DAQ

FC

System Architecture



Driving Requirements

ID	Requirement	Verification Method
Da.1	Software will convert deflection measurements to Impulse measurements and corresponding **uncertainties in the range of ±1.125 µlbf*s (5 µN*s)**. As well as steady state and corresponding **uncertainties in the range of ±11.2 µlbf (0.05 mN)**	*Analysis*
Da.2	Software will record raw deflection data from the rangefinder at a **sampling rate of 100 to 1000 Hz**	*Analysis*

Data Analysis: DAQ

FC

*Da.1: uncertainties in the range of ±1.125 μlbf*s (5 **μ**N*s)*

Calibration - Uncertainties for c and Impulse

- Error propagation techniques ensure reliable estimation of impulse data and calibration constant
- C uncertainties:
  - First will calculate the uncertainty of the calibration constant until it is *(c ± Δc)*
  - This will then that would be used to calculate the impulse uncertainty for our system
- Impulse uncertainties:
  - With uncertainty of the calibration constant and uncertainty from the laser *(I_b ± ΔI_b)*
- **Da.1 is satisfied**

$$s_f = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 s_x^2 + \left(\frac{\partial f}{\partial y}\right)^2 s_y^2 + \left(\frac{\partial f}{\partial z}\right)^2 s_z^2 + \cdots}$$

$$\Delta c = \sqrt{\left(\frac{1}{V} \times \Delta I\right)^2 + \left(-\frac{I}{V^2} \times \Delta V\right)^2}$$

$$\Delta I_b = \sqrt{(V \times \Delta c)^2 + (c \times V)^2}$$

General, calibration constant, and impulse uncertainty error propagation formulas

Data Analysis: DAQ

FC

*Da.1: uncertainties in the range of ±1.125 μlbf*s (5* ***μ****N*s)*

Design

- NI-DAQmx Driver Software:
  - Verify the *DAQ device is recognized* by the computer
  - Python *integration* with NI-DAQmx Driver & PySerial
- Data acquisition and analysis with NI-DAQmx Driver and PySerial
  - TTL trigger implemented to initiate the firing sequence of the pulsed plasma thruster.
  - Recording deflection data: *record_deflection()* reads raw deflection data from the DAQ
  - The low pass filter aids in smoothing the data by attenuating high-frequency noise and fluctuations, thereby facilitating more precise analysis.
  - Errors: The *try-except* commands is used if any exceptions (errors) occur, it will then handle the errors

Data Analysis: DAQ

FC

Da.2: sampling rate of 100 to 1000 Hz

Design

Sampling Clock:

- Read *rate* = *100 - 1000 Hz* of deflection data from the rangefinder
- using the timing.cfg_samp _clk_timing method
- Mode is set to continuous
- **Da.2 is satisfied**

```
# Configure the timing for data acquisition
task.timing.cfg_samp_clk_timing(rate=1000, sample_mode=nidaqmx.constants.AcquisitionType.CONTINUOUS)
# Read raw deflection data from the DAQ device
deflection_data = task.read(number_of_samples_per_channel=1000)  # Reading raw data from the DAQ device
```

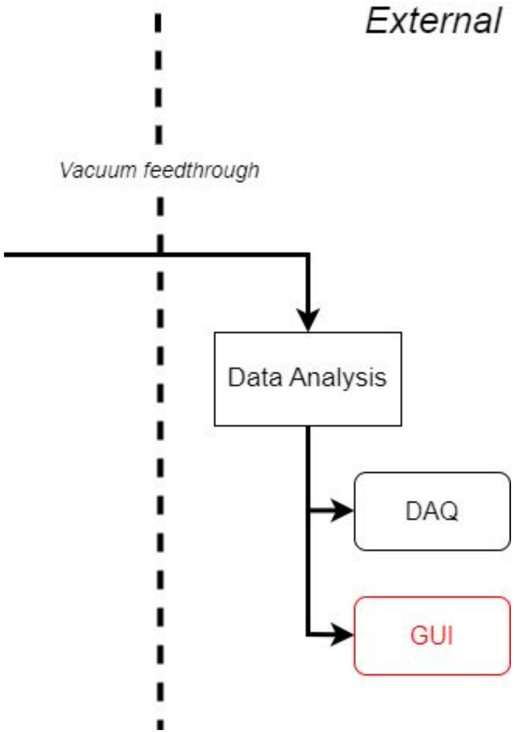
Data Analysis: DAQ

Requirements Review

ID	Requirement	Satisfied via:	Sys. req. met:
Da.1	Software will convert deflection measurements to impulse measurements **and corresponding uncertainties in the range of ±1.125 μlbf*s (5 μN*s).** As well as **steady state and corresponding uncertainties in the range of ±11.2 μlbf (0.05 mN)**	Through calibrations, calculating V_{max} peak, constant 'c' will show impulse measurements and uncertainties	**Sys.3** **Sys.4**
Da.2	Software will record raw deflection data from the rangefinder at a **sampling rate ranging from of 100 to 1000 Hz**	Sampling clock timing parameters are set up using the timing.cfg_samp_clk_timing method	**Sys.3**

Data Analysis: GUI

System Architecture



Driving Requirements

ID	Requirement	Verification Method
Da.3	Software will **display deflection measurements and corresponding uncertainties** recorded at a **rate of 100 to 1000 Hz** graphically	*Demonstration*
Da.4	Software will allow for the **export of produced figures and raw data**	*Demonstration*

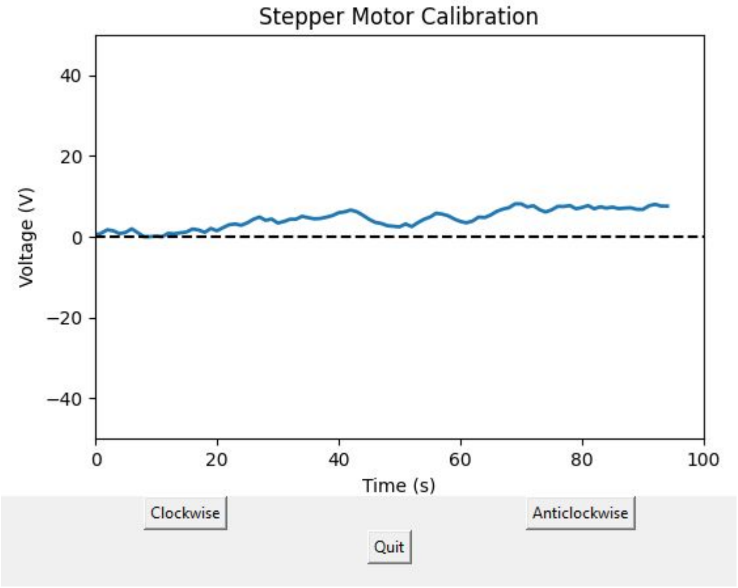
Data Analysis: GUI

FC

Da.1: display at a rate of 100 to 1000 Hz, Da.2: export of produced figures and raw data

Design - Arduino

- *PySerial* send commands to the Arduino, instructing it on how to *control the stepper motor* to be able to level system to adjust up to ±3° as desired
- Sending data to serial port:
  - sendData: Sends motor control data to the Arduino
- GUI Integration:
  - *Tkinter* window and designs GUI elements
  - Plot: Visual display to adjust the stepper motor displacement between tests
  - Buttons: *RotateClockwise()* and *RotateAnticlockwise() to* step up and down. Quit to close the command window



Stepper motor control GUI

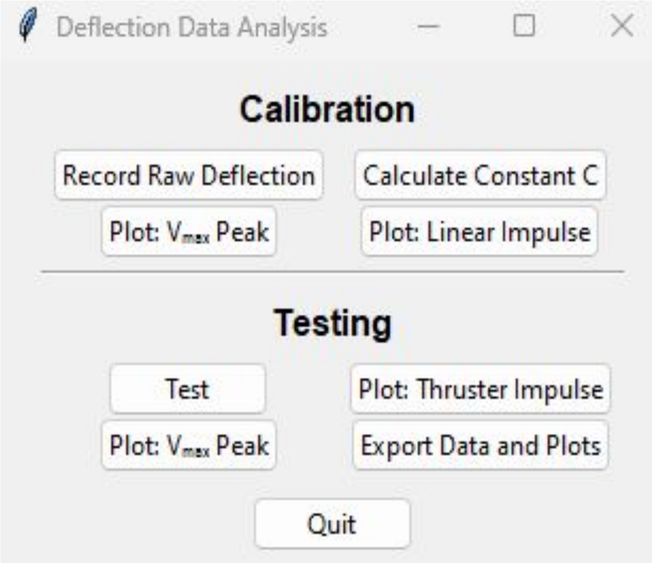
Data Analysis: GUI

FC

Da.1: display at a rate of 100 to 1000 Hz, Da.2: export of produced figures and raw data

Design - DAQ

- TTL Trigger firing sequence implemented to all thruster avionics and record deflection data from the rangefinder at a *rate=1000* samples per second using the ni-daqmx, storing it in the global variable deflection_data
- **Calibration:**
  - Finding the V_{max} peak, calculating the constant 'c', and plotting both the V_{max} peak and V_{max} vs Known Impulse
- **Testing:**
  - Thruster Impulse & Uncertainties and V_{max} peak plot
- **GUI Integration:**
  - *Tkinter* window and designs GUI elements
  - Calibration and Test sections
- **Export Options:**
  - Both figures (as .png) and raw data (as .csv)
- This satisfies the **Da.3 and Da.4** of the system requirements



Data Analysis GUI Command Window

Data Analysis: GUI

KLV, FC

Requirements Review

ID	Requirement	Satisfied via:	Sys. req. met:
Da.3	Software will **display deflection measurements** recorded at a **rate of 1000 samples per second** corresponding uncertainties graphically, allowing for the **export of produced figures and raw data**	Tkinter window and designs GUI elements for calibration and test	**Sys.3**
Da.4	Software will allow for the **export of produced figures and raw data**	Both figures (as .png) and raw data (as .csv)	**N/A**

Data Analysis: Budget Summary

Category	Item	Cost	Total
Structure			
Avionics			
Software	1 TB Hard Drive	$ 63.15	$ 96.81
	USB to USB A Cable	$ 6.06	
	Arduino	$ 27.60	
Other			
			96.81

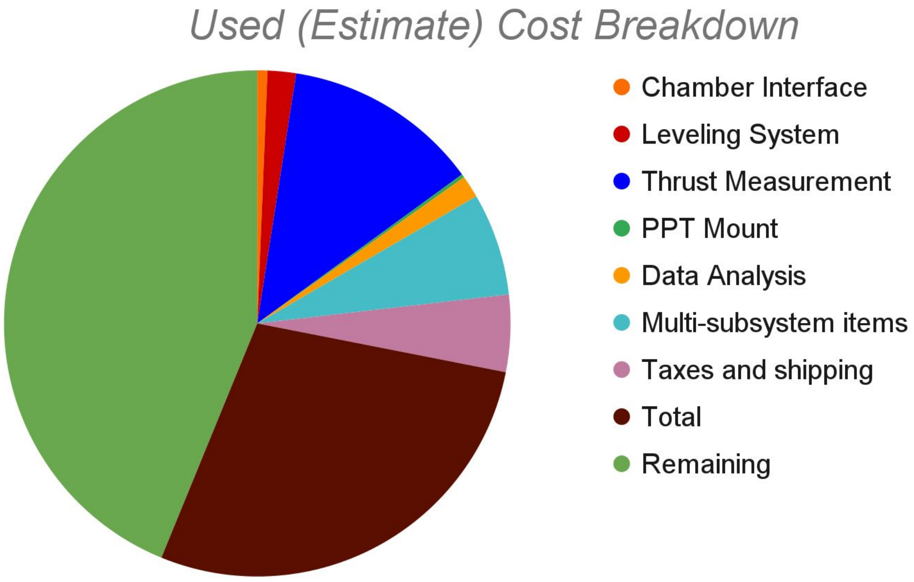
Agenda

- Motivation and Objective
- System Overview
  - CONOPS
  - Functionality
  - Requirements
  - Architecture
- Subsystems
  - Chamber Interface
  - Leveling System
  - Thrust Measurement
  - PPT Mount
  - Data Analysis
- **Budget Evaluation, Risk Assessment, & Next Steps**
- Conclusion

Budget Summary

NC

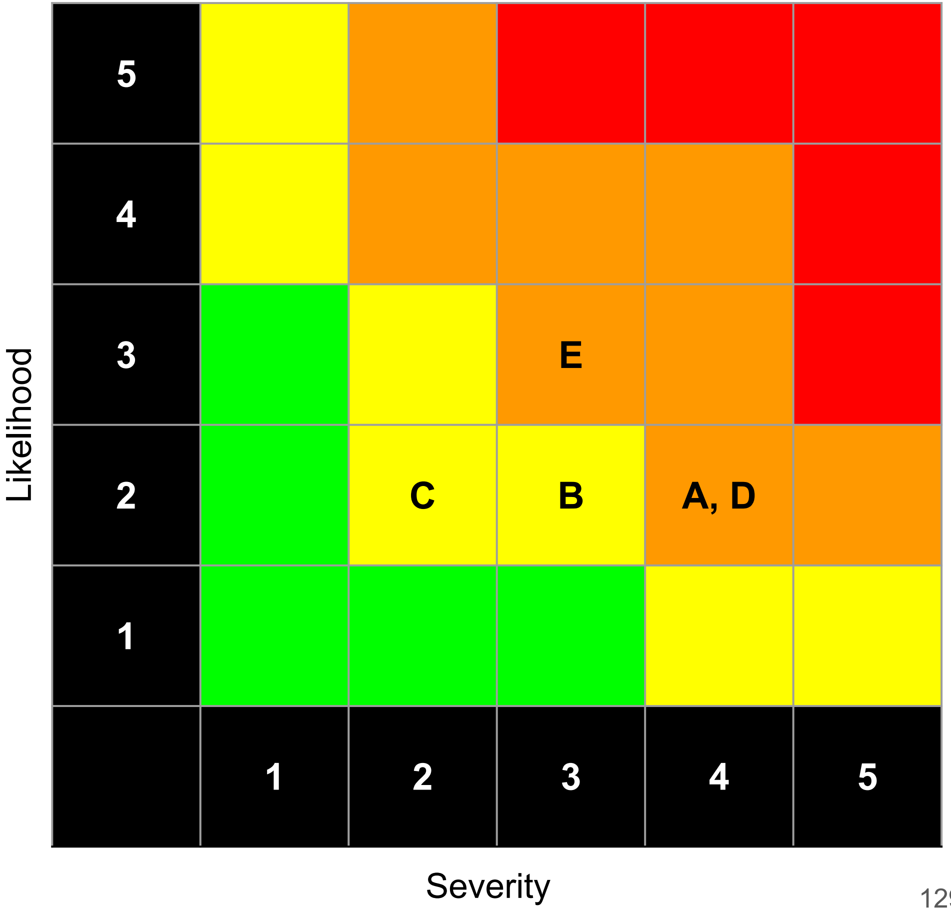
Category	Cost
Chamber Interface	$ 44.08
Leveling System	$ 123.49
Thrust Measurement	$ 853.33
PPT Mount	$ 15.01
Data Analysis	$ 96.81
Multi-subsystem items	$ 446.18
Taxes and shipping	$ 335.18
Total	$1914.08
Remaining	**$ 2985.92**



System Overview

Risk Assessment

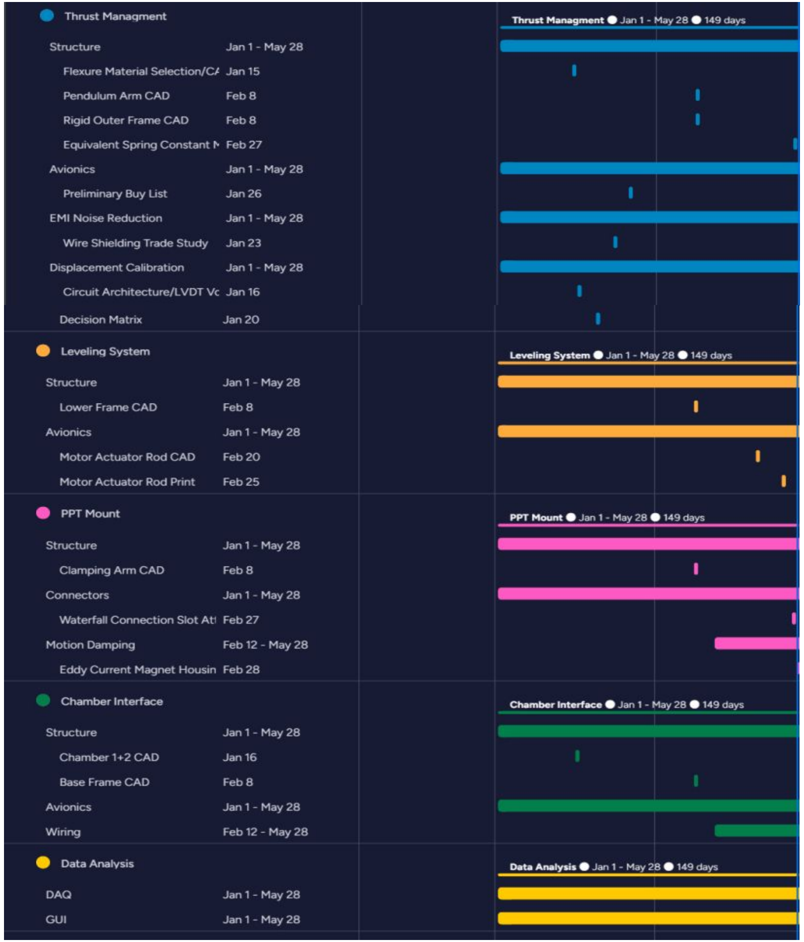
Item	Label	Mitigation strategy
Imprecise measurement stemming from insufficient EMI shielding, conductive parts	A	Maximize shielding without hindering impulse measurement performance and minimize conductive parts without hindering structural integrity
DAQ code incompatibility	B	Revising calibration code
Manufacturing Equipment Training	C	Team members must coordinate early on in Sp24 with other departments to complete required water jet training
Waterfall induces unexpectedly large effective spring constant	D	Minimize weight/stiffness of wires contained within waterfall
Pendulum dynamic response modeling accuracy	E	Further prototyping of dynamic system to validate range of masses, thrusts, and impulses



Project Timeline

Next Steps

Subteam	Item
Avionics	● Hardware purchasing and testing
Software	● Improve DAQ code ● Stepper motor testing ● DAQ testing
Structures	● Finalize technical drawings and assembly procedures ● Continuing prototyping ● Manufacturing final parts
Propulsion	● Vacuum & plasma exposure material performance testing ● Electrostatic fin calibration testing
Power	● Wiring and shielding assembly/testing



Agenda

- Motivation and Objective
- System Overview
    - CONOPS
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    - Data Analysis
- Budget Evaluation and Risk Assessment
- **Conclusion**

Requirements Verification Matrix

ID	Requirement	Status
Sys.1	Test stand must be an **inverted pendulum style**	*Expected Pass*
Sys.2	Test stand shall **minimize the use of conductive materials**	*Expected Pass*
Sys.3	Test stand must be able to **resolve a minimum stand deflection of half the lowest predicted deflection** such that **impulse bits ranging from 2.25 μlbf*s to 22.5 mlbf*s ± 11.3 μlbf*s (10 μN*s to 100 mN*s ± 5 μN*s)** can be measured	*May Pass*
Sys.4	Test stand must be able to **resolve a minimum stand deflection of half the lowest predicted deflection** such that **steady-state thrusts ranging from 22.5 μlbf to 22.5 mlbf ± 11.3 μlbf (0.1 mN to 0.1 N ± 0.05 mN)** can be measured	*May Pass*

Requirements Verification Matrix

ID	Requirement	Status
Sys.5	Test stand must be able to **support thrusters up to 17.6 lbf** without buckling	*Expected Pass*
Sys.6	Test stand must accommodate **thruster diameters up to 10.0 in, and thruster lengths up to 9.1 in**	*Expected Pass*
Sys.7	Test stand shall be able to be horizontally leveled to within **±0.05 degrees**	*May Pass*
Sys.8	Test stand must **return thruster to 0.002 ± 0.001 degrees of zero-point** between tests	*Expected Pass*
Sys.9	The stand must be installed, securely operated, and safely removed from the vacuum chamber **without causing any structural or cosmetic damage** to the chamber wall.	*Expected Pass*

References - Papers

[1] Thoreau, P. & Little, J. (2019) Development of the SPACE Lab Thrust Stand for Millinewton Thrust Measurement. http://electricrocket.org/2019/715.pdf

[2] Rayburn, Christopher & Campbell, Mark & Hoskins, W & Cassady, R.. (2000). Development of a micro Pulsed Plasma Thruster for the Dawgstar nanosatellite. 10.2514/6.2000-3256.

[3] Cassady, R. & Hoskins, William & Campbell, Mark & Rayburn, Christopher. (2000). A micro pulsed plasma thruster (PPT) for the “Dawgstar” spacecraft. IEEE Aerospace Conference Proceedings. 4. 7 - 14 vol.4. 10.1109/AERO.2000.878359.

[4] Masterson, P. (2002). The basics of vibration isolation using elastomeric materials AEARO Company. http://www.vibrationdata.com/tutorials_alt/vib_iso.pdf

[5] Zakrzwski, C., Davis, M., and Sarmiento, C. “Addressing Eo-1 spacecraft pulsed plasma thruster EMI concerns,” *37th Joint Propulsion Conference and Exhibit*, Jul. 2001.

[6] Hollowell, T; Kahl, J; Stanczak, M; Wang, Y Eddy Current Brake Design for Operation with Extreme Back-drivable Eddy Current Motor, 2010

[7] Polk, J. “Recommended Practices in Thrust Measurement.” *33rd International Electric Propulsion Conference, October 2013.*

References - Images

[i1] Aliexpress

[i2] Siamhitech

[i3] National Instruments

[i4] OMC

[i5] OMC

[i6] Amazon

[i7] Tinkercad

[i8] Noramco

[i9] Glenair

[i10] Holland Shielding

[i11] Glenair

[i12] Glenair

[i13] Lumen

[i14] Keyence

[i15] Boegger

[i16] Newark

[i17] IdealVac

[i18] Journal of Physics D: Applied Physics

[i19] Power supply

[i20] Electronics box

[i21] TPSM265R1EVM

[i22] Metal bearing

[i23] Isolator mount

[i24] Digikey

[i25] SpeakerBuilderSupply

[i26] Boegger

[i27] Garolite sheet

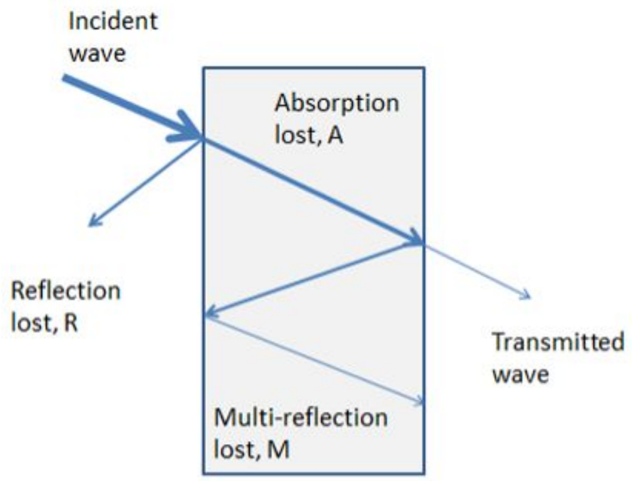
Thank you! Questions?

Name	Initials
Nathan Cheng	NC
Felicity Cundiff	FC
Adam Delbow	AD
Ben Fetters	BF
Lillie LaPlace	LL
Kai Laslett-Vigil	KLV
Winston Wilhere	WW

Backup Slides

Thrust measurement: EMI Shielding

- Determine thickness of copper mesh needed to shield frequency range:
  - 5 - 247 MHz range



Electromagnetic Shielding Schematic Diagram

Shielding effectiveness expressed as:

$$SE_{dB} = R_{dB} + A_{dB} + M_{dB}$$

Reflection lost: R_{dB} = 33.557 dB

$$R = 20log_{10}\left|\frac{(Z_0+Z_1)^2}{4Z_0Z_1}\right|$$

Absorption lost:

$$A = 20log_{10}e^{\frac{L}{\delta}}$$

Multi-reflection lost: M ≅ 0

$$M = 20log_{10}\left|1 - e^{-2(1+j)\frac{L}{\delta}}\right|$$

Given attenuation of 35dB, copper thickness needed:

- **0.0615mm**

Nomenclature:

SE_{dB} : shielding attenuation
Z_0 : impedance of air
Z_1 : impedance of copper
L : thickness
δ : skin depth

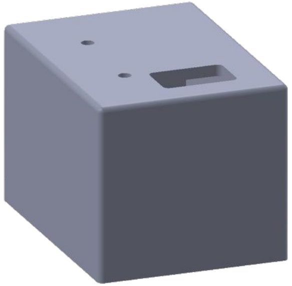
Thrust Measurement: EMI Shielding

[i24]

[i25]

Braided sheath covering for wires

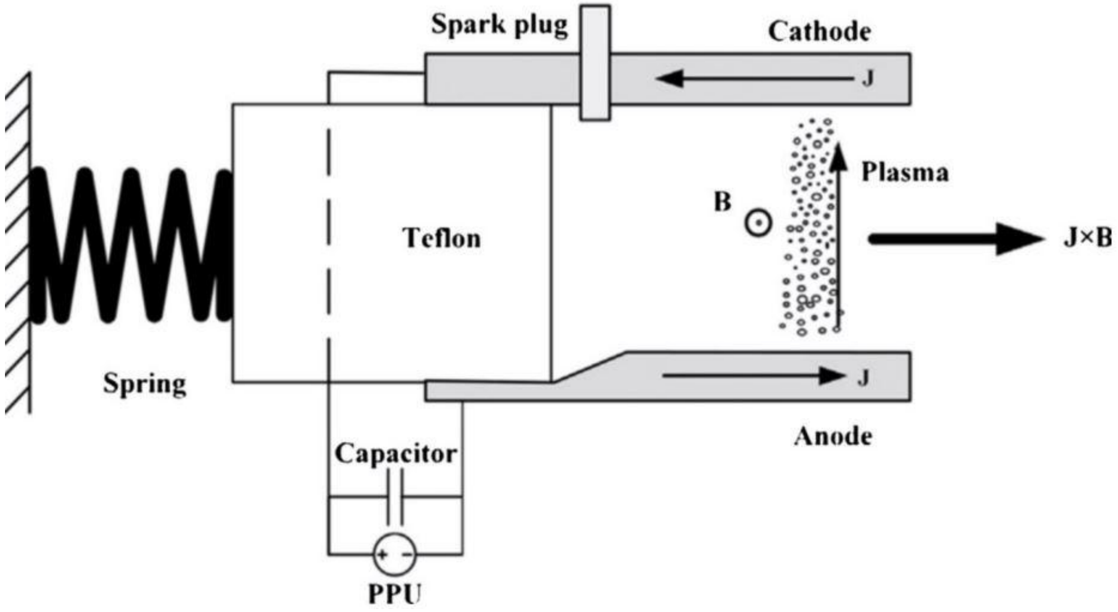
[i15]



Proposed 3D printed Faraday cage design for IL-030 sensor

[i14]

Thrust Measurement:



- Strong magnetic fields generate EMI
- EMI presence in vacuum chamber leads to high frequency noise in analog signals
- Noise can be filtered using both hardware and software

Thrust Measurement: EMI Shielding

Driving Requirement: During thruster operation, the spectrum of EMI emissions must be characterized to inform shielding material and configuration selection

Design - Pulse Signal Noise

- Based on published data for the EO-1 PPT, which the DawgStar's design was strongly inspired by [2], we expect the frequency spectrum of each plasma pulse (for EMI) to have a peak intensity at approximately 10 MHz, which will be used for initial shielding selection

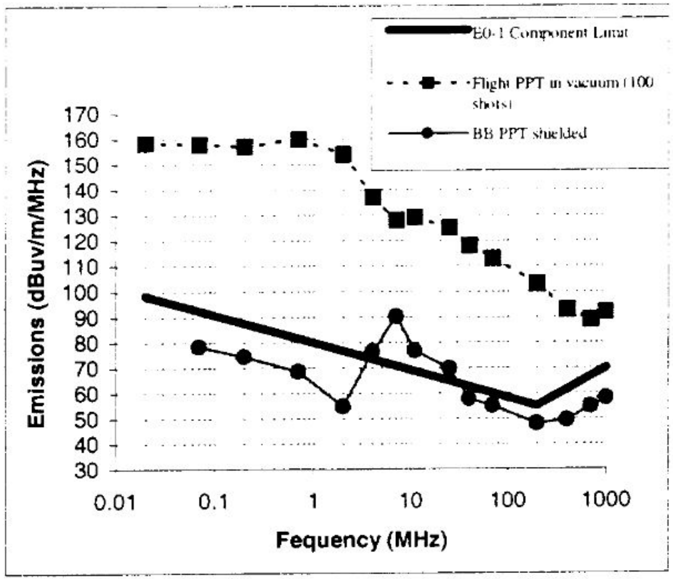


Figure 9: REO2 Results from PPT Shield Test

Image Credit: [5] Addressing EO-1 Spacecraft Pulsed Plasma Thruster EMI Concerns

Data Analysis: Overview

Driving requirements

- Recording Deflection Data:
  - The software must capture raw deflection data from the rangefinder.
- Conversion of Measurements:
  - The software should convert deflection measurements into thrust measurements along with their respective uncertainties.
- Graphical Display:
  - The software must present deflection measurements and their uncertainties graphically.
  - It should support exporting both figures and raw data.
- Calibration System:
  - The test stand requires an integrated calibration system.
  - This system must be capable of calibrating to 10 micronewtons.

Data Analysis

Design - Python overview

- PySerial:
  - Arduino: PySerial enables the Python script to send commands to the Arduino, instructing it on how to control the stepper motor.
  - DAQ (NI DAQ-6009): PySerial, along with NI-DAQmx / nidaqmx, allows the Python script to communicate with the NI DAQ-6009 device, enabling data acquisition and control operations.
- NI-DAQmx / nidaqmx:
  - Facilitates communication with the NI DAQ-6009 device.
  - NI-DAQmx driver installed, nidaqmx enables Python to communicate with the DAQ device, configure data acquisition settings, collect data from sensors.
- Graphical User Interface (GUI):
  - Tkinter: Assigning Functions to Buttons
  - Pandas: Export Option
  - Matplotlib: Plot display

Software

Design - Arduino

- Serial Communication
  - Arduino communicates with the computer via serial port.
  - Commands from the computer control the stepper motor.
- Stepper Motor Control
  - Four digital output pins (portIN1 to portIN4) interface with the stepper motor's driver
- Data Processing
  - The Parse_the_Data() function extracts and parses parameters from the received string
- Motor Operation
  - Loop continuously checks for incoming data.
  - Parsed parameters determine motor speed, angle, and direction.
- Parameter Conversion
  - Received parameters are converted for motor control:
    - Speed is converted to a delay between steps.
    - Angle is converted to the number of steps required for rotation
- Motor Control Functions
  - stepper_Anticlockwise() and stepper_Clockwise() control motor rotation.
  - Direction and step count determined by received commands.

Software: Tests

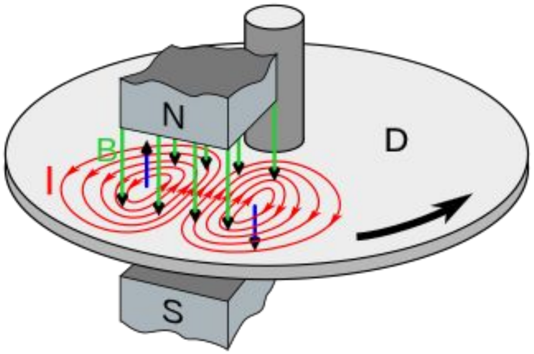
- Raw Deflection Data Recording:
  - Test objective - Ensure software can accurately record raw deflection data from the displacement sensor.
  - Test: Set up the sensors, record raw deflection data, verify that the software records and stores, lastly validate the recorded deflection data against the expected values.
  - Measure test stand deflection using known weights and a displacement laser sensor.
- DAQ Software Interface GUI:
  - Test objective - Verify reliability of the DAQ GUI software interface.
  - Test: After receiving deflection data select each option to ensure data acquisition runs smoothly.

NC

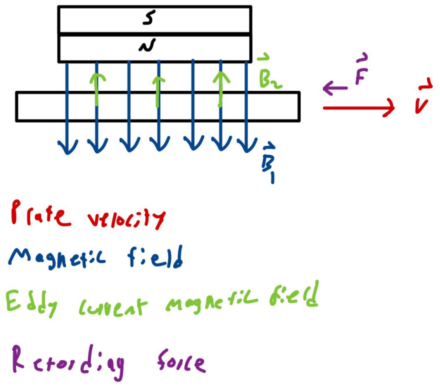
PPT Mount: Motion Damping

Analysis - Eddy Current Damping Ratio

- Eddy currents are an application of Lenz's law
  - As a conductor moves in the presence of a magnetic field, a current is induced
  - Induced field of induced current opposes initial magnetic field → creates retarding force
- Retarding force is proportional to velocity between conductor and magnetic field [6]
  - Acts as a damper



Eddy current disk brake



Test stand motion damping