Preliminary Design Review

Pulsed Plasma Thruster Test Stand

Nathan Cheng, Felicity Cundiff, Adam Delbow, Ben Fetters, Lillie LaPlace, Kai Laslett-Vigil, Winston Wilhere

Mentor: Dr. Justin Little

Image Credit: UW SPACE Lab High-Pulse-Rate Pulsed Inductive Thruster (HiPeR-PIT)

Agenda

- Mission Overview
- Mission Objective
- CONOPS
- System Requirements
- System Architecture
- Subsystem Requirements
- Budget Matrix
- Risk Analysis Matrix
- Requirements Verification Table

Mission Overview: Motivation

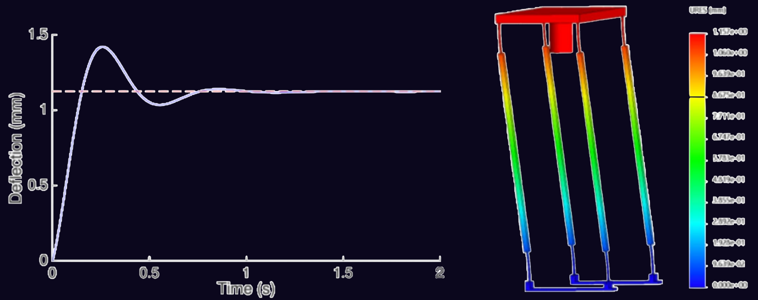
- The SPACE Lab recently acquired a new vacuum chamber from the Earth and Space Sciences department.
- Lab staff have designated it to be used for the purposes of characterizing pulsed plasma thruster (PPT) performance.
- A new test stand must be designed that can be integrated into this new chamber.

[1]

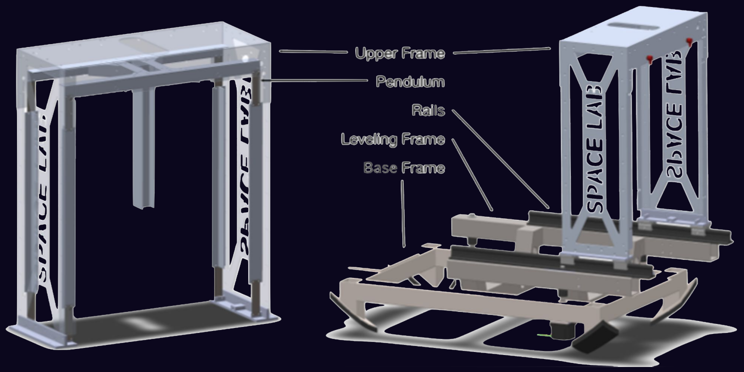
Mission Overview: What is a Test Stand?

- In electric propulsion applications, test stands are used to measure micro quantities of thrust. The limited thrust offered by electric propulsion systems means that the stand must measure impulses ranging from 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.



Test stand steady state response



Test stand structure
Images Credit: Development of the SPACE Lab Thrust Stand for Millinewton Thrust Measurement, Thoreau & Little

Mission Objective

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 within a 10 μN*s to 100 mN*s range and with the capacity to accommodate a variety of thruster dimensions and weights.

CONOPS

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
2. CALIBRATE test stand with known impulse
3. FIRE thruster
4. ALLOW for pendulum arm to stop swinging

Disassembly

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

System Requirements (1)

ID	Requirement	Verification Method
Sys.1	Test stand must be an inverted pendulum style	*Inspection*
Sys. 2	Test stand shall be horizontally level to within ± 0.05 degrees	*Demonstration*
Sys. 3	Stand must be installed, operated, and removed from vacuum chamber without causing visible scratching to the chamber wall	*Inspection*
Sys.4	Test stand must be able to support thrusters up to 8kg in mass	*Analysis*
Sys.5	Test stand must accommodate thruster diameters up to 42 cm, and thruster lengths up to 23 cm	*Demonstration*

System Requirements (2)

ID	Requirement	Verification Method
Sys.6	Test stand must be able to measure impulse values ranging from 10 μN*s to 100mN*s	*Test*
Sys.7	Test stand must be able to capture steady-state measurements ranging from 0.1 mN to 0.1 N	*Test*
Sys.8	System must have a minimum data collection rate of 10x the displacement sensor output frequency	*Test*
Sys.9	Test stand must return thruster to 0.002 degrees of zero-point between tests	*Test*
Sys.10	Test stand shall minimize the use of conductive materials	*Inspection*

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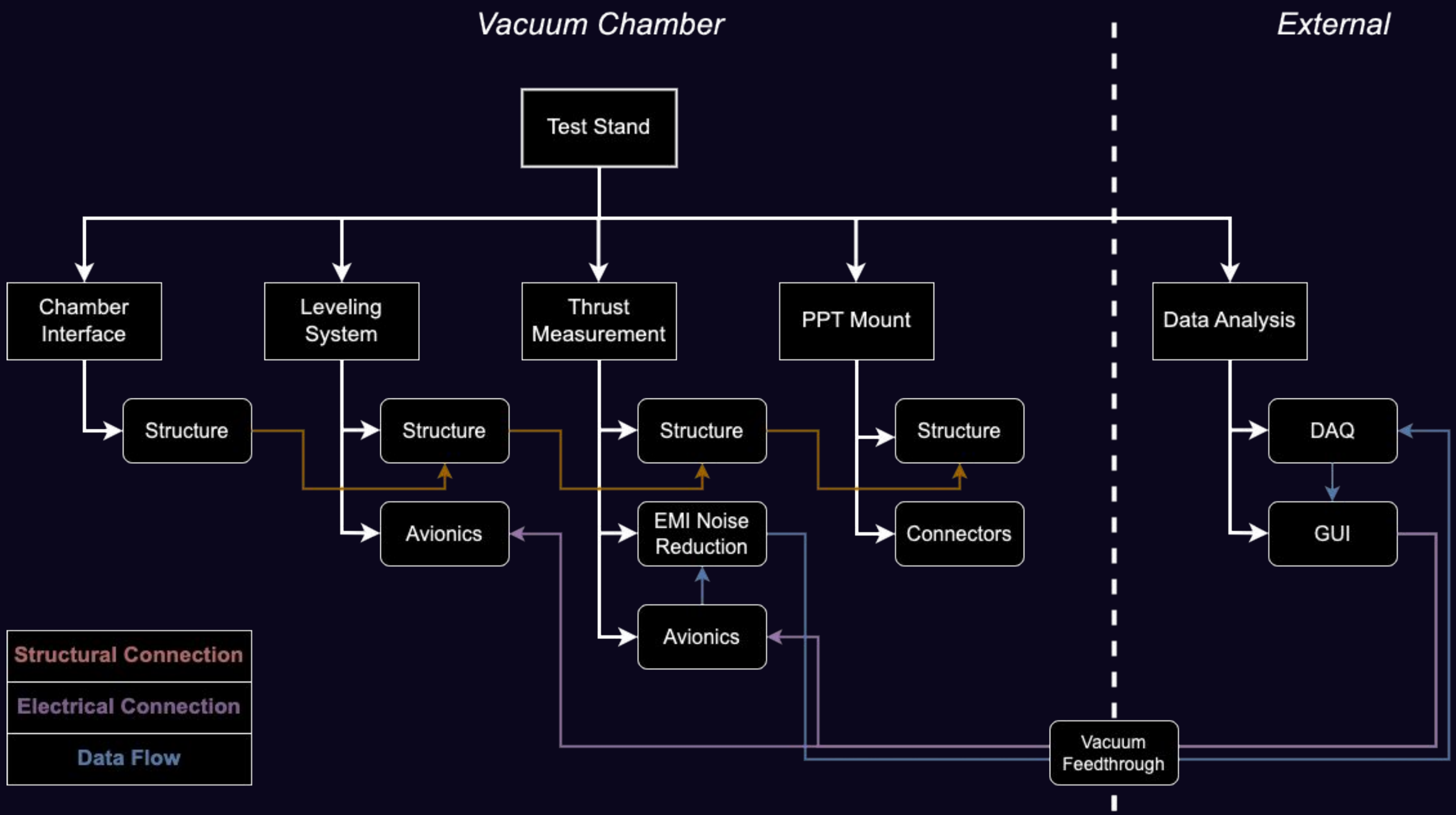
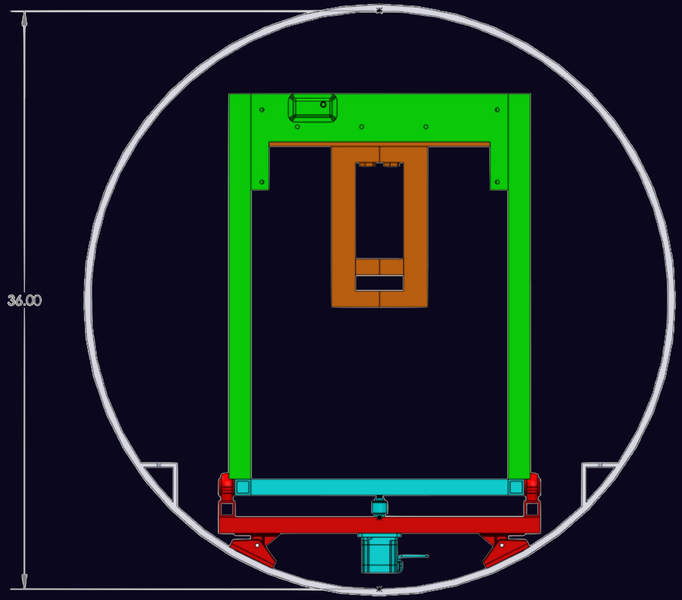
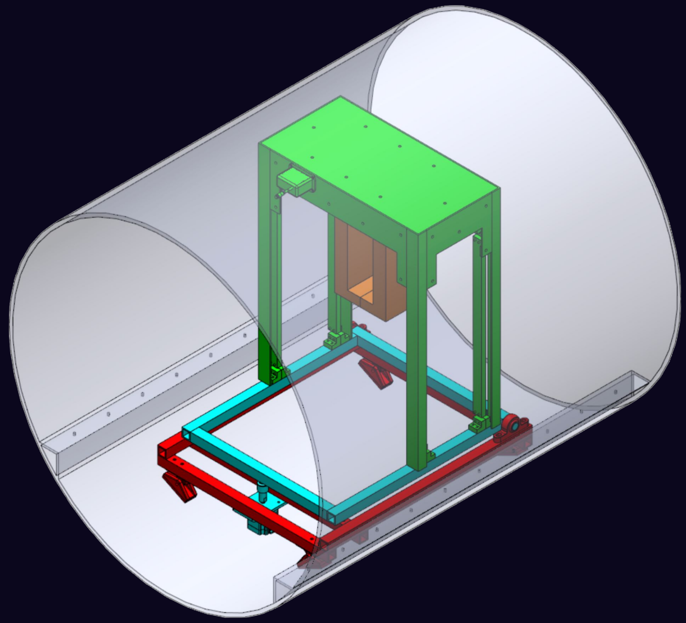
System Architecture



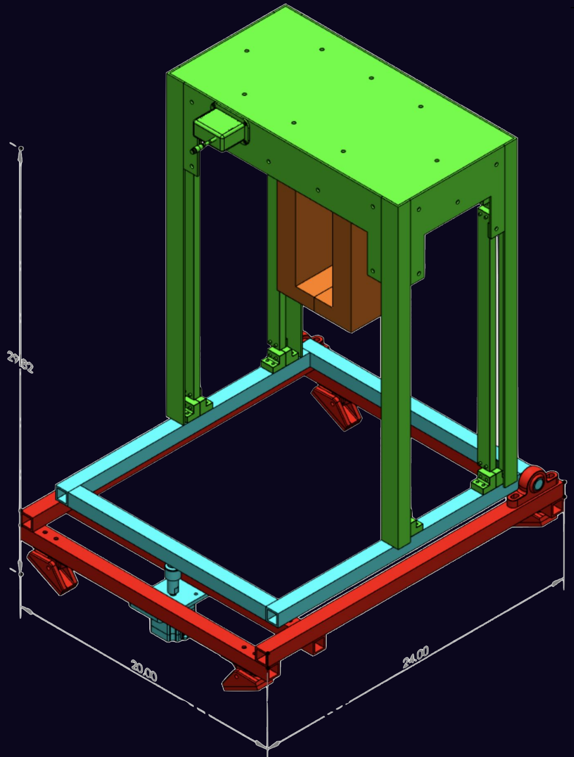
System Architecture



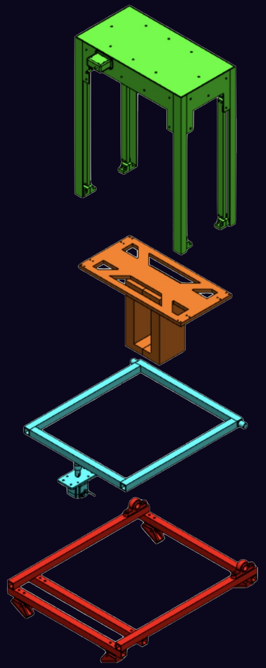


Concept Test Stand

System Architecture



Concept test stand



- Thrust Measurement
- PPT Mount
- Leveling System
- Chamber Interface

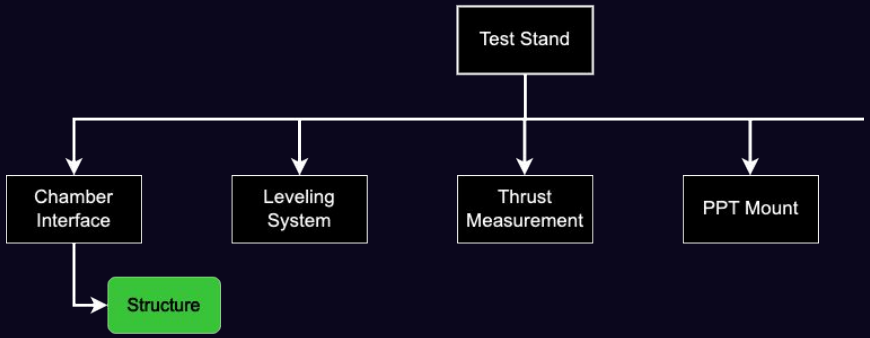
Subsystem Breakdown

Systems	Nathan Cheng
Power	Kai Laslett-Vigil
Avionics	Winston Wilhere
Structures	Adam Delbow, Ben Fetters
Propulsion	Lillie LaPlace
Software	Felicity Cundiff

WW, BF, NC

Chamber Interface: Structure

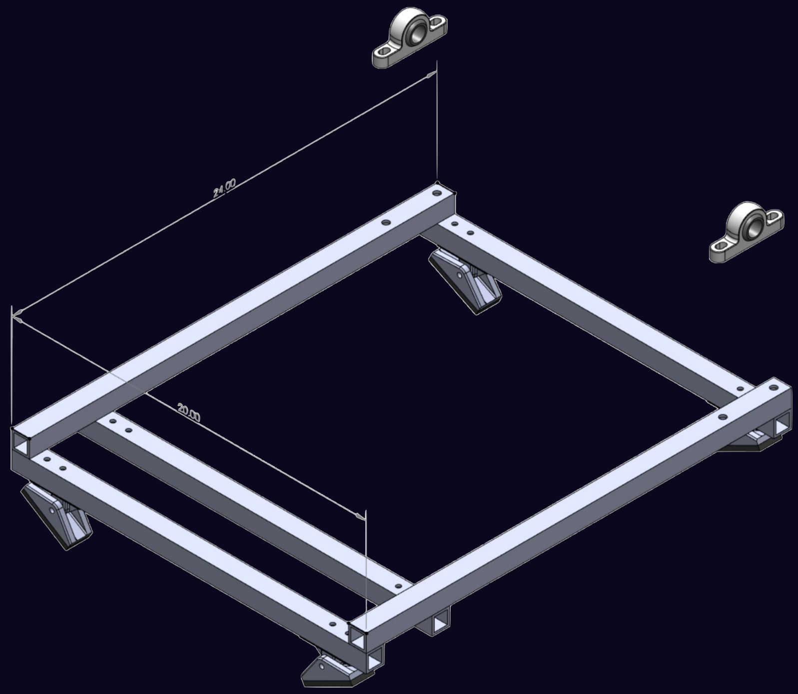
System Architecture



Driving Requirements

ID	Requirement	Verification Method
St.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 30 inches	*Analysis*
St.2	Stand must be designed to avoid scratching to chamber walls	*Inspection*
St.3	Test stand must be isolated from vibrations through vacuum chamber walls (TBD)	*Analysis*
St.4	Thruster must be centered to within 10% of the vacuum chamber radius	*Inspection*

Chamber Interface: Structure



Concept CAD of Structure

- ➢ Nylon Bushings for rotation of Leveling System

Chamber Interface: Structure

Concept CAD of Structure

Adjustable feet will be used to accommodate variations in radius of curvature. The max and min radii are 18 and 15 inches, respectively. The chamber interface will meet requirement St.1. Not shown: Bolts for friction locking.

Chamber Interface: Structure

Design - Chamber Interface

- Base of adjustable feet will be made of rubber to isolate stands from external vibrations and protect chamber walls.
- Once final stand is designed material and geometry of rubber isolators can be chosen to isolate vibration. Vibration frequency at chamber wall will also have to be measured. Natural frequency of block should be 1/√2 vibration frequency
- St.2 and St.3 will be met by using feet with rubber base

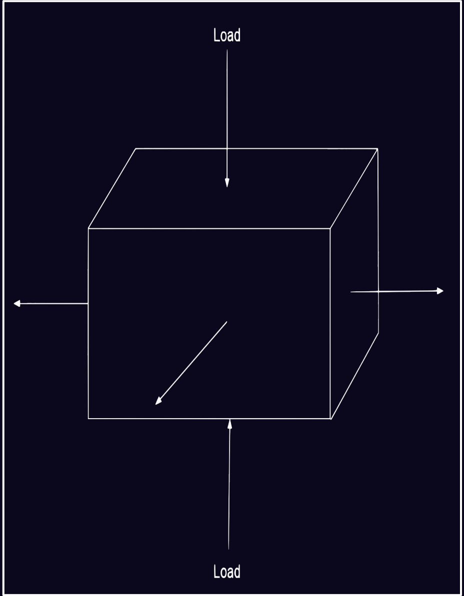
$$S = \frac{\text{area under load}}{\text{area allowed to bulge}}$$

$$E_{corrected} = \frac{4}{3}E(1 + S^2)$$

$$k = \frac{E_{corrected}lw}{t}$$

$$f_n = 3.13\sqrt{k/W}$$

$$f_n = 0.16\sqrt{k/m}$$

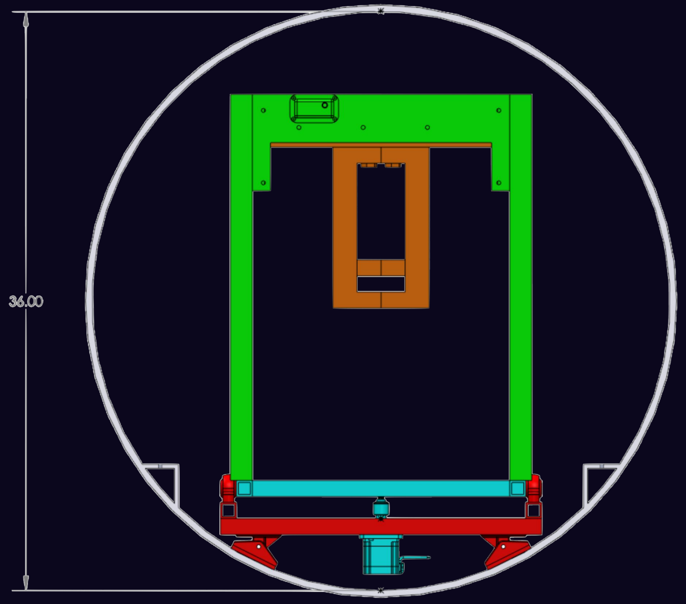


Equations and concepts taken from [4]

Chamber Interface: Structure

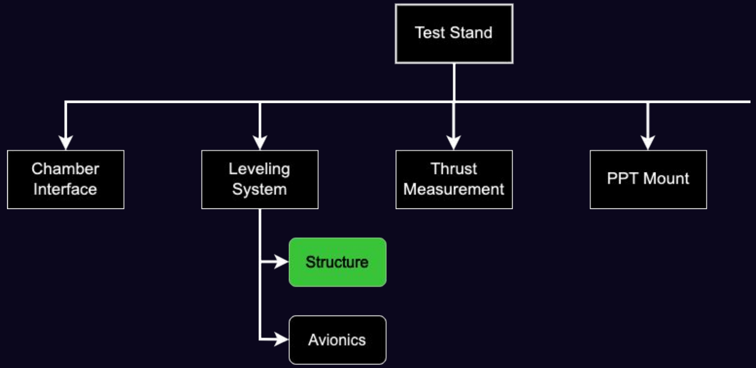
Plan to Verify St.4

- St.4 was added to requirements late in the cycle and is not shown to be met in CAD.
- This requirement will be incorporated into the design within a week after this presentation
  - *Have an adjustable PPT mount height and verify the distance of the mount from the center of the chamber using CAD measurement tools*



Leveling System: Structure

System Architecture



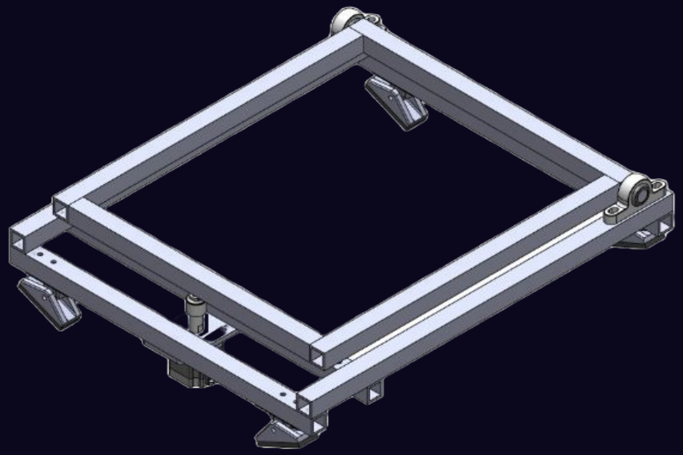
Driving Requirements

ID	Requirement	Verification Method
St.6	Structure must be allowed to pivot to allow leveling system to adjust test stand plus or minus 3 degrees	*Test*

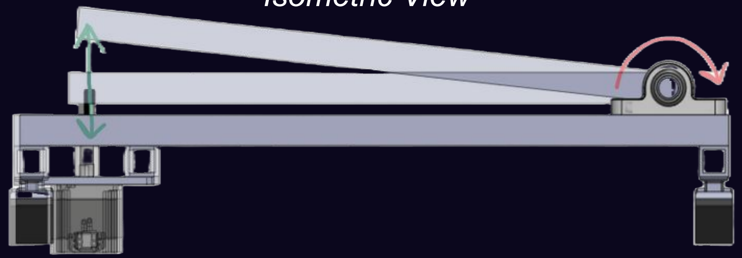
Leveling System: Structure

Design - Leveling System

- Base of test stand will be levelled by way of a stepper motor
- Base will be allowed to pivot through TBD angle on nylon bushings
- St.6 will be met through the use of nylon bushings
- TBD angle will be gathered from Peter Thoreau at SPACE Lab



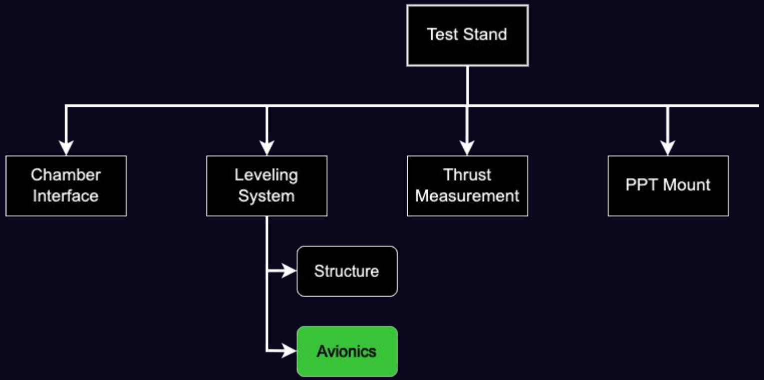
Conceptual Leveling System Isometric View



Conceptual Leveling System Side View and Actuation

Leveling System: Avionics

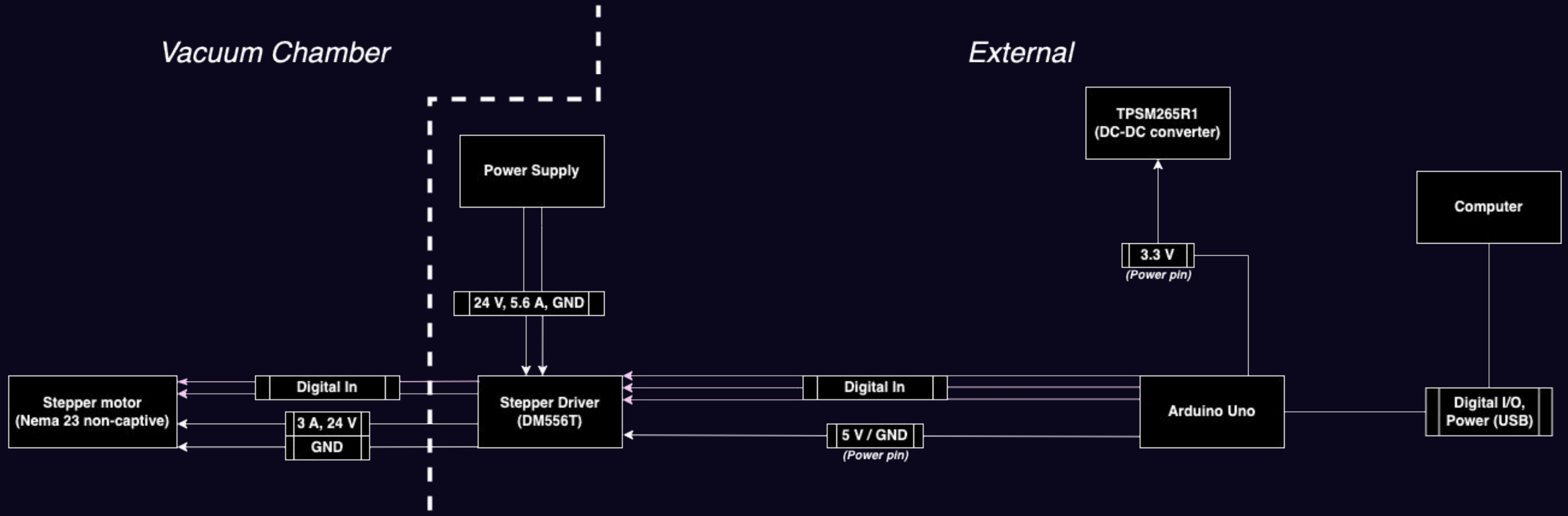
System Architecture



Driving Requirements

ID	Requirement	Verification Method
Av.1	Electronics/hardware must have minimal conductive components	*Inspection*
Av.2	Stand must be adjustable between -5 to 5 degrees with resolution of 0.01 degrees	*Test*

Leveling System: Avionics



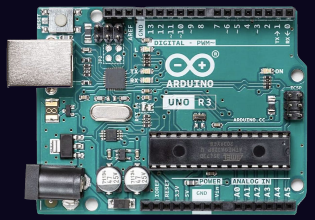
Leveling System: Avionics

Item	Relevant Specifications
Nema 23 non-captive	1.27 mm displacement per revolution, Custom total displacement range
DM556T	Compatible with stepper motor and arduino

Nema 23 non-captive actuator [i4]

- Nema 23 controlled and powered by DM556T driver, which is controlled by Arduino Uno
- Actuator screw will be replaced with a nylon version
  - Satisfies Av.1
- With lever arm of 508 mm, stand angle can be adjusted with resolution of 0.000044 degrees per revolution
  - Satisfies Av.2

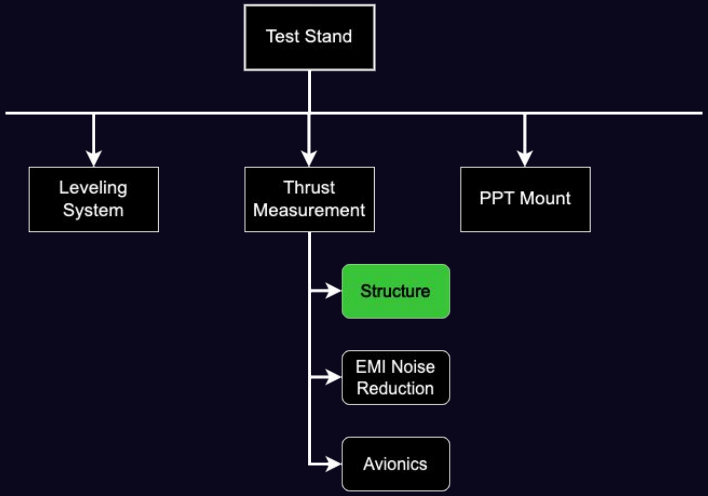
[i5]



[i6]

Thrust Measurement: Structure

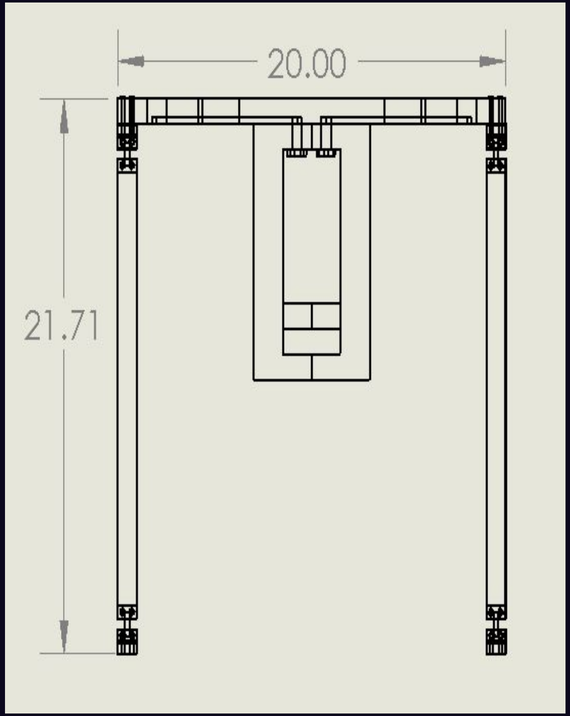
System Architecture

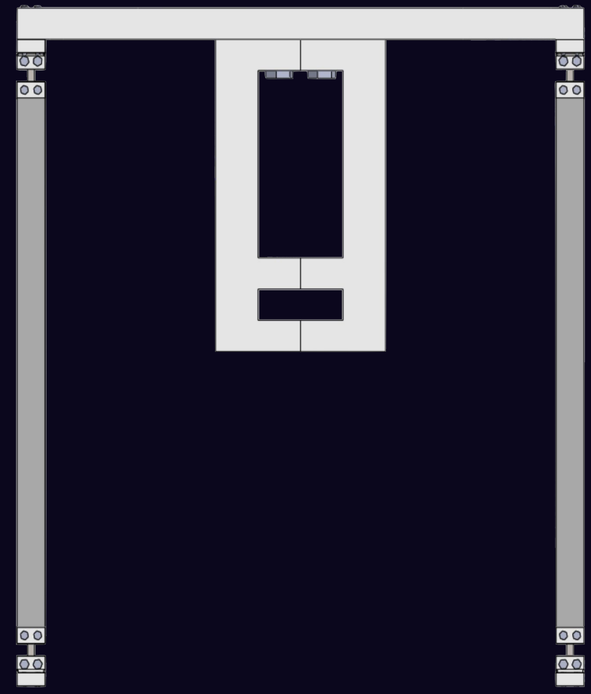


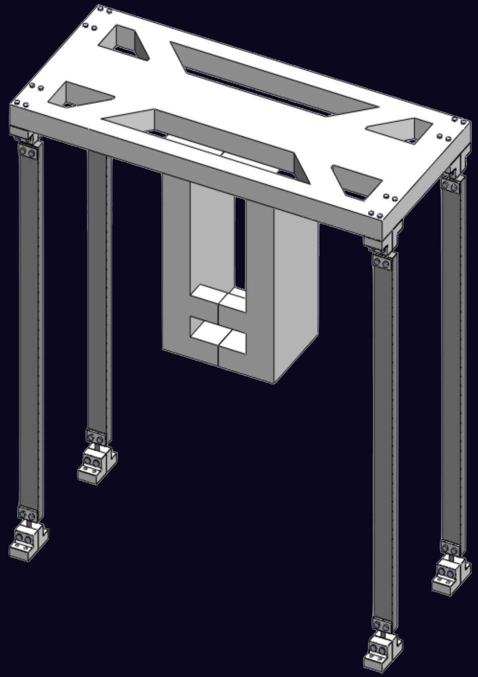
Driving Requirements

ID	Requirement	Verification Method
St.7	Flexure spring constants must allow for full range of impulse to be tested 10 **μ**N*s to 100 mN*s	*Analysis*
St.8	Flexures must be replaceable/interchangeable	*Inspection*
St.9	Oscillations of thruster must be brought to steady state within 6 seconds	*Demonstration*

Thrust Measurement: Structure







Conceptual Thrust Pendulum With Adjustable Thruster Mount

Thrust Measurement: Structure

Design - Flexures

- Based on the given thrust range of 10 **µ**N to 100 mN and a 0.25 m height thruster position, the flexures' spring constants must all fall between 0.700 N*m < k < 7.81E4 N*m for an 8 kg thruster with a rangefinder precision of 10E-6 m
  - An 8 flexure design was selected
  - For the DawgStar's PPT design (5 kg) with an average thrust of 5.68E-5 N [1] and moment arm of 0.25 m, this would correspond to <u>k = 42.8 N*m</u>

$$\boxed{k = \frac{\frac{F_t L_t^2}{x_{ss}} - mgL_t}{8}}$$

Thrust Measurement: Structure

Design - Flexures

- To achieve k = 42.8 N*m, a beam bending assumption was used for a rectangular cross-sectioned flexure
    - For garolite (E = 16.5 GPa): <u>h = 0.25 mm</u>, b = 2.5 mm, L = 1.4 cm
    - For PETG (E = 2 GPa): <u>h = 0.5 mm</u>, b = 2.5 mm, L = 1.4 cm

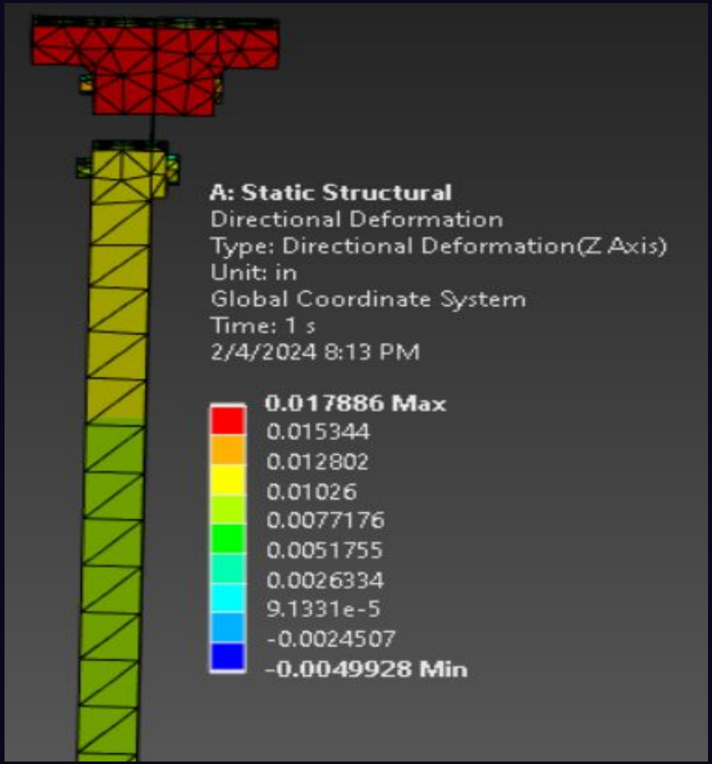
$$k = \frac{3EI}{L^3}$$

$$I = \frac{bh^3}{12}$$

Thrust Measurement: Structure

Finite Element Analysis of test stand

- Ansys FEA was performed for a single leg of the pendulum due to software restrictions on student version
- Load of thruster scaled to account for only simulating one leg of pendulum
- Total displacement of 0.0227 inches (0.576 mm) using 0.01 in thick spring steel flexure
- The IL-100 rangefinder's minimum resolution is 60 µm
- Requirement St.7 is met on the low end of the scale, flexure thickness can be changed to meet the upper end

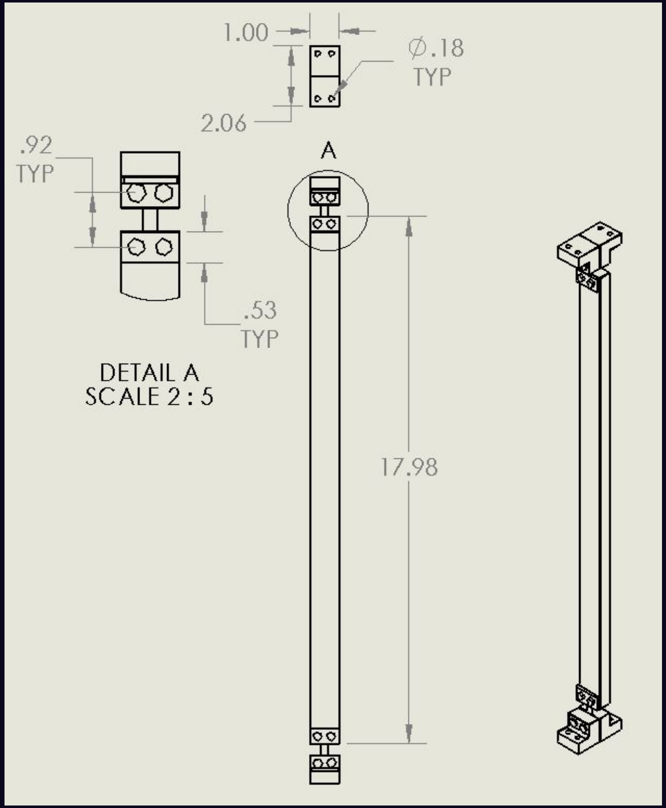


Deflection at 10µN from 8 kg thruster

Thrust Measurement: Structure

Design - Flexures

- Simple design using 4 bolts to hold flexures in place
- Flexure bolts easily accessed when test stand fully assembled, making for easy removal and installation
- Flexures of many thicknesses ranging from 0.01 inches to 0.6 inches will be manufactured
- Requirement St.8 will be met by utilizing this design strategy

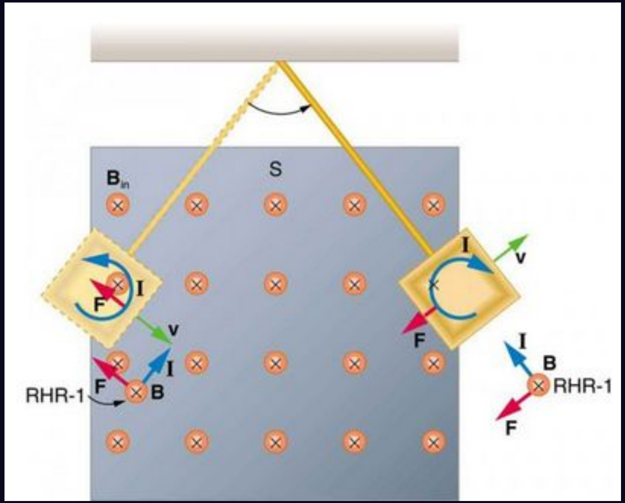


CAD of Flexure Support Structure

Thrust Measurement: Structure

Design - Oscillation Damping

- Despite wanting to minimize conductive materials, eddy current dampers are proven to be reliable for small thrust applications
- Magnetic interactions create a damping force opposing the velocity vector
- Trade off of using conductive materials for damping deemed suitable by SPACE Lab
- Requirement St.9 will be satisfied using eddy current dampers



Eddy Current Damper [i13]

Thrust Measurement: Structure

Design - Additional Considerations

- The DawgStar PPT will not allow us to characterize the upper end of our impulse range (10E-4 to 10E-1 N*s), meaning that another thruster must be used to characterize performance in this range

Proposed Solution

- Test an additional thruster with an impulse range between 10E-4 and 10E-1 N*s to cover the full spectrum of resolvable impulses requested in the system requirements
  - The current proposal is to design and build such a thruster outside of capstone, under A A 499 research credits

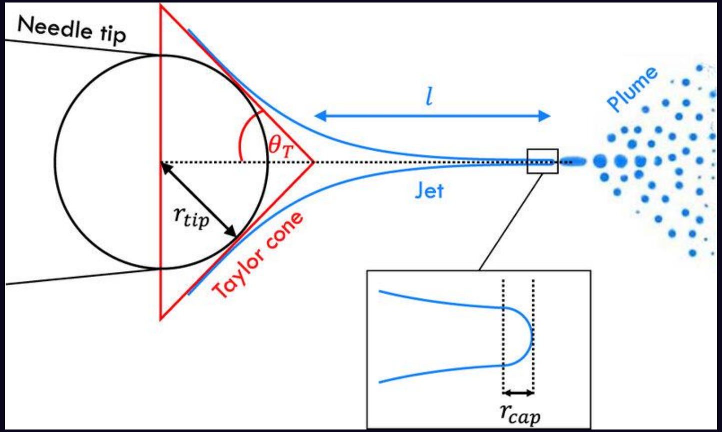
Thrust Measurement: Structure

Design - Additional Considerations

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

Proposed Solution

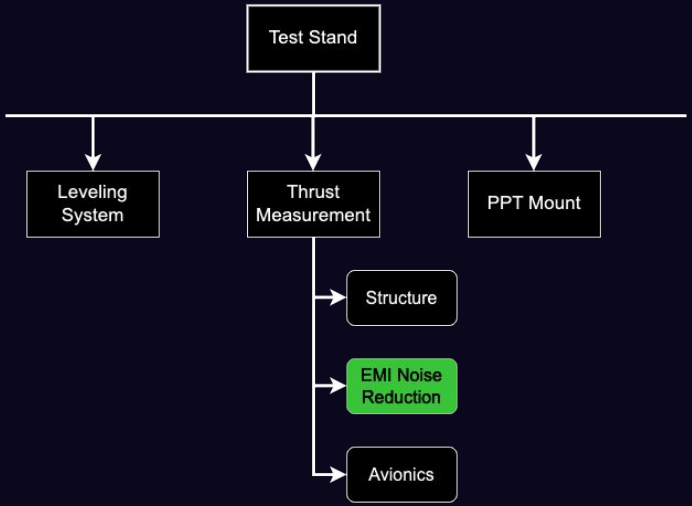
- A Taylor Cone shall be used to generate a known impulse to calibrate the displacement of the pendulum arm of the test stand
  - A Taylor cone functions by producing a known amount of thrust by releasing a stream of fluid into the chamber
  - The calibration shall occur after vacuum chamber pump down and PPT firing



Taylor Cone Device Schematic [i18]

Thrust Measurement: EMI Shielding

System Architecture

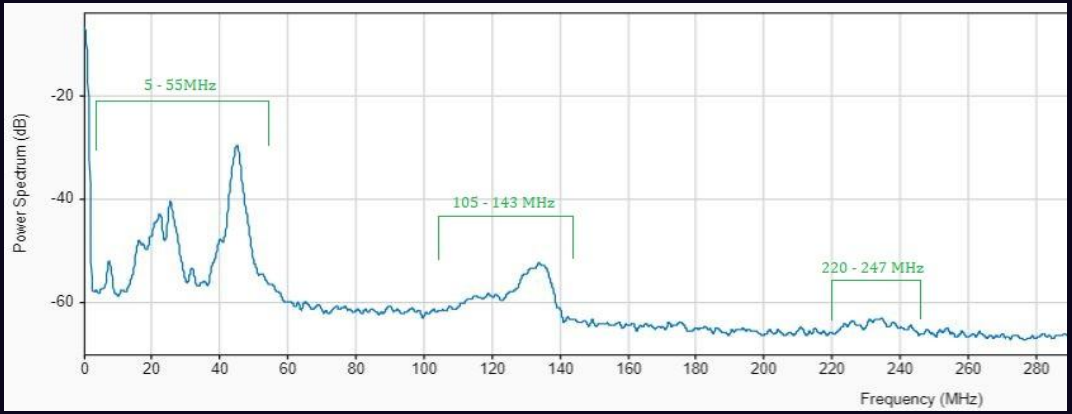


Driving Requirements

ID	Requirement	Verification Method
Av.3	Minimized interaction of analog signals with EM waves between the frequencies of 5 MHz to 250 MHz	*Test*

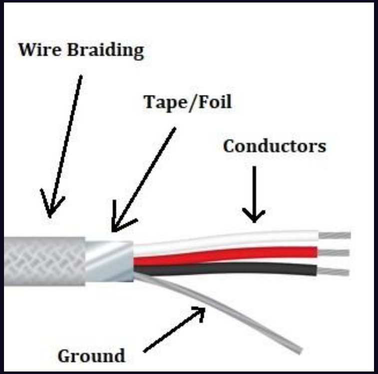
Thrust Measurement: EMI Shielding

- Collected EMI attenuation data from Dawgstar and applied a FFT to determine peak frequency intensities
- Notable frequency peaks:
  - 5 - 247 MHz range



Noise Power Spectrum from 0-280 MHz

- Combine wire braid/foil shielding:
- Conductive braiding sheath
  - EMI and abrasion resistance
  - ~ 75-80% EMI Coverage
- Conductive foil/tape
  - 100% EMI coverage
  - Vulnerable to abrasion

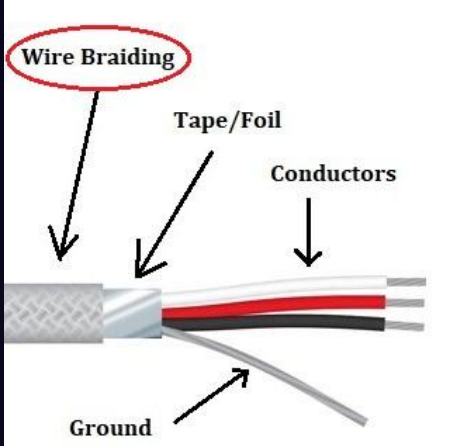


[i8]

Thrust Measurement: EMI Shielding

Glenair 100-002

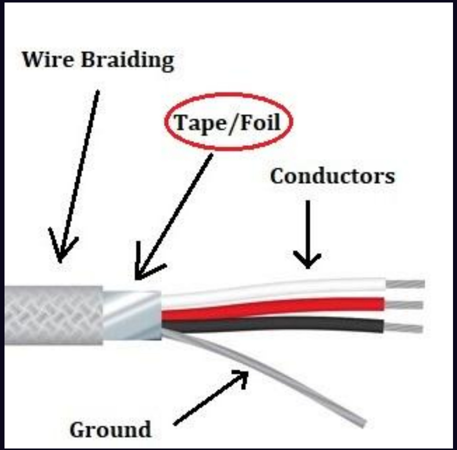
- Soft drawn Silver plated Copper
- EMI coverage: 10kHz - 1 GHz +
  - Satisfies Av.3
- Abrasion resistance: Fair



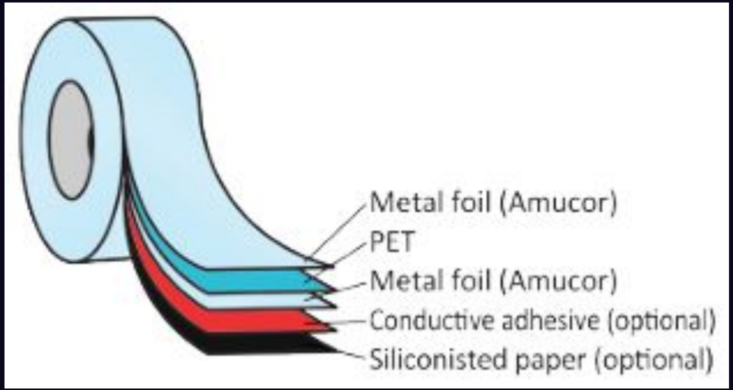
[i9]

Thrust Measurement: EMI Shielding

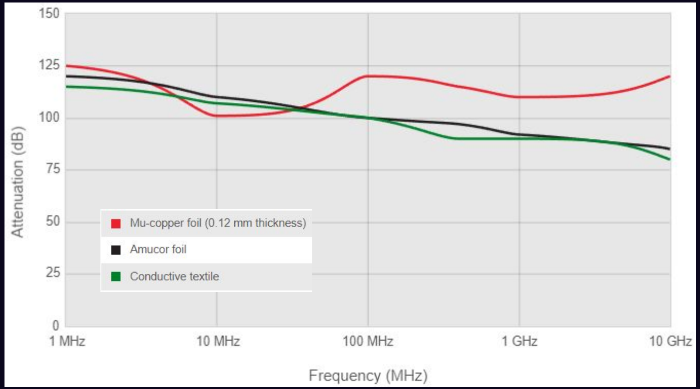
- Current selection: Amucor 4718
  - Foil material: Amucor + PET
  - EMI Coverage: TBC
  - Adhesive: Synthetic conductive Resin
- Conductive adhesive applications:
  - Ground/seal wire braiding to flanges
  - Properly adhere to wires to ensure maximum coverage



Braided Shielding Schematic [i11]



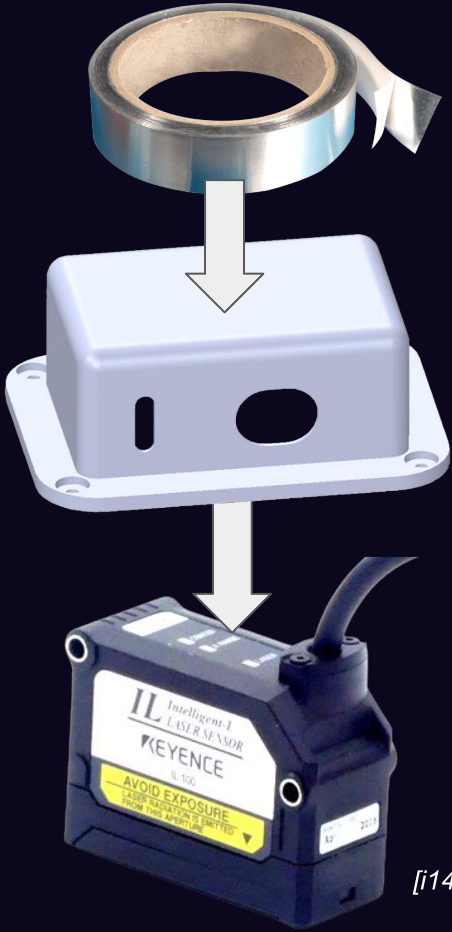
[i10] *Adhesive Shielding Layering Schematic*



[i12] *Noise Frequency Attenuation for Mu-copper foil, Amucor foil, and Conductive textile shielding*

Thrust Measurement: EMI Shielding

- 3D printed housing wrapped in Amucor foil:
- Internal Faraday cages:
  - Envelopes IL-xxx (sensor)
- External Faraday cages:
  - IL-1000 (amplifier)
  - USB-6009 (DAQ)



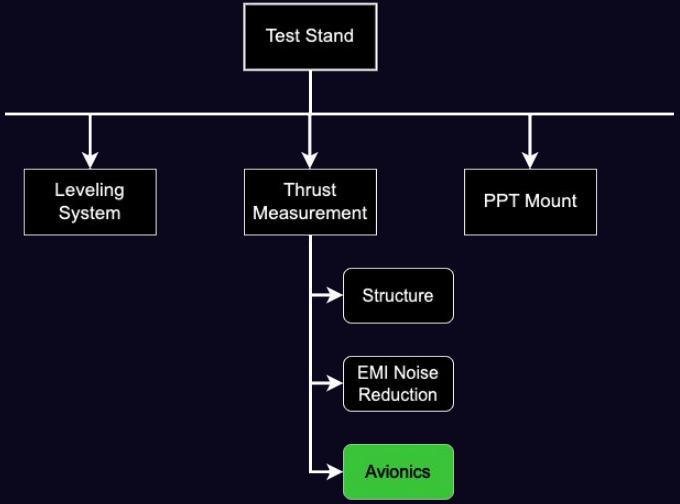
[i15]

[i14]

Proposed 3D printed Faraday cage design for IL-100 sensor

Thrust Measurement: Avionics

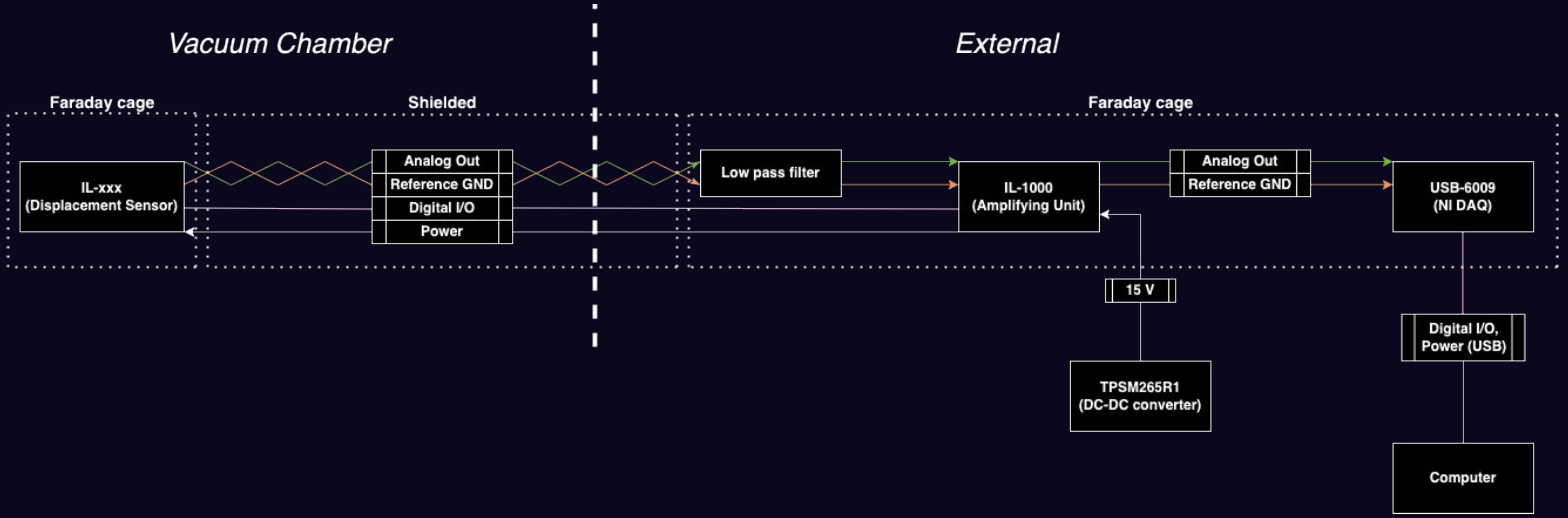
System Architecture



Driving Requirements

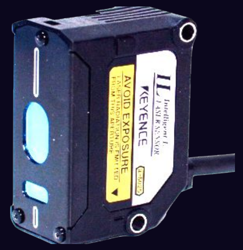
ID	**Requirement**	**Verification Method**
Av.4	DAQ must sample at least 10x the output frequency of the displacement sensor	*Demonstration*

Thrust Measurement: Avionics



Thrust Measurement: Avionics

Item	Relevant Specifications
NI USB-6009	Sampling rate of 48 kHz, reads analog inputs @ 13 bit resolution
IL-xxx	Resolution of 10 - 60 μm depending on model, 1 - 3 kHz output frequency
IL-1000	Compatible with displacement sensor



IL-100 [i1]

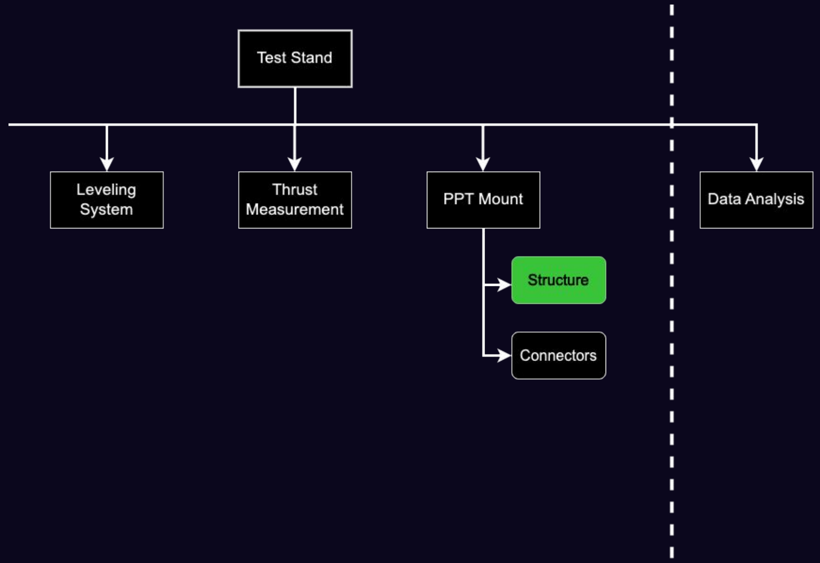
- IL-xxx output amplified by IL-1000, read and digitized by USB-6009 DAQ
- DAQ chosen for compatibility with NIDAQmx and sampling rate
  - Satisfies Av.4
- Laser model (IL-xxx) dependent on mount location
- External hardware requires EMI shielding (fields still exist outside vacuum chamber)

IL-1000 [i2]

USB-6009 [i3]

PPT Mount: Structure

System Architecture



Driving Requirements

ID	Requirement	Verification Method
St.10	Structure must be able to support up to an 8 kg thruster	*Analysis*
St.11	Test stand must be able to accommodate thrusters up to 16.5 inches wide	*Inspection*
St.12	Structure must outgas at a pressure at least one order of magnitude below nominal chamber pressures	*Test*

PPT Mount: Structure

Analysis - Buckling

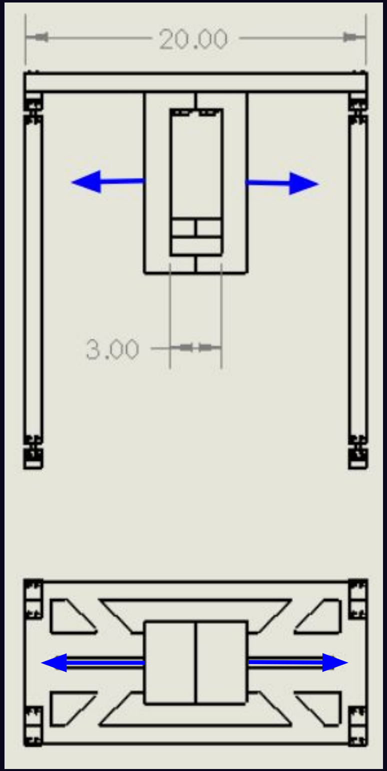
- Only flexure buckling considered. They are the weakest point in the structure.
- Each leg of pendulum carries ¼ of the load of the thruster and stand.
- Thinnest flexures can support 8 kg thruster and mass of test stand structure with a factor of safety of 1.31.
- Structures will meet requirement St.10

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

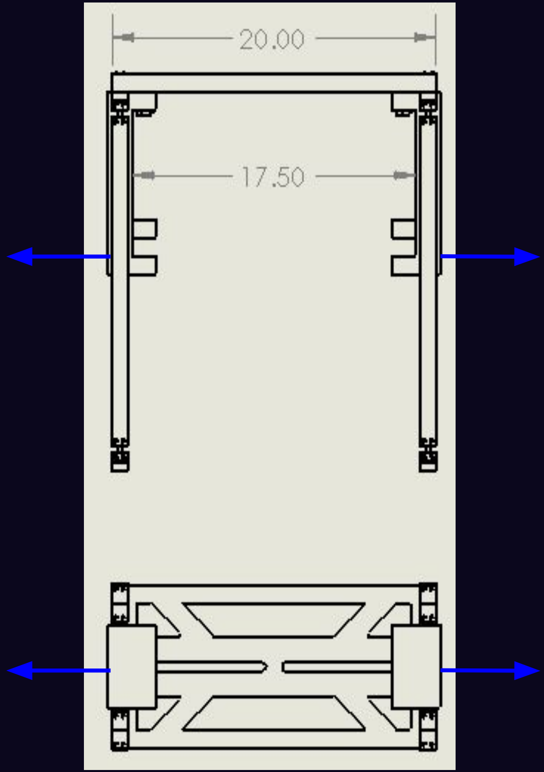
$$P_{cr} = 131.7N$$

$$P_t = 100.7N$$

PPT Mount: Structure



Slotted rails (shown in bottom view) allow for horizontal motion (indicated by arrows in top view) of the thruster mount, with a minimum spacing of 3 inches.



Slotted rails allow the sliding thruster mount to open to a maximum width of 17.5 inches to accommodate a 16.5 inch wide thruster.

Structures will meet requirement St.11

PPT Mount: Structure

Material Selection

- Non-conductive materials are preferred, as the introduction of conductive materials increases the probability of unwanted EMI
- Non-conductive fasteners, such as nylon, will be purchased to test their feasibility for stand construction. Metal screws will also be purchased as back up
- Fiberglass and assorted polymer 3D printer filaments were assessed for their suitability as primary test stand structures
- 3D printed material was primarily chosen for both its high modulus of elasticity and ease of manufacturing

PPT Mount: Structure

- Material Selection
  - 3D Printer Filament Selection

Material	Moisture Absorption at Equilibrium	Modulus Elasticity (GPa)	Thermal Conductivity (W/m*K)	Cost ($/kg)	Ease of Printing (qualitative)
PETG	0.200-0.300%	1.10-20.3	0.162-0.225	29	most printers (including Prusa)
PLA	0.06-2%	0.05-13.8	0.0320-0.170	22	can be printed on any standard printer
ABS	0.000-0.300%	0.150-2.65	0.150-0.200	22	has shrinking issues post-cooling, toxic fumes to humans while printing

	Factor Weight	PETG	PLA	ABS
Moisture Absorption at Equilibrium	0.1	0.3	0.1	0.2
Modulus of Elasticity	0.5	1.5	1	0.5
Thermal Conductivity	0.1	0.1	0.3	0.2
Cost	0.1	0.1	0.3	0.2
Ease of Printing	0.2	0.4	0.6	0.2
Total	1	2.4	2.3	1.3

Sources: Matweb, Monofilament Direct

PPT Mount: Structure

Material Selection

- 3D Printer Filament Treatment
  - PLA, PETG, and ABS all outgas on the order of 0.2-0.3% mass, releasing material into the vacuum chamber and introducing the potential for undesirable chemical reactions with the plasma plume and material deposition over time
- Any 3D printed components will be printed with 100% infill, as trapped air within the components may cause structural damage as pressure decreases within the vacuum chamber
- 3D printed components will be treated with a sealant such that they do not lose an appreciable amount of mass (more than 0.1 mg/cm^2 per 25 hours cited for Vacseal) under vacuum pumping conditions
  - Space Environment Laboratories' Vacseal aerosol spray is proposed
- St.12 will be met by following these steps

PPT Mount: Structure

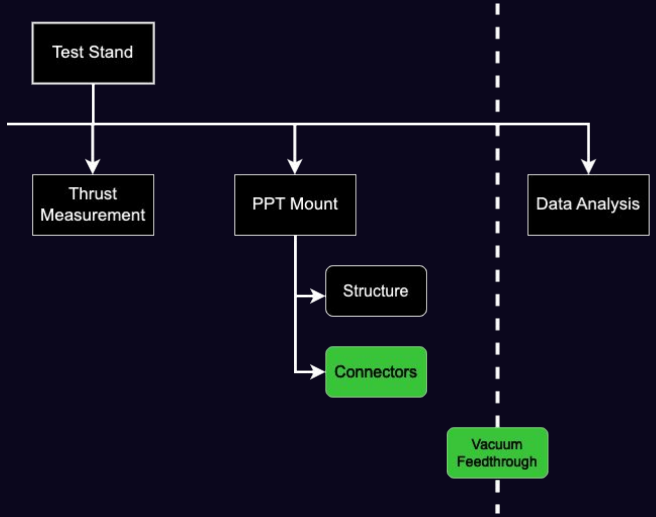
3D Printer Filament Treatment

Design - Electrochemical Erosion

- As Teflon ablates, it releases fluorine ions, highly reactive particles within the plasma plume that can erode the structural integrity of the stand over time
- Unintended arcing across test stand components could lead to structural damage
  - Both these sources of damage must be considered throughout the stand’s design
  - To mitigate these effects, an electrically insulating alumina ceramic spray coat is proposed to coat all plasma-facing structural components

PPT Mount: Connectors (Vacuum Feedthrough)

System Architecture



Driving Requirements

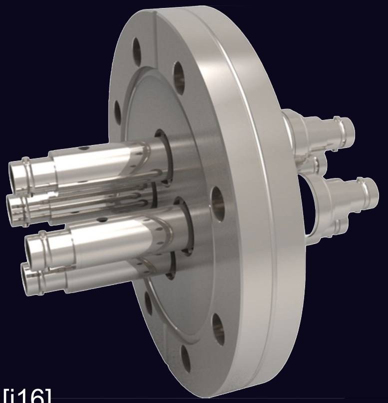
ID	Requirement	Verification Method
Cn.1	Have sufficient number of connection inputs to support test stand and PPT	*Inspect*
Cn.2	Electrical feedthroughs shall be able to interface with the flanges provided by the SPACE lab	*Inspect*
Cn.3	Ground sources shall comply with SPACE lab standards on grounding	*Test*

PPT Mount: Connectors (Vacuum Feedthrough)

- Flange usage requires 11 ports:
  - IL-xxx 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 3 connections
    - 2 power inputs
    - Analog output
  - Flanges utilize BNC ports (TBC)
- Electrical feedthrough ports
  - Interfaces with BNC ports (TBC)

- Flanges provided by SPACE lab provide 16+ feedthrough ports
  - Ability to add additional ports as required
- Standardized ConFlat flanges provide reference GND
  - Compliant with SPACE lab standards

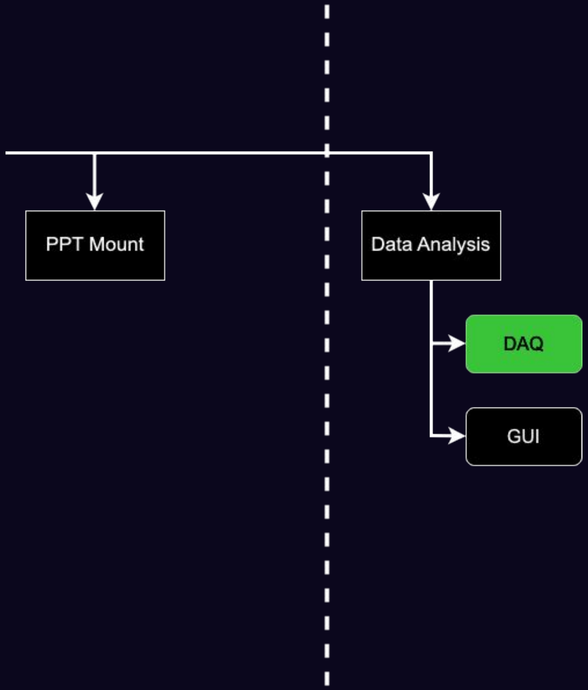
[i17]



[i16]

Data Analysis: DAQ

System Architecture



Driving Requirements

ID	Requirement	Verification Method
Sw.1	Software will convert deflection measurements to thrust measurements and corresponding uncertainties.	*Analysis*
Sw.2	Software will record raw deflection data from the rangefinder.	*Analysis*

Data Analysis: DAQ

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
    - Recording Deflection Data: *record_deflection()* reads raw deflection data from the DAQ

```python

# Function to record raw deflection data from the rangefinder
def record_deflection():
    global deflection_data
    try:
        with nidaqmx.Task() as task:
            task.ai_channels.add_ai_voltage_chan("your_channel")
            task.timing.cfg_samp_clk_timing(rate=1000, sample_mode=nidaqmx.constants.AcquisitionType.CONTINUOUS)
            deflection_data = task.read(number_of_samples_per_channel=1000)  # Recording Deflection Data

    except nidaqmx.DaqError as e:
        print(f"DAQ Error: {e}")
        print(f"Error Code: {e.error_code}")
        print(f"Error Details: {e.__cause__}")

```

Data Analysis: DAQ

Design

- Conversion of Measurements: Sensitivity based on the *measured deflection and a calibration force*. Facilitating the *conversion* of deflection measurements into thrust measurements.

- Calculation of Uncertainties:
  - Thrust uncertainty is estimated by scaling the *standard deviation of deflection*.
  - Error propagation techniques ensure reliable *estimation of thrust uncertainties during conversion*.

```

    # Error propagation: Propagate uncertainties from deflection to thrust
    deflection_std_dev = np.std(deflection_data)
    thrust_uncertainties = deflection_std_dev * sensitivity  # Scale the standard deviation

    uncertainties = np.full_like(thrust_data, thrust_uncertainties)  # Set uncertainties based on scaled standard deviation

```

Data Analysis: DAQ

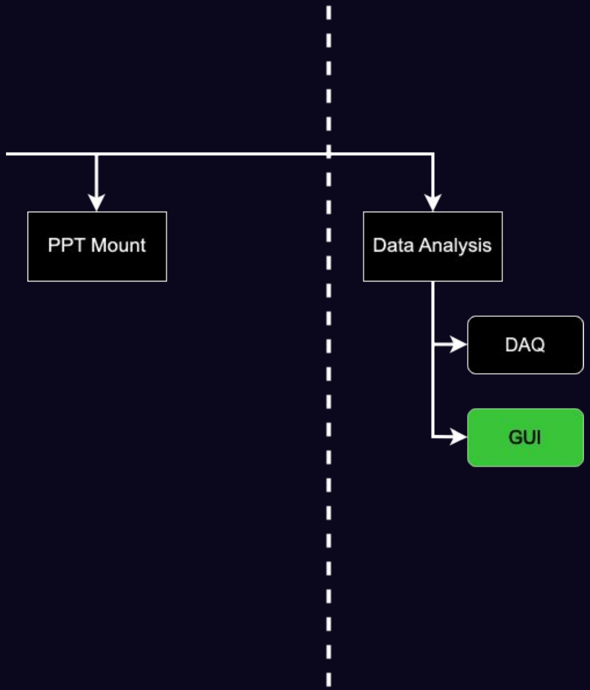
Design

- Calibration:
  - convert_to_thrust() function is used to *calibrate raw deflection measurements to thrust*.
  - Raw deflection is calibrated to thrust by defining a 10 micronewton calibration force.
  - *Sensitivity is calculated as the ratio* of measured deflection to the calibration force.

```python

# Function to convert deflection measurements to thrust measurements
def convert_to_thrust():
    global deflection_data, uncertainties
    try:
        # Calculate the sensitivity (scale factor)
        calibration_force = 0.01  # Calibrating to 10 micronewtons (0.01 Newtons)
        measured_deflection = 50  # Example measured deflection in units

        sensitivity = measured_deflection / calibration_force

        # Apply calibration to convert deflection measurements to thrust measurements
        thrust_data = deflection_data * sensitivity

```

Data Analysis: GUI

System Architecture



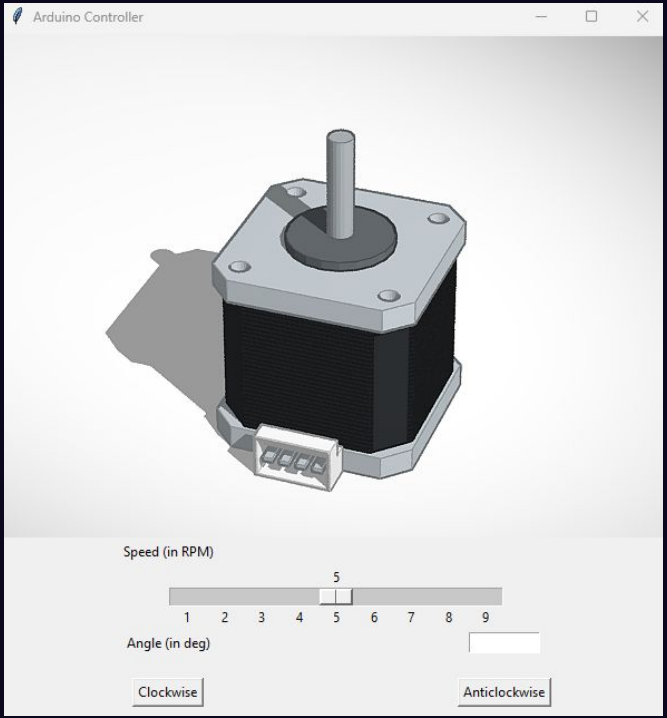
Driving Requirements

ID	Requirement	Verification Method
Sw.3	Software will display deflection measurements and corresponding uncertainties graphically, allowing for the export of produced figures and raw data.	*Inspection*

Data Analysis: GUI

Design - Arduino

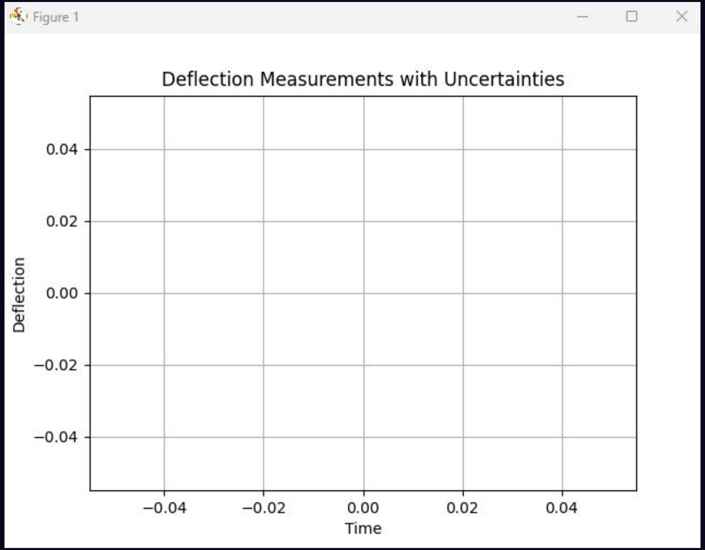
- Serial Communication Setup:
  - *PySerial* send commands to the Arduino, instructing it on how to *control the stepper motor*.
- Sending Data to Serial Port:
  - sendData: Sends motor control data to the Arduino.
  - low_pass_filter: Smoothing motor speed changes.
- GUI Integration:
  - Constructs a *Tkinter* window and designs GUI elements.
  - *Visual*: Clockwise/Anticlockwise buttons, Speed (RPM) sliders, and angle (deg).



Data Analysis: GUI

Design - DAQ

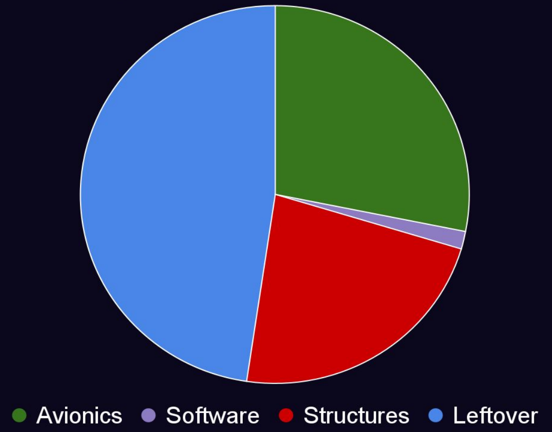
- Recording Deflection:
    - Raw deflection data using the ni-daqmx.
    - Data acquisition is stored in the global variable deflection_data.
- Convert to Thrust:
    - Converts deflection to thrust measurements by calibrating with known force and deflection values, storing the resulting data in global variables.
- Graphical Display:
    - Deflection measurements and their uncertainties
    - Error bars representing the uncertainties.
    - Generated using *Matplotlib*
- Export Options:
    - Both figures (as .png) and raw data (as .csv).
    - Acquired using *pandas*



Budget

Subteam	Limit (TBR)	Margin	Allocated	Items	Individual Cost	Used (Estimate)	Available
Avionics	$ 2000	15%	$ 1700	Stepper Motor	$ 60.72		
				Motor Controller	$ 89.88		
				Laser Rangefinder	$ 544.19		
				Laser Transducer	$ 261.80		
				DAQ	$ 68.20		
				EMI Shielding	-	$1024.79	$ 675.21
Software	$ 700	30%	$ 490	Hard drive	$ 48.99		
				USB cable	$ 6.80		
				DAQ License	$ 0.00	$55.79	$ 434.21
Structures	$ 1750	40%	$ 1050	Dampers	$ 40		
				Frame	$ 157.82		
				Pendulum	629.34		
				Mount	-	$827.16	$ 222.84
Other	$ 450	10%	$ 405	-	-	-	$405
Total	$ 4900	24%	$ 3645			$ 1907.74	$ 1737.26.

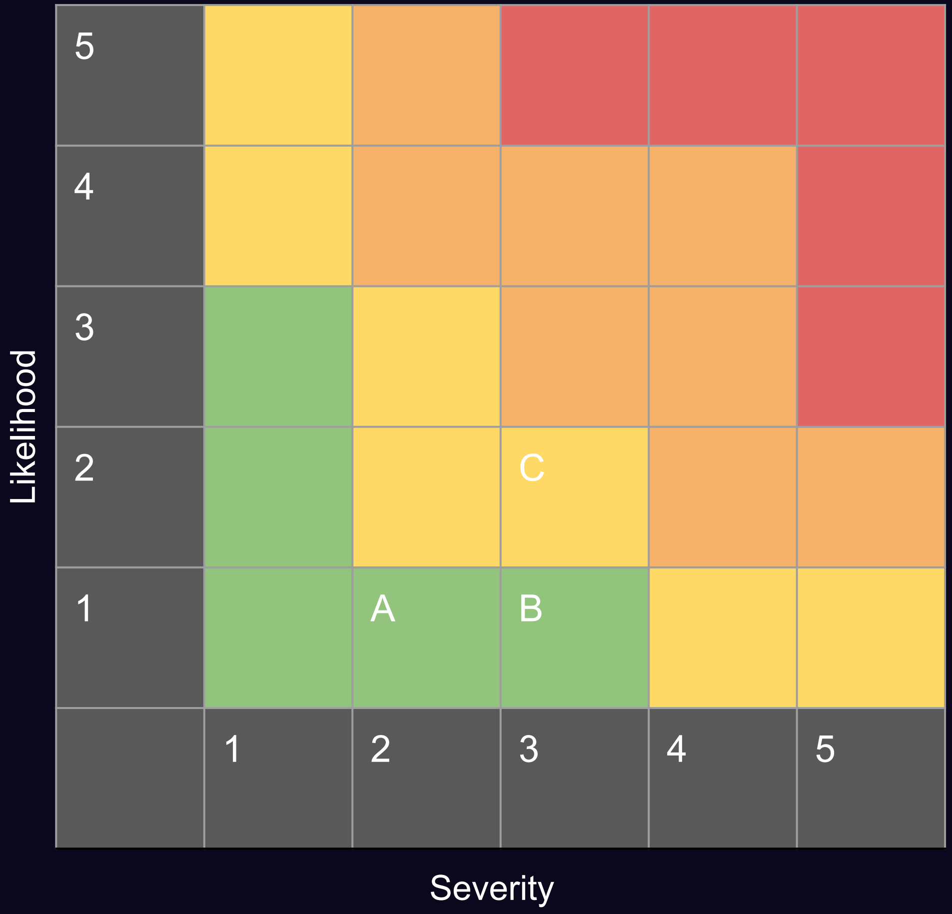
Used (Estimate) Cost Breakdown



System Overview

Risk Assessment

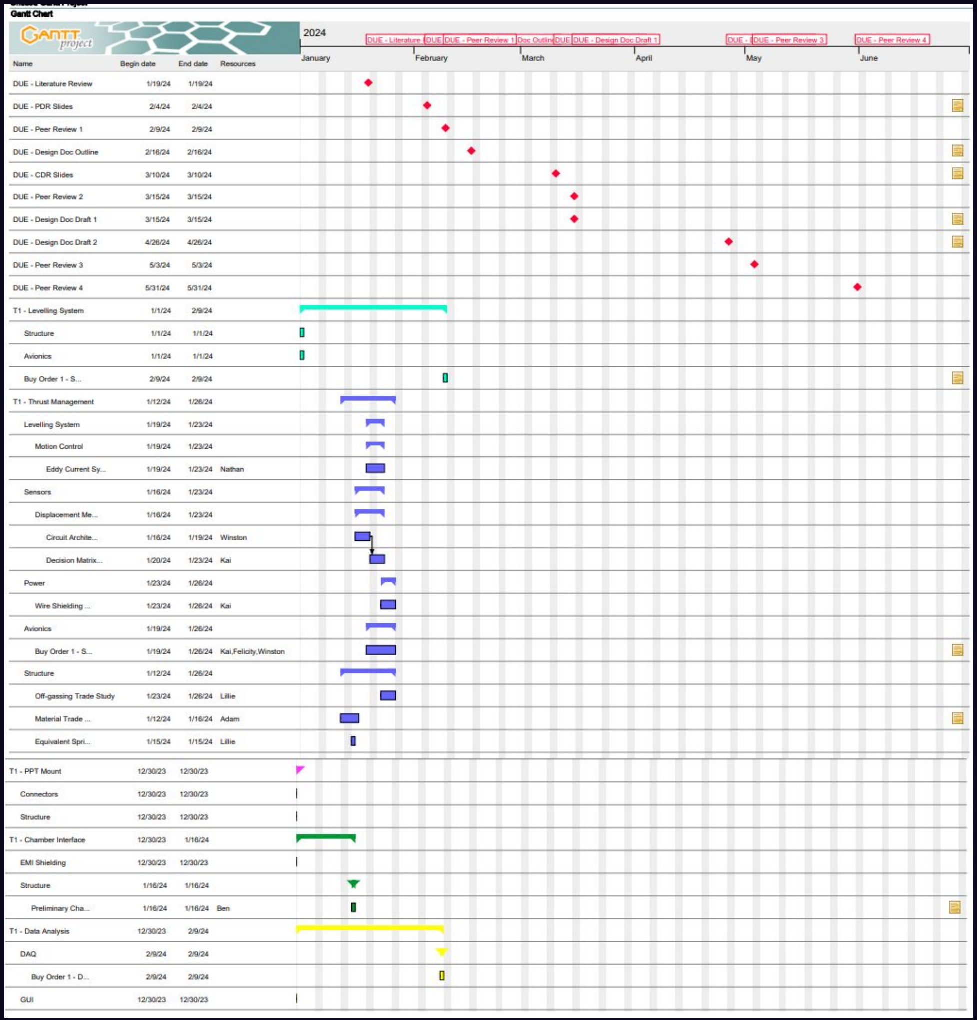
Item	Designation	Mitigation strategy
Vacuum compatibility of materials	A	Materials trade studies
Imprecise measurement stemming from insufficient EMI shielding, conductive parts	B	Maximize shielding without hindering impulse measurement performance and minimize conductive parts without hindering structural integrity
DAQ code incompatibility	C	Revising calibration portion of code



Project Timeline

Next Steps

Subteam	Item
Avionics	• Hardware purchasing
Software	• Improving DAQ code • DAQ, stepper, Arduino purchasing
Structures	• Finalizations to CAD • FEA static analysis • Replacing printed parts
Propulsion	• Thrust measurement deflection FEA • Vacuum & plasma exposure material performance testing
Power	• EMI shielding purchasing



Requirements Verification Matrix (1)

ID	Requirement	Status
Sys.1	Test stand must be an inverted pendulum style	*Currently Met*
Sys. 2	Test stand shall be horizontally level to within ± 0.05 degrees	*Currently Approved*
Sys. 3	Stand must be installed, operated, and removed from vacuum chamber without structural damage to the chamber	*Currently Approved*
Sys.4	Test stand must be able to support thrusters up to 8kg in mass	*Currently Approved*
Sys.5	Test stand must accommodate thruster diameters up to 42 cm, and thruster lengths up to 23 cm	*Currently Approved*

Requirements Verification Matrix (2)

ID	Requirement	Status
Sys.6	Test stand must be able to measure impulse values ranging from 10 μN*s to 100mN*s	*Currently Approved*
Sys.7	Test stand must be able to capture steady-state measurements ranging from 0.1 mN to 0.1 N	*Currently Approved*
Sys.8	System must have a minimum data collection rate of 10x the displacement sensor output frequency	*Currently Approved*
Sys.9	Test stand must return thruster to 0.002 degrees of zero-point between tests	*Currently Approved*
Sys.10	Test stand shall minimize the use of conductive materials	*Currently Approved*

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.

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] Holland Shielding

[i16] Kurt J. Lesker

[i17] Kurt J. Lesker

[i18] Journal of Physics D: Applied Physics

Thank you, any questions?

Initials Key

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

NC

Gantt Chart

Name	Begin date	End date	Resources
DUE - Literature Review	1/19/24	1/19/24	
DUE - PDR Slides	2/4/24	2/4/24	
DUE - Peer Review 1	2/9/24	2/9/24	
DUE - Design Doc Outline	2/16/24	2/16/24	
DUE - CDR Slides	3/10/24	3/10/24	
DUE - Peer Review 2	3/15/24	3/15/24	
DUE - Design Doc Draft 1	3/15/24	3/15/24	
DUE - Design Doc Draft 2	4/26/24	4/26/24	
DUE - Peer Review 3	5/3/24	5/3/24	
DUE - Peer Review 4	5/31/24	5/31/24	
T1 - Levelling System	1/1/24	2/9/24	
Structure	1/1/24	1/1/24	
Avionics	1/1/24	1/1/24	
Buy Order 1 - S...	2/9/24	2/9/24	
T1 - Thrust Management	1/12/24	1/26/24	
Levelling System	1/19/24	1/23/24	
Motion Control	1/19/24	1/23/24	
Eddy Current Sy...	1/19/24	1/23/24	Nathan
Sensors	1/16/24	1/23/24	
Displacement Me...	1/16/24	1/23/24	
Circuit Archite...	1/16/24	1/19/24	Winston
Decision Matrix...	1/20/24	1/23/24	Kai
Power	1/23/24	1/26/24	
Wire Shielding ...	1/23/24	1/26/24	Kai
Avionics	1/19/24	1/26/24	
Buy Order 1 - S...	1/19/24	1/26/24	Kai,Felicity,Winston
Structure	1/12/24	1/26/24	
Off-gassing Trade Study	1/23/24	1/26/24	Lillie
Material Trade ...	1/12/24	1/16/24	Adam
Equivalent Spri...	1/15/24	1/15/24	Lillie
T1 - PPT Mount	12/30/23	12/30/23	
Connectors	12/30/23	12/30/23	
Structure	12/30/23	12/30/23	
T1 - Chamber Interface	12/30/23	1/16/24	
EMI Shielding	12/30/23	12/30/23	
Structure	1/16/24	1/16/24	
Preliminary Cha...	1/16/24	1/16/24	Ben
T1 - Data Analysis	12/30/23	2/9/24	
DAQ	2/9/24	2/9/24	
Buy Order 1 - D...	2/9/24	2/9/24	
GUI	12/30/23	12/30/23	

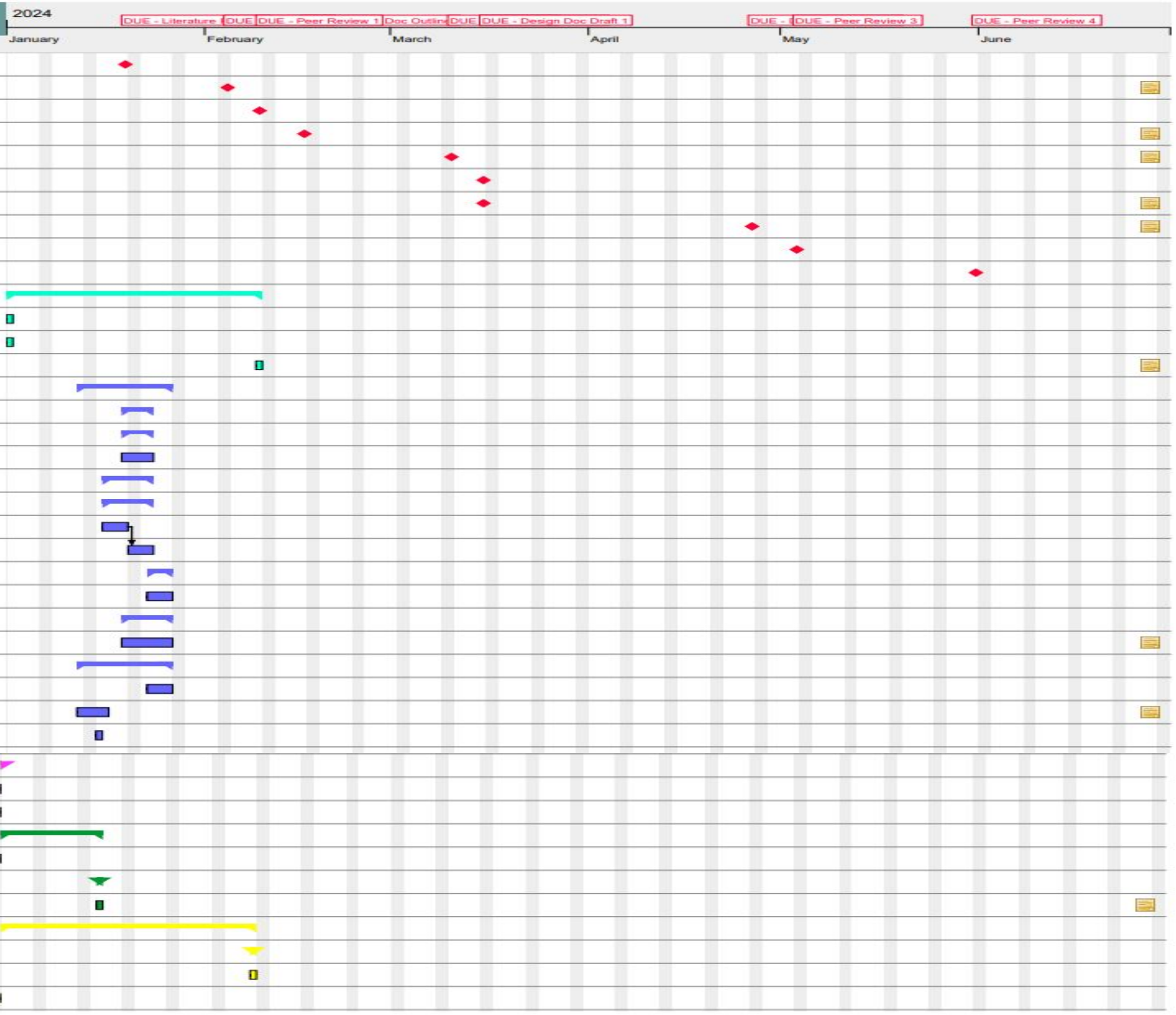


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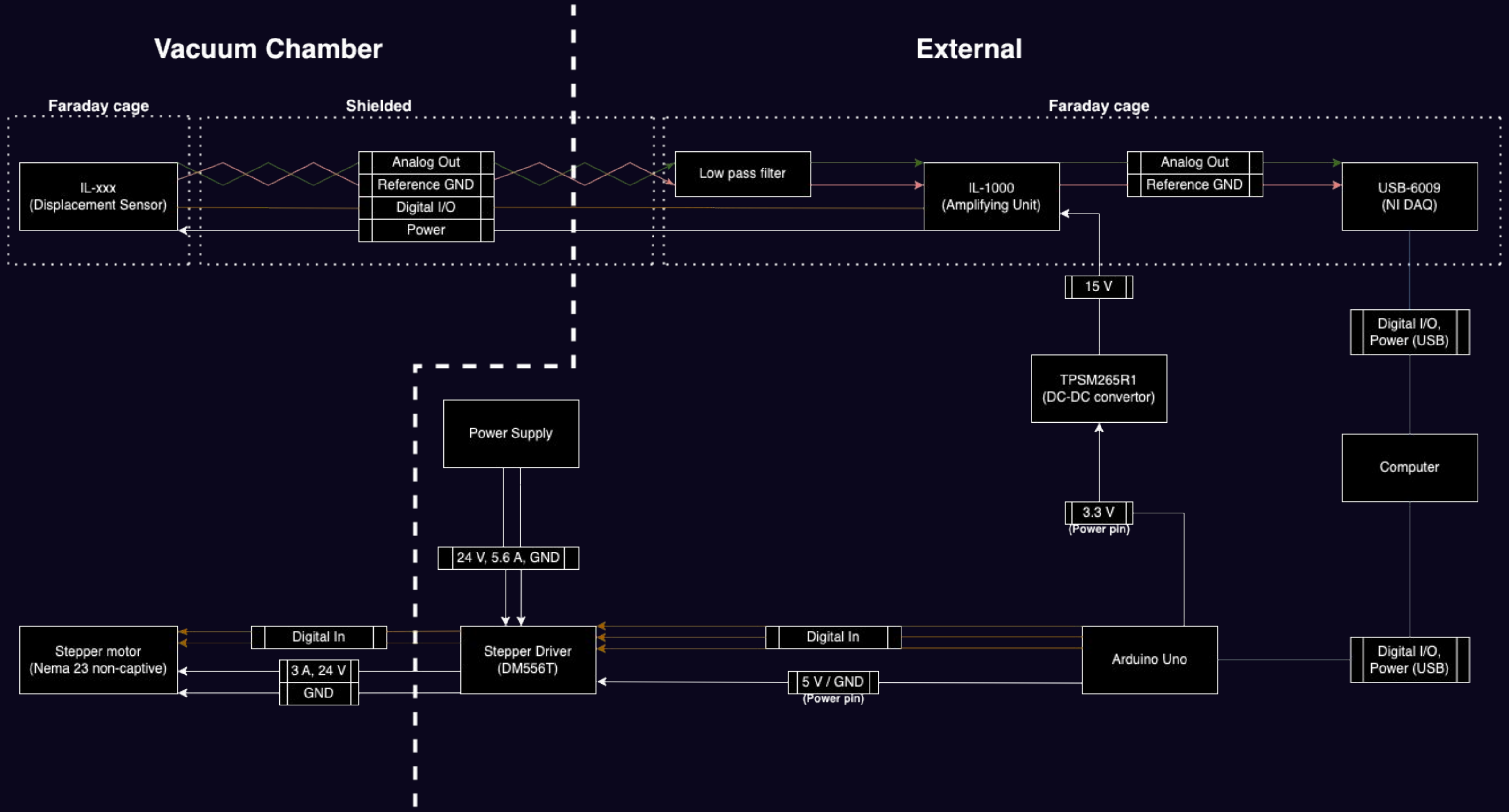
Image

Avionics: Driving Requirements

ID	Requirement	Verification Method
Av.1	DAQ must sample at least 10x the output frequency of the displacement sensor	*Demonstration*
Av.2	Minimized interaction with EM waves between the frequencies of 5 MHZ to 250 MHz	*Test*
Av.3	Electronics/hardware must have minimal conductive components	*Inspection*
Av.4	Stepper motor must actuate leveling system -5 to 5 degrees with resolution of 0.1 degrees	*Test*

Avionics: Wiring Overview



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.

PPT Mount: Structure

- Design, operations
  - Material Selection
  - Environmental Conditions
  - FEA
  - Integration

Image

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

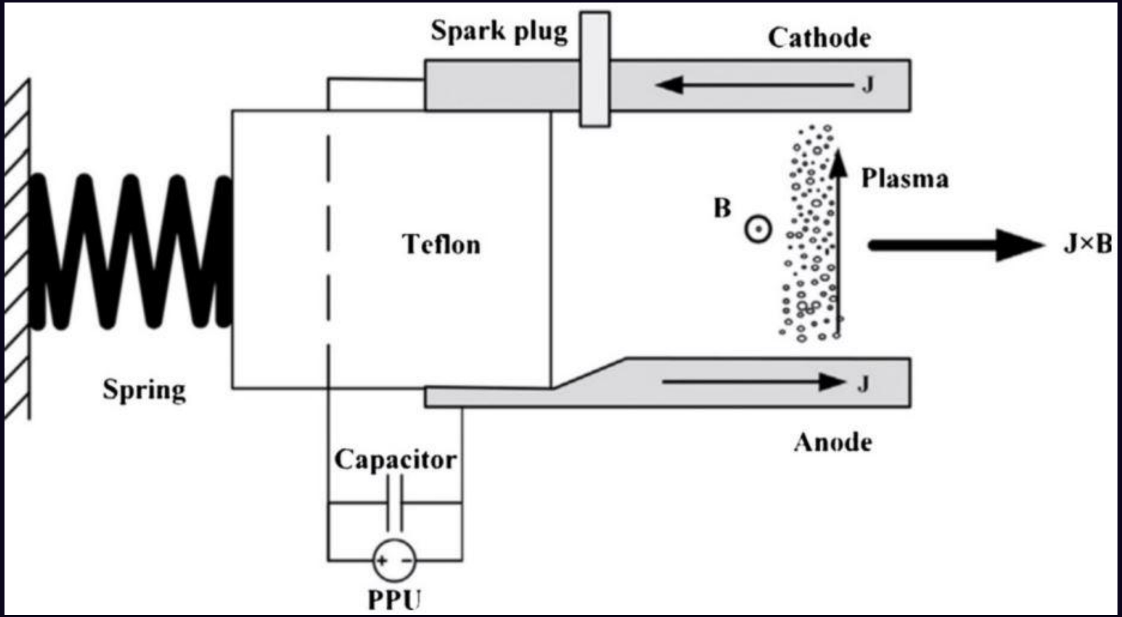
Design - Arduino

- 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.

Thrust Measurement: EMI Shielding



- 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

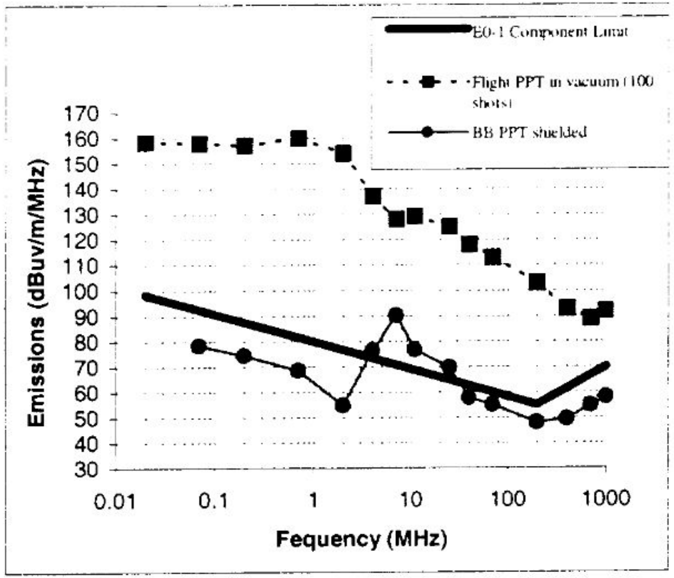
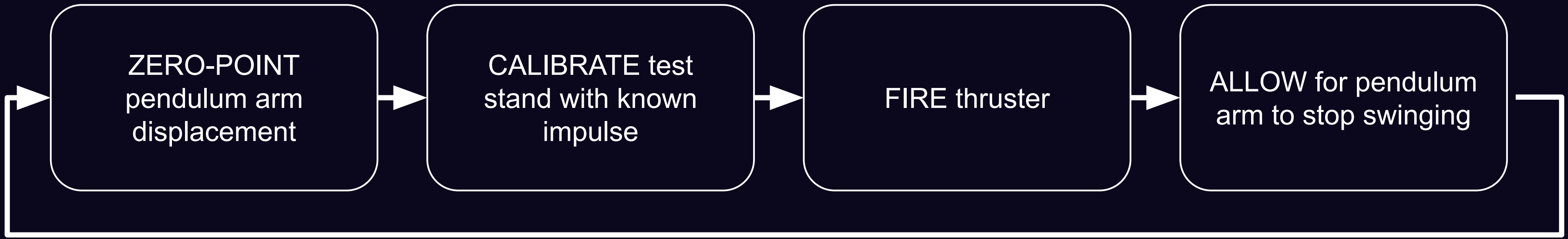


Figure 9: REO2 Results from PPT Shield Test

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

CONOPS

Data Collection



CONOPS

Disassembly

Repressurize, OPEN chamber → REMOVE signal/power connections → REMOVE thruster from stand → REMOVE test stand from vacuum chamber

15 min | 3 hrs | 1 hr | 3 hrs