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S·P·A·C·E

Acceptance Review

Pulsed Plasma Thruster Test Stand

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

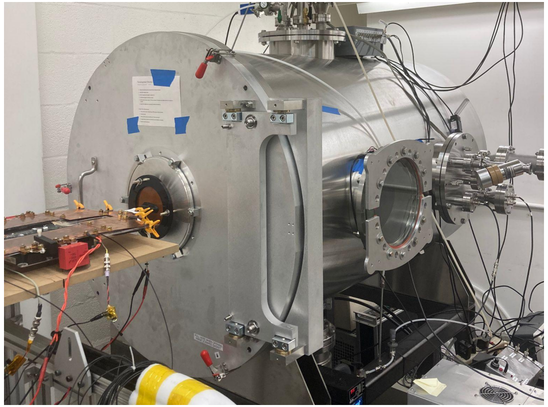
Mentor: Dr. Justin Little

Agenda

- Introduction
- Background and Analysis
- Integration
- Results
- Conclusions

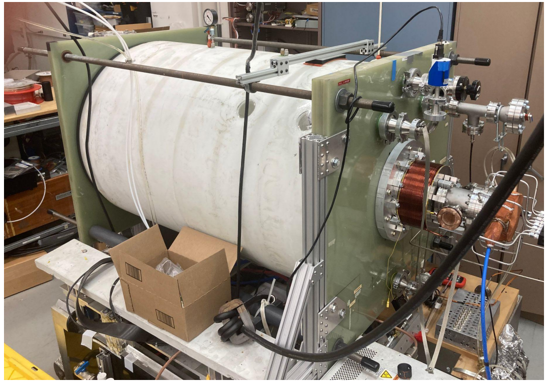
Mission Overview: Motivation

- 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)

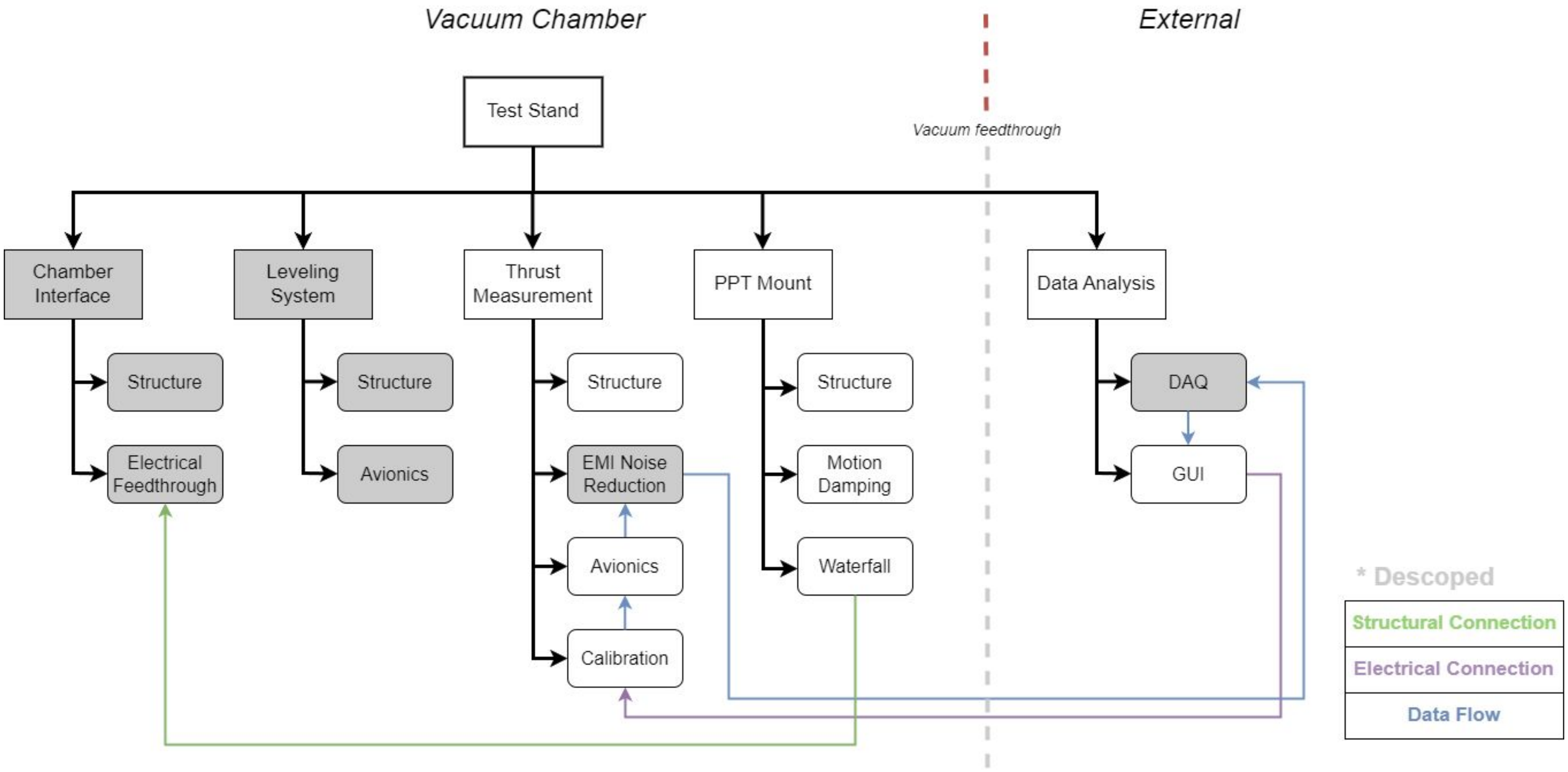


Mission Objective

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 from 10 μN*s to 100 mN*s** and with the capacity to **accommodate a variety of thruster dimensions and masses**

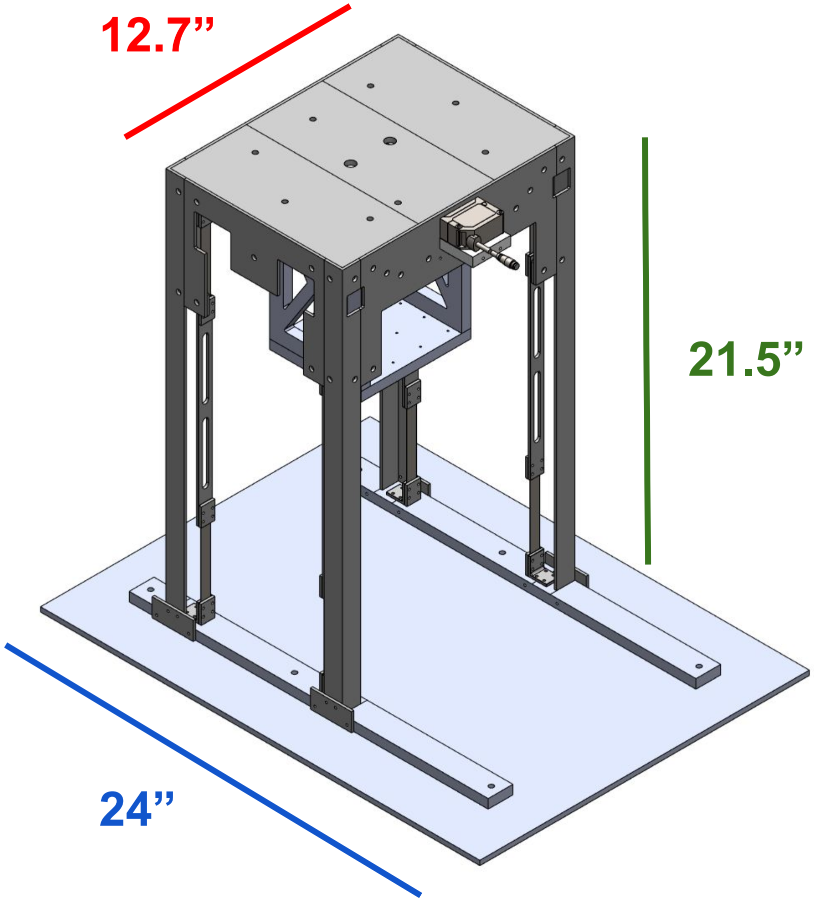
System Architecture

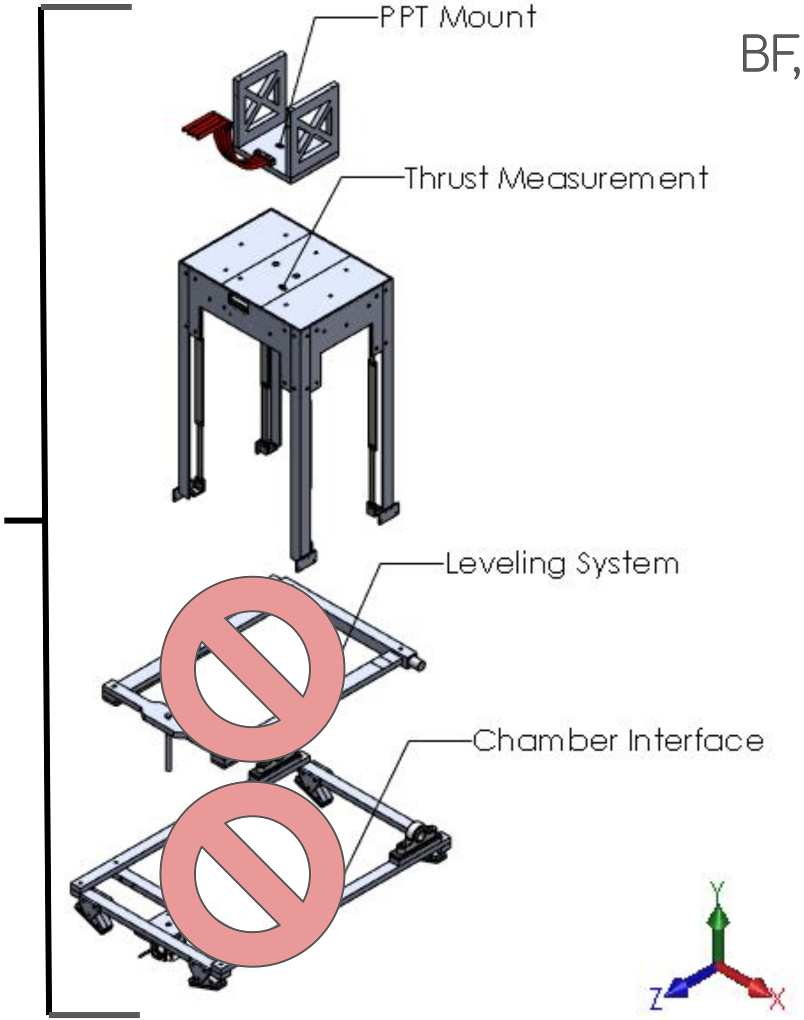
KLV, NC



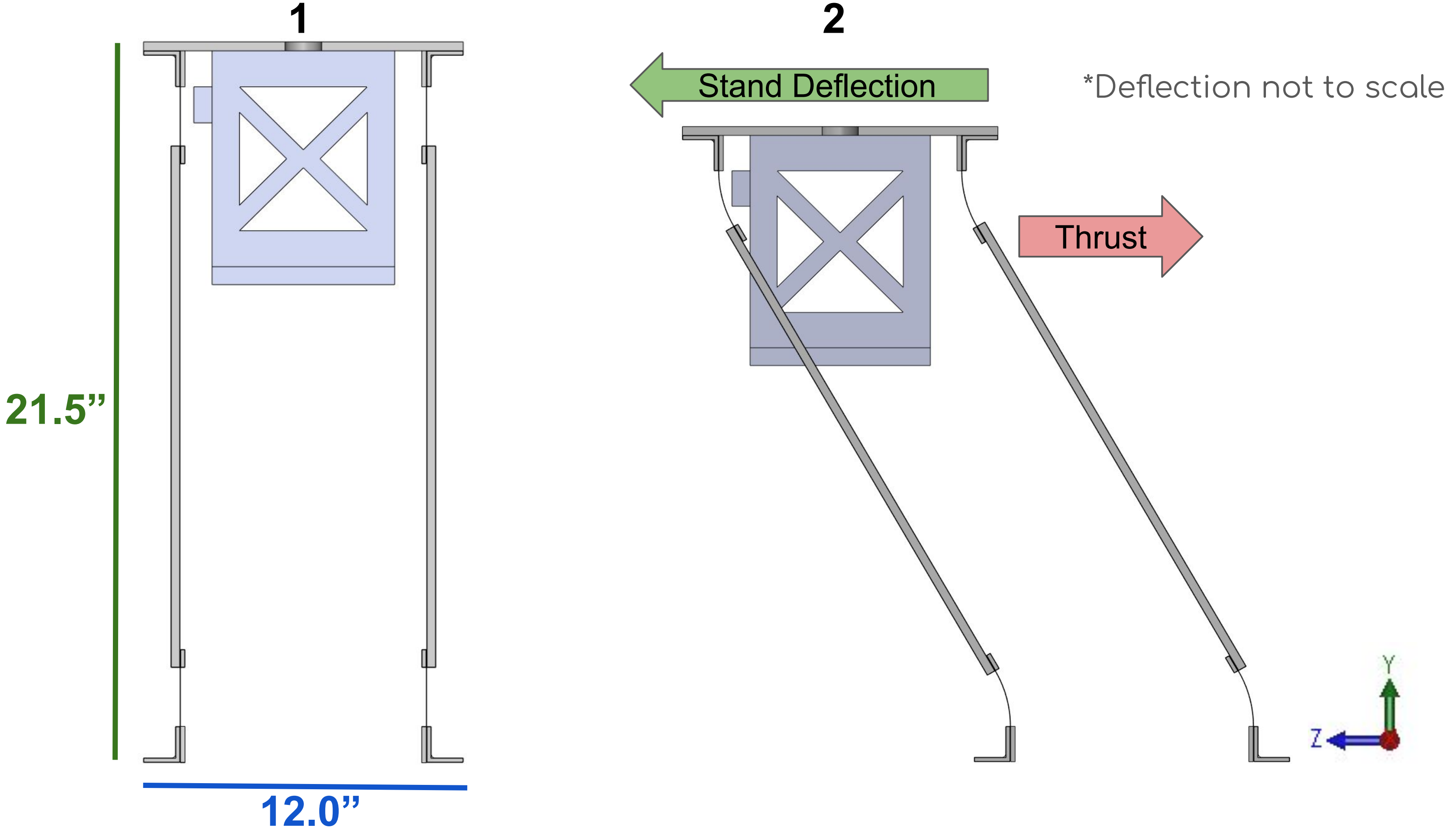
Assembly Overview (Descoped)

BF, NC

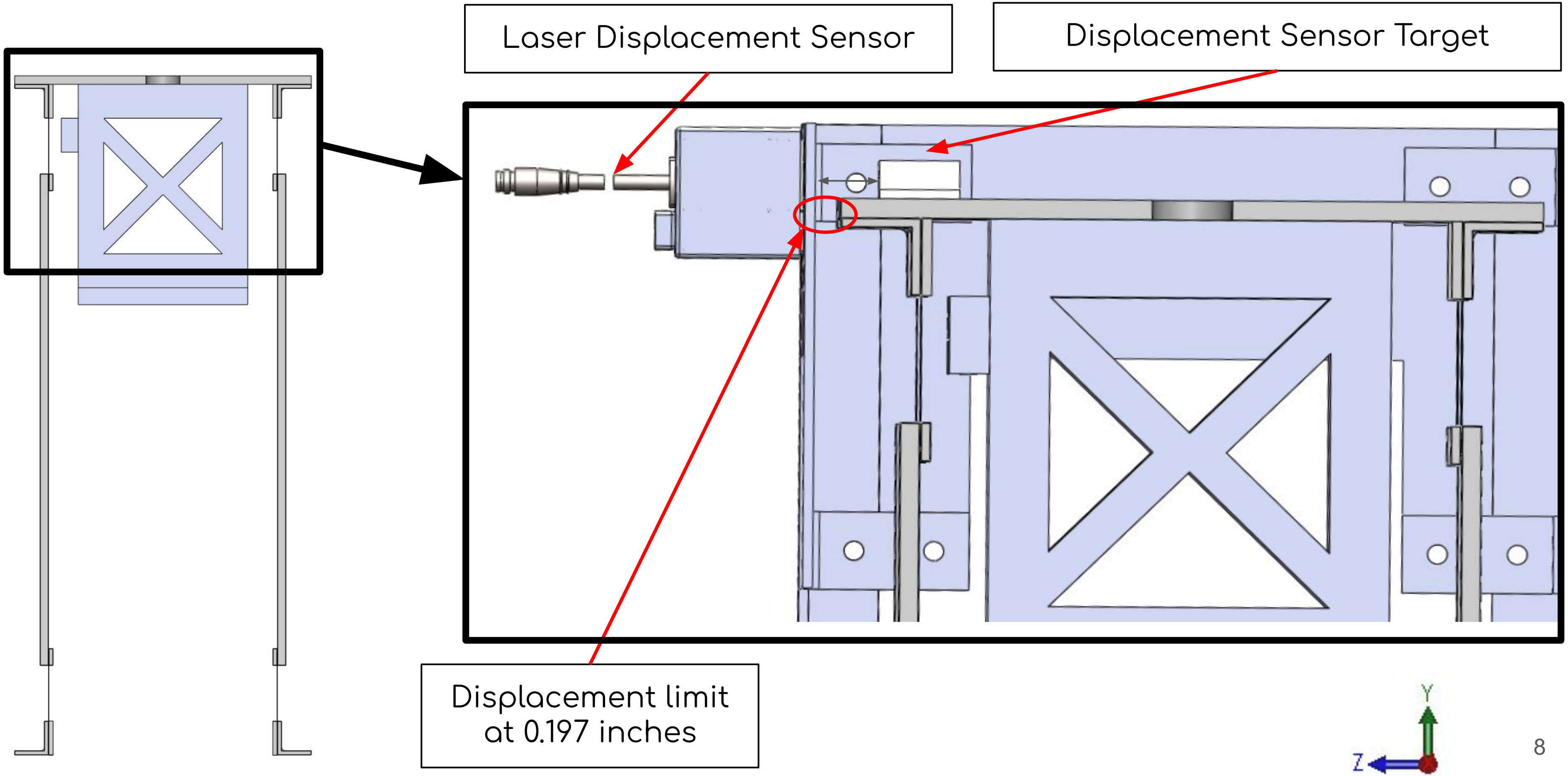




Function - Stand Deflection



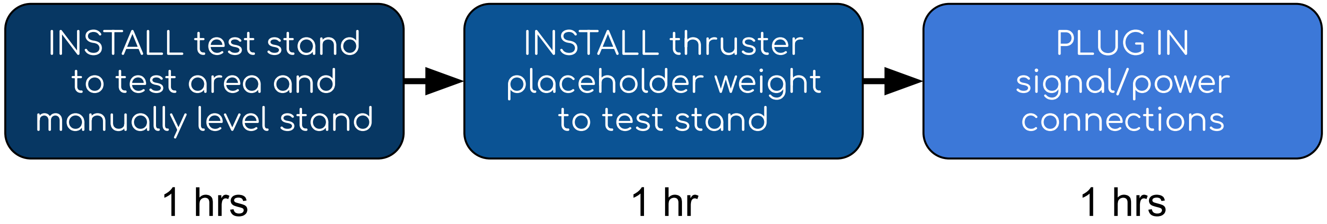
Function - Data Capture



CONOPS (Descoped) (1/3)

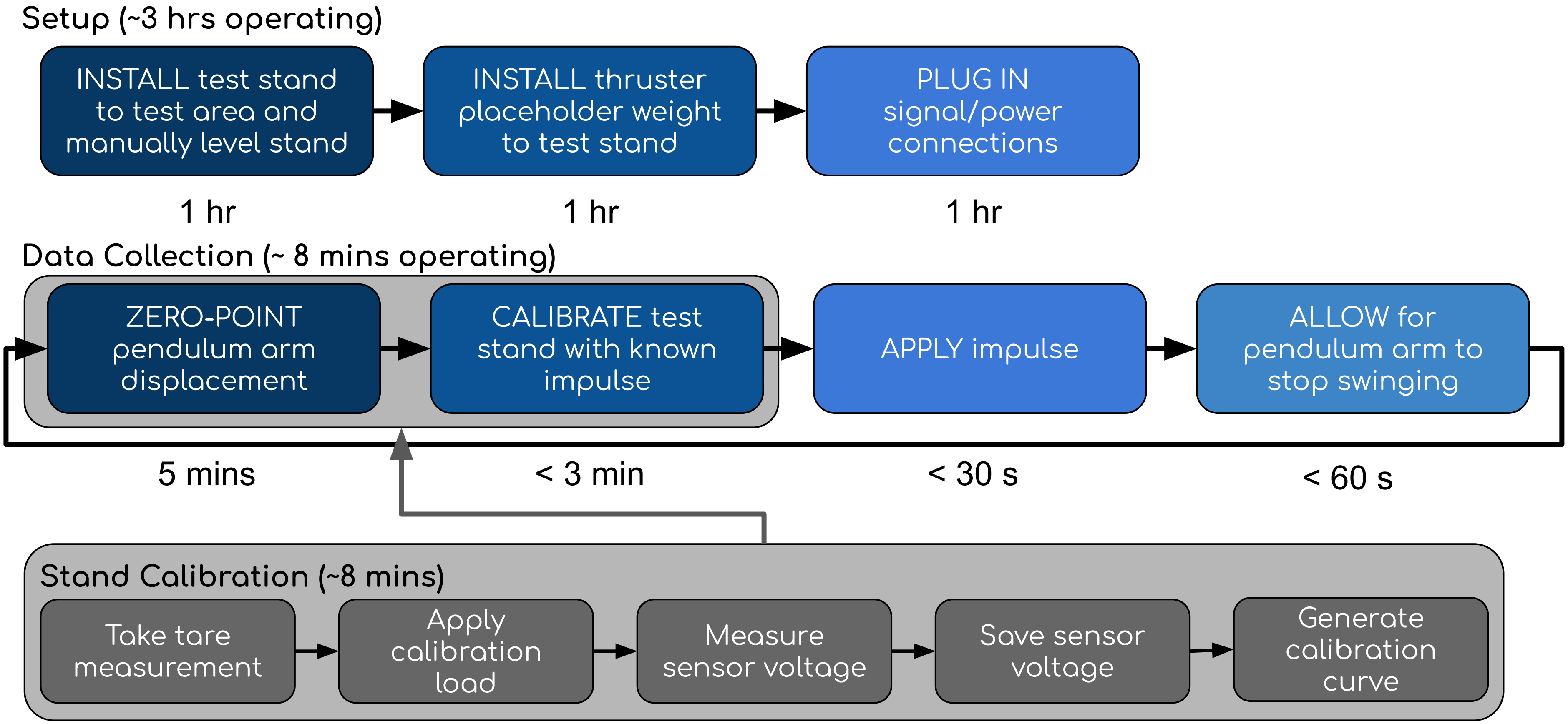
NC

Setup (~3 hrs operating)



CONOPS (Descoped) (2/3)

NC



CONOPS (Descoped) (3/3)

NC

Setup (~3 hrs operating)

1. INSTALL test stand to test area and manually level stand — 1 hr
2. INSTALL thruster placeholder weight to test stand — 1 hr
3. PLUG IN signal/power connections — 1 hr

Data Collection (~ 8 mins operating)

1. ZERO-POINT pendulum arm displacement — 5 mins
2. CALIBRATE test stand with known impulse — < 3 min
3. APPLY impulse — < 30 s
4. ALLOW for pendulum arm to stop swinging — < 60 s

(loops back to ZERO-POINT pendulum arm displacement)

Disassembly (~2 hrs operating)

1. REMOVE signal/power connections — 1 hrs
2. REMOVE thruster placeholder weight from stand — 1 hr

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 10 μN*s to 100 mN*s ± 5 μN*s** can be measured	*Analysis /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 0.1 mN to 0.1 N ± 0.05 mN** can be measured	*Analysis /Test*

System Requirements

De-Scoped

WW, KLV

ID	Requirement	Verification Method
Sys.5	Test stand must be able to **support thrusters up to 8 kg** without buckling	*Test*
Sys.6	Test stand must accommodate **thruster diameters up to 10.0 in, and thruster lengths up to 9.1 in**	*Inspection*
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	*Demonstration*

System Verification Matrix

De-Scoped for TRR

WW

	System Requirements								
	1	2	3	4	5	6	7	8	9
Test Stand	*I*	*I*	*T*	*A/T*	*A/T*	*D*	*D*	*T*	*D*
Thrust Measurement	*I*	*I*	*T*	*A*					
Chamber Interface		*I*					*D*		*D*
Leveling System		*I*						*T*	
PPT Mount		*I*			*T*	*D*			

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Project Background

- Pulsed Plasma Thruster Operation:
  - **Thrust Magnitude**
    - PPTs produce **thrusts on the order of micronewtons**
    - Traditional load cell thrust measurement techniques are not capable of resolving these impulses
    - Requires more sensitive designs like **inverted pendulums**
  - **EMI:**
    - PPTs operate through **discharging high voltages** across an ablated fuel
    - EMI is generated that can **adversely affect the system's signal to noise ratio** at different periods in operation
    - **Stand must be electromagnetically shielded** from generated noise

Project Background

- Material Limitations:
  - **Outgassing:**
    - PPTs operate in conditions around 10E-7 Torr
    - Materials must not outgas volatile material
    - Introducing outgassed material may increase pressure beyond this value and introduce unwanted species during spectroscopic measurements
  - **Material Rigidity:**
    - Material must not deform throughout stand operation
    - Inverted pendulums are sensitive to small changes in pendulum geometry
  - **Non-conductivity:**
    - EMI produced during PPT operation may induce currents in metallic structures, contributing to noise
    - Requires minimization of metallic components

Project Background

- Test Environment:
  - **VC Feedthroughs:** all electrical feedthroughs must be compatible with flanges provided by the SPACE Lab
  - **VC Diameters:** the stand must be designed to operate in either vacuum chamber by accommodating both diameters
  - **Surface Scratching:** the stand must not damage either vacuum chamber through scratching; materials must be soft enough to not scratch silica or aluminum

Trade Studies - Material

- Several materials were assessed for various applications within the test stand, including leveling system, pendulum, and shelf structure:

Material	Weight	Garolite	Carbon Fiber Filled PET-G	PLA
Machinability	0.1	0.4	0.5	1
Cost	0.2	0.5	1	1
Vacuum Compatibility	0.3	1	0.5	0.4
Density	0.2	0.75	1	0.5
Yield Strength	0.2	1	0.3	0.1
Total	1	0.79	0.66	0.54

Weighted Decision Matrix for PPT Mount Materials Table

Trade Studies - Material

- Garolite was selected for use in primary structure (pendulum, leveling system, chamber interface, housing) for its structural rigidity and vacuum compatibility
- Remaining structures' materials were selected based on application:
  - **Thruster Shelf:** Delrin was selected for its vacuum compatibility and ease of machining
  - **Mounting Plate:** Aluminum 6061 due to AA shop availability and descoped vacuum chamber testing
  - **Damping System Housing & Waterfall Clamps:** Carbon-fiber reinforced PETG due to small feature size and ease of manufacturing through 3D printing

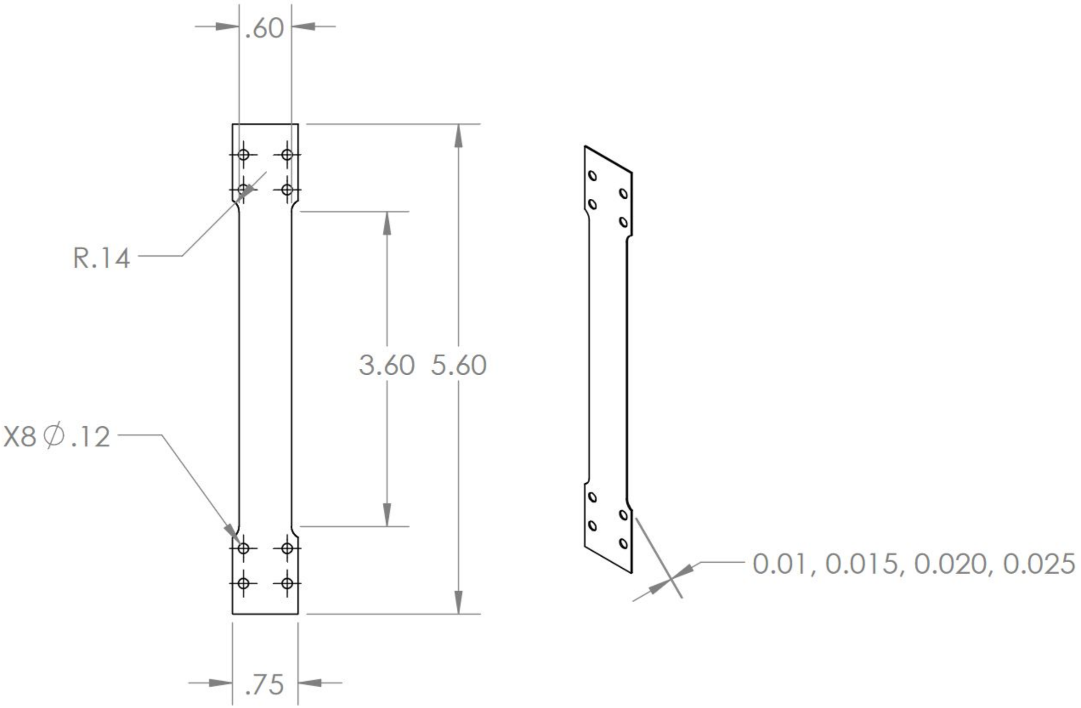
Analysis - Flexure Design

- Four sets of flexures were ultimately designed assuming an approximately linear positive correlation between thruster mass and impulse
- The flexures were modeled as follows:
  - Angular equation of motion iterated through using ode89 to solve for peak deflection
  - 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
  - This gives a range of measurable impulses from of 100 μN*s to 0.1 N

	FS1	**FS2**	**FS3**	**FS4**
Impulse Range (N*s)	100μ-5.36m	5.36m-0.0422	0.0422-0.0159	0.0159-0.1
Thickness	0.01"	0.015"	0.020"	0.025"

Analysis - Flexure Design

- All units in inches:



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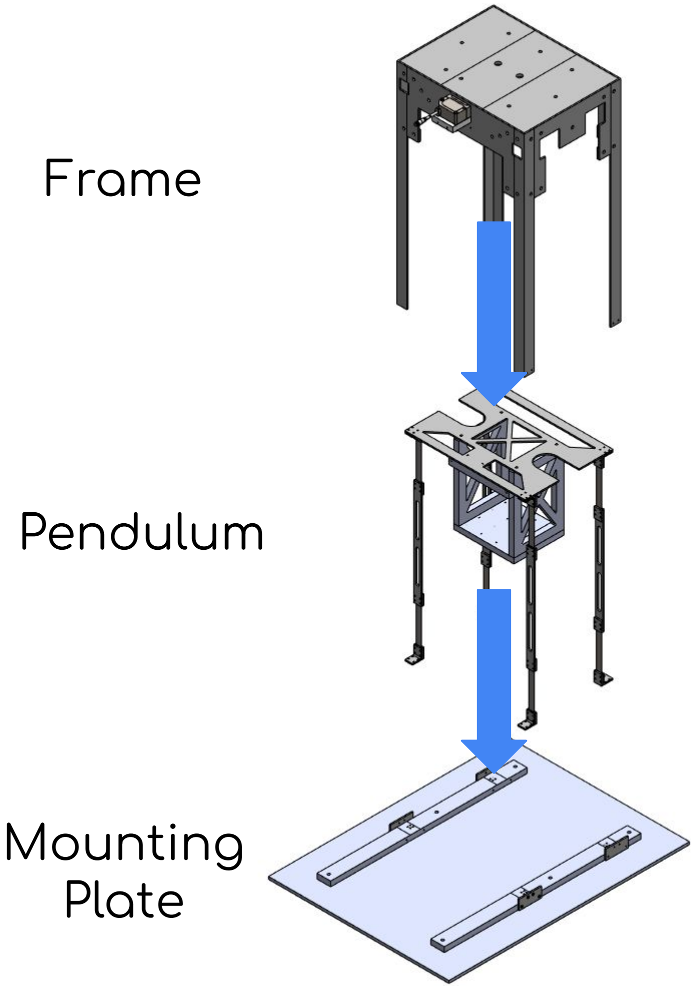
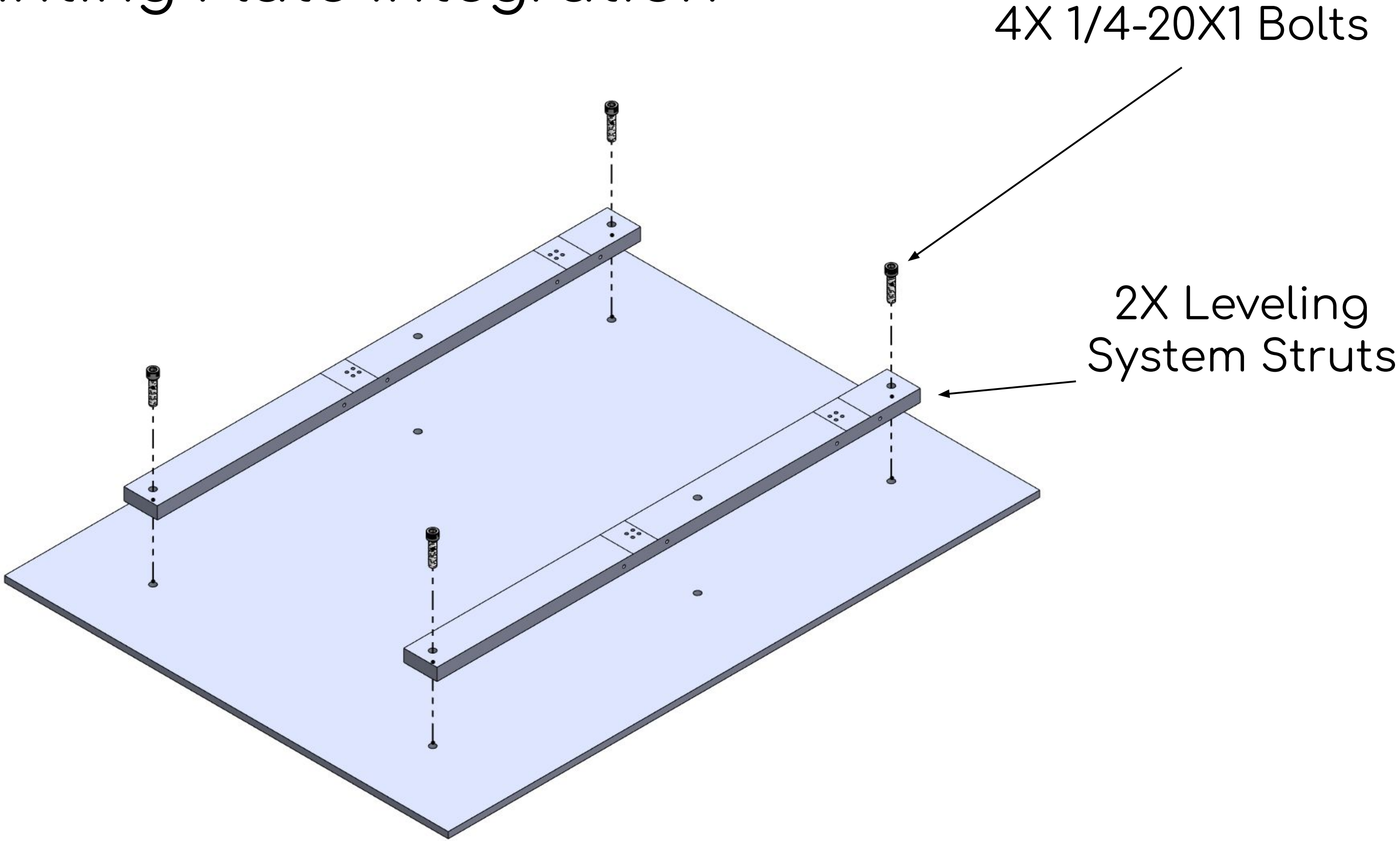
Structures Integration Overview

BF, LL



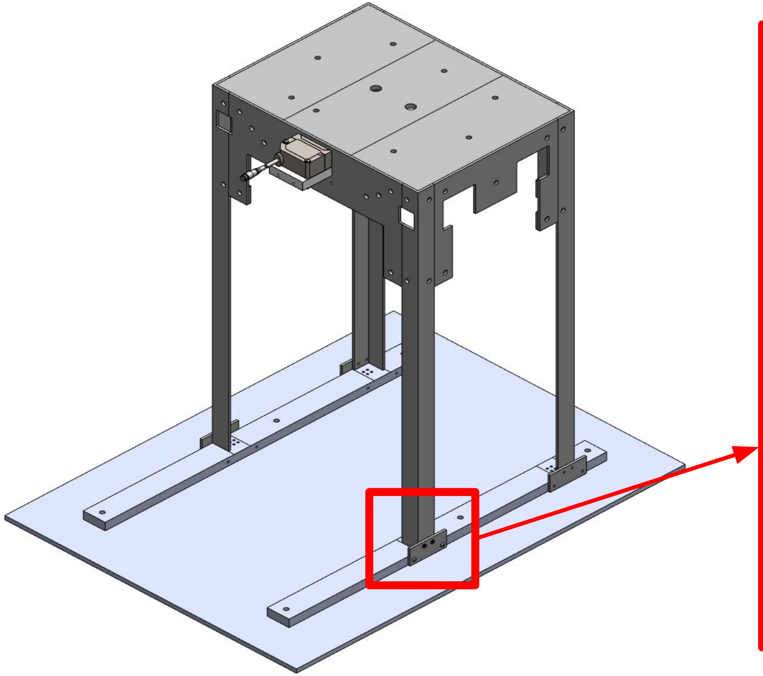
Mounting Plate Integration

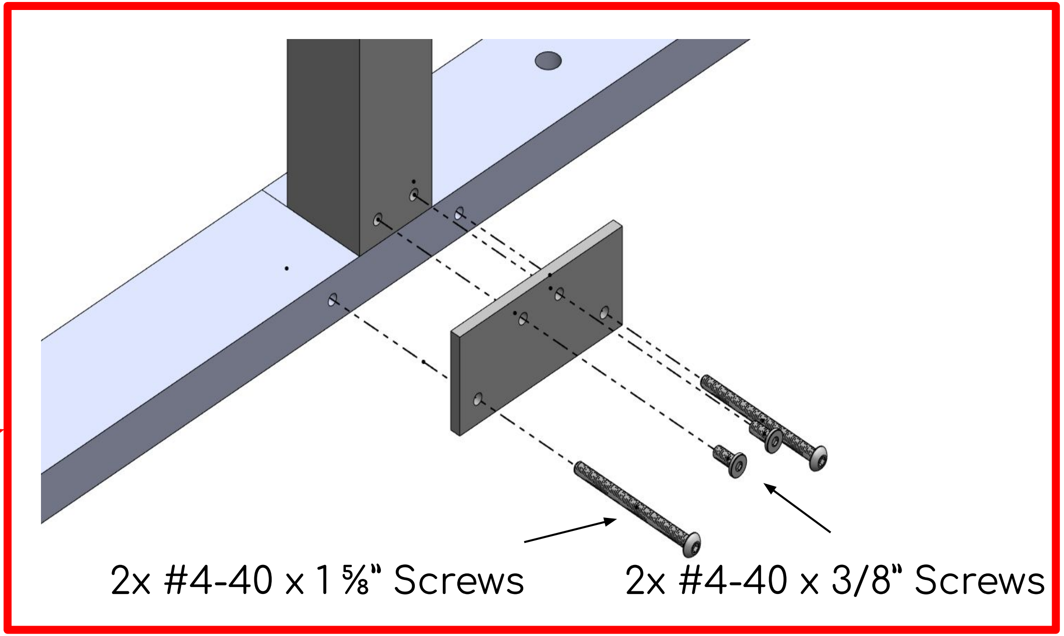
BF



Frame to Mounting Plate Integration

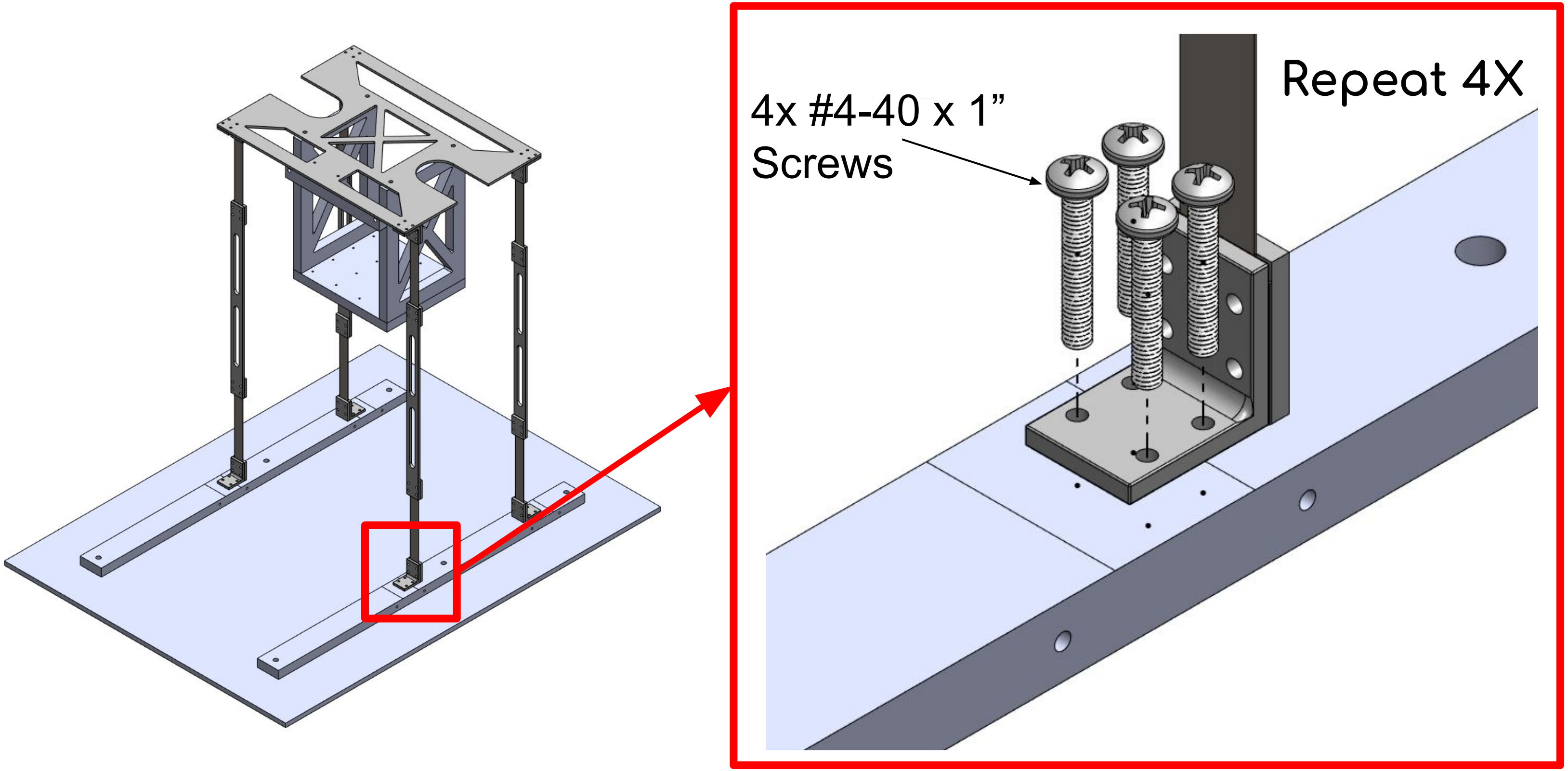
BF, LL





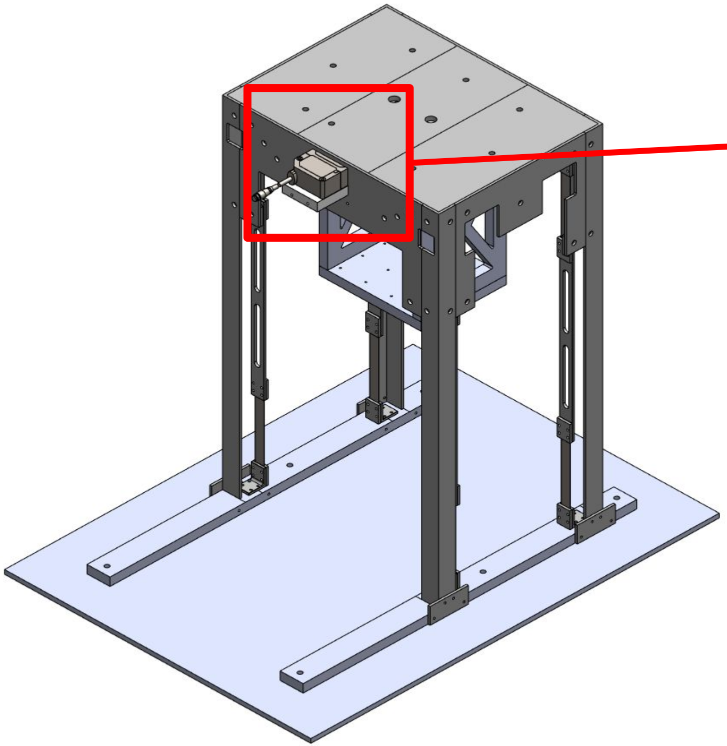
Pendulum to Mounting Plate Integration

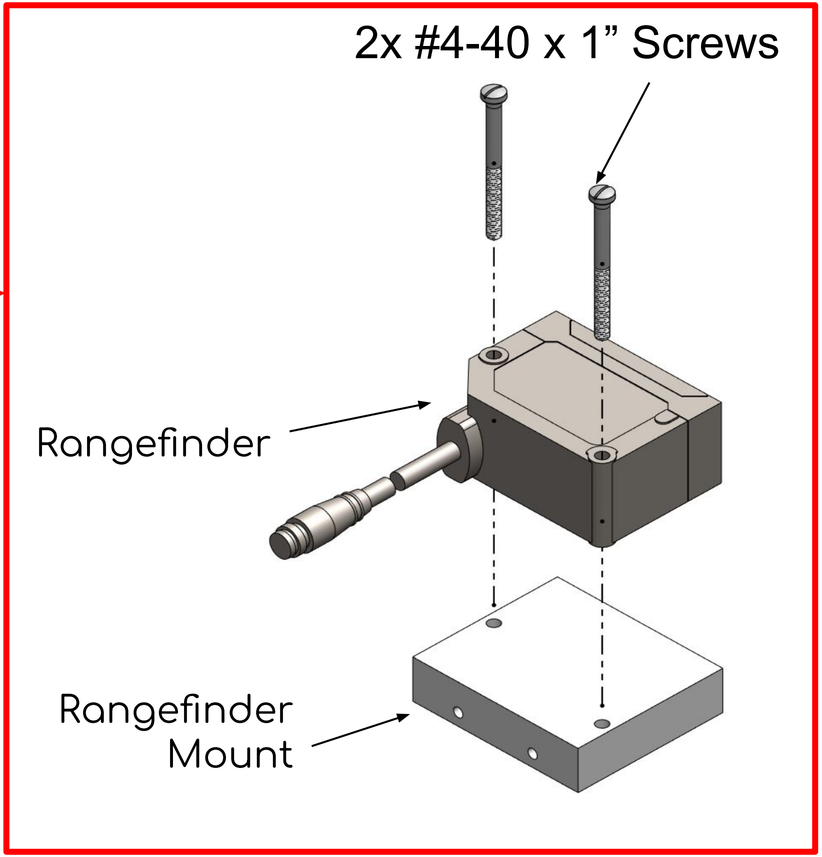
BF



Sensor Integration

BF





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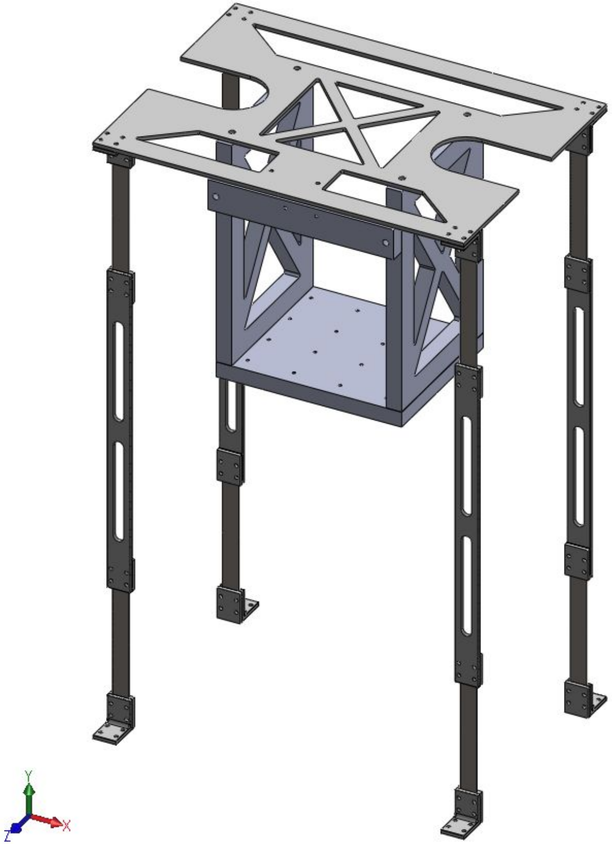
Inverted Pendulum Type Test Stand

AD, FC



- Sys.1 - Test stand must be an **inverted pendulum style.** Verified through inspection
- Test stand designed and constructed as an inverted pendulum type as requested by SPACE Lab
- Requirement Sys.1 has been verified by inspection

Minimally Conductive Test Stand

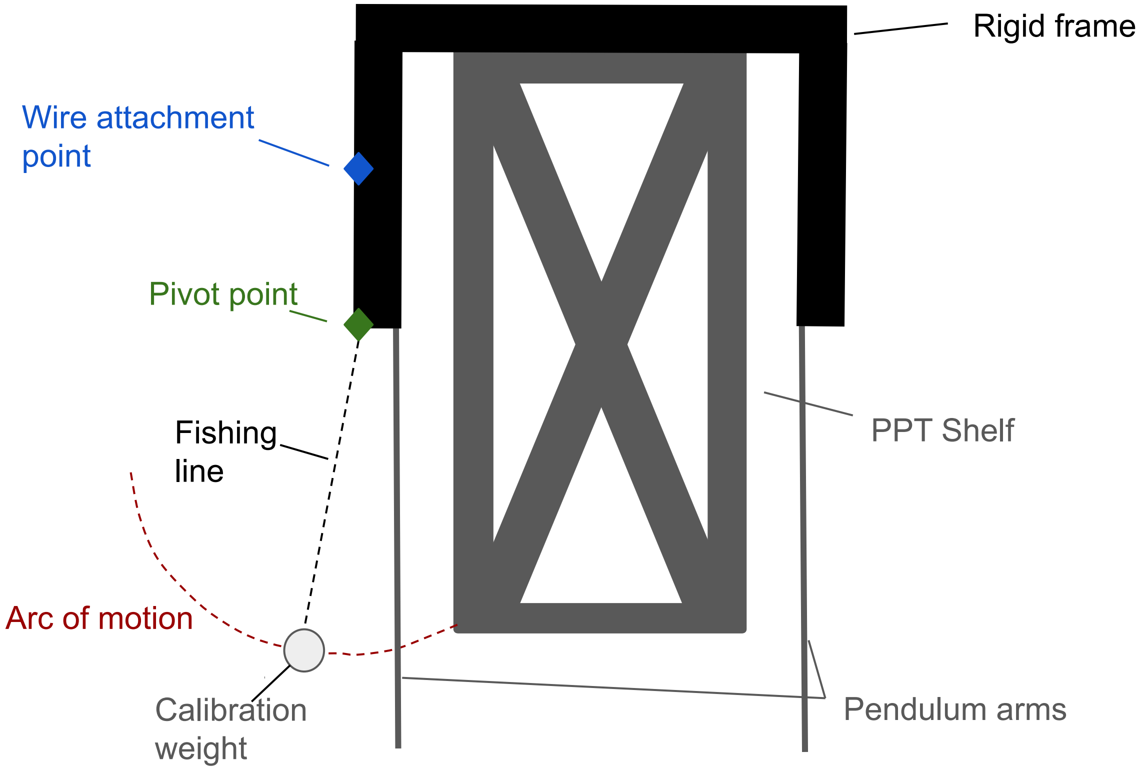
AD, LL, FC

Part	Material	#	Minimum Distance to Shelf Surface (cm)
Flexures	1075 Steel	8	8.7
Flexure Bolts	Stainless Steel	64	14.9
Flexure Nuts	Stainless Steel	64	14.9
Damper Magnet	Neodymium	1	20.3
Damper Sheet	Aluminum	1	21.5
Leveling Bracket Bolts	Stainless Steel	16	35.4
Leveling Bracket Nuts	Stainless Steel	16	35.4
IL-030	Various Metals	1	19.8

- Sys.2 - Test stand shall **minimize the use of conductive materials.** Verified through inspection
- All frame and pendulum parts other than flexures made of garolite or delrin
- All fasteners made of nylon except where noted
- Requirement **Sys.2 has been verified by inspection**

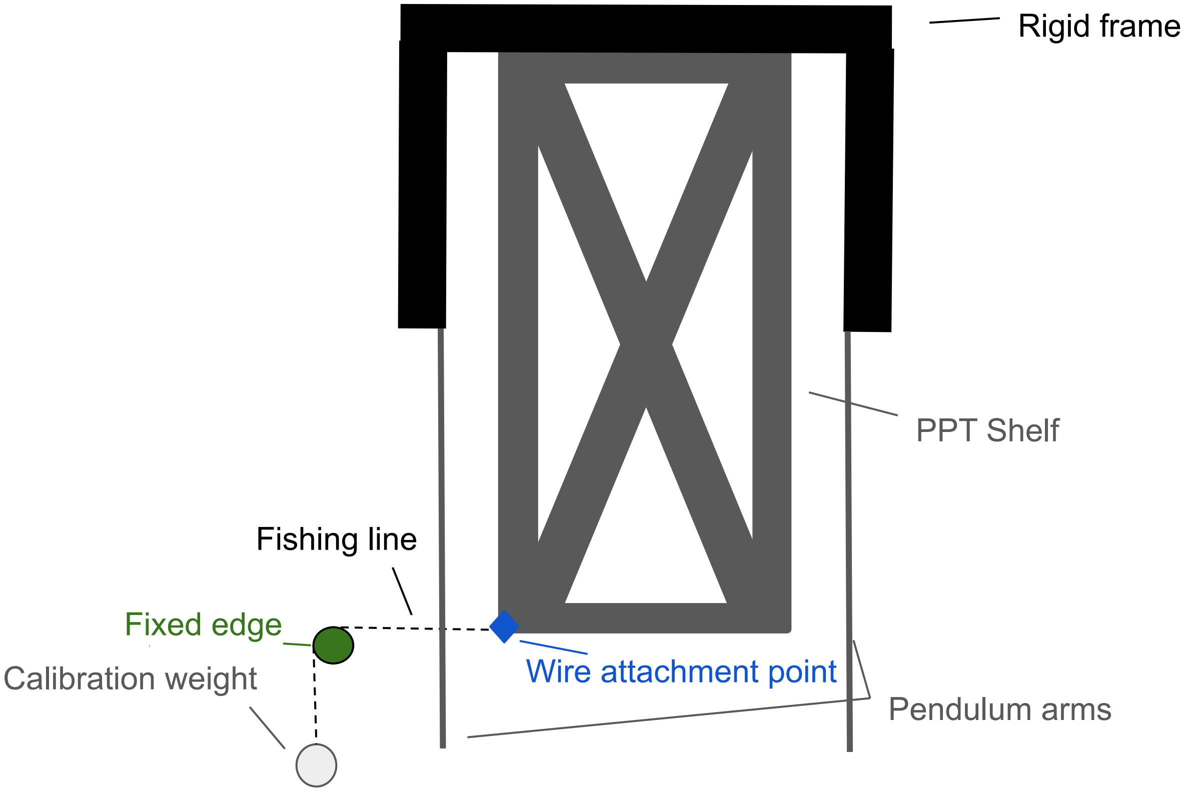
Atmospheric Impulse Test Configuration

- Fishing line with calibration weight is attached to stand frame
- Weight is pulled back and strikes PPT shelf
- Dynamics are measured by slow-motion camera
- Change in momentum (i.e. impulse) can be derived



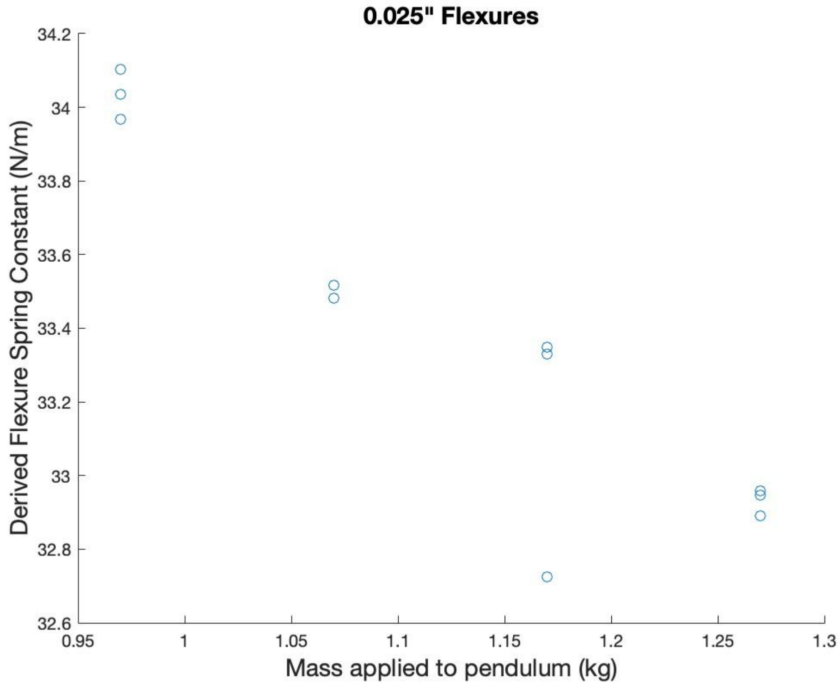
Atmosphere Steady State Test Configuration

- Fishing line with calibration weight is attached to pendulum shelf and directed over a fixed edge
- A known force is generated from the calibration weights gravitational force
- Steady state deflection due to this force is measured



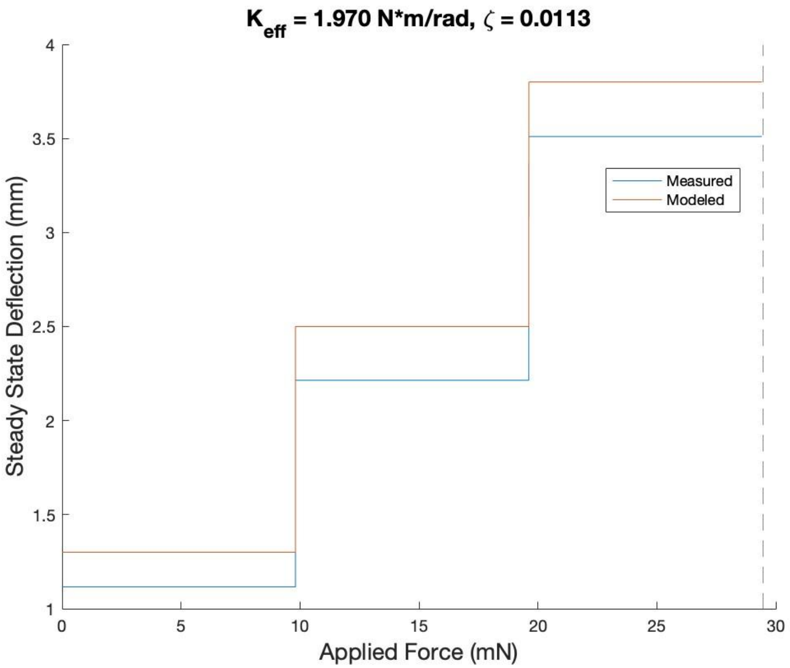
Pendulum Flexure Characterization

- Natural frequency of the stand under various loading conditions calculated from damped impulse response
- Eight 0.025" thick flexures provide a total spring constant of K_{flex} = 33.4 N/m with standard deviation of 0.5 N/m
- Flexures with thickness below 0.025" were found to be always unstable
- Error sources attributed to use of 8-bit scope for data collection



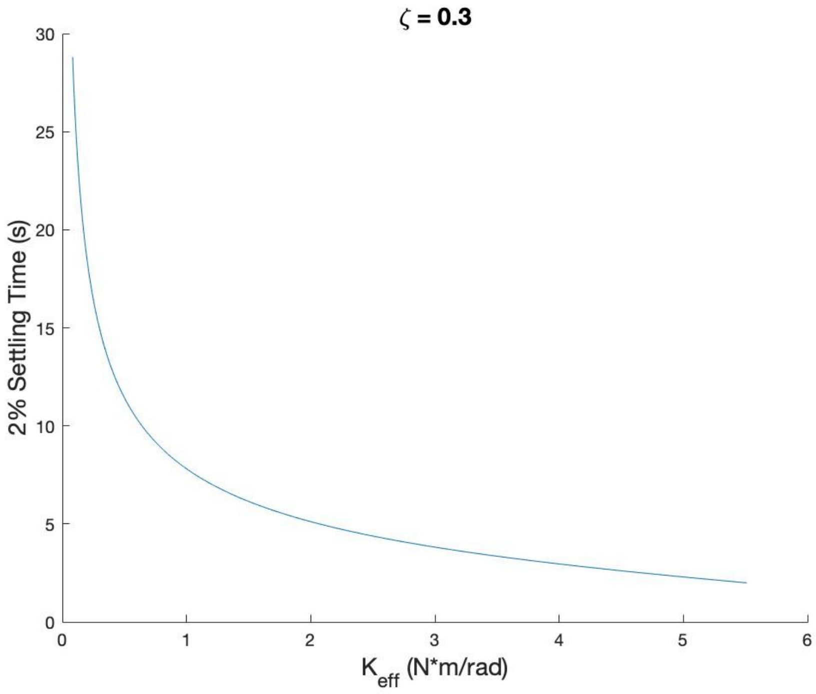
Pendulum Steady State Response Testing

- 9.8 mN, 19.6 mN, 29.4 mN forces applied to the pendulum and steady state deflection was measured
  - Sys. 4 is partially verified through test
- Design model showed a predicted response 1.114 ± 0.033 times that of empirically collected data
- Predictions can now be made for pendulum response for lower input states
- Impulse response predictions can be made since the mechanical system remains the same



Pendulum Response Modeling

- Flexure buckling begins at 10 kg of load
- Pendulum becomes unstable at approximately 1.375 kg of load
  - Model predicts this at 1.316 kg of load
- Arbitrarily low effective spring constants may be achieved
  - Theoretically this should verify system requirements 3 and 4!
  - **But what is actually a reasonable value of spring constant for operation?**
  - Choose a maximum 2% settling time of 15 s

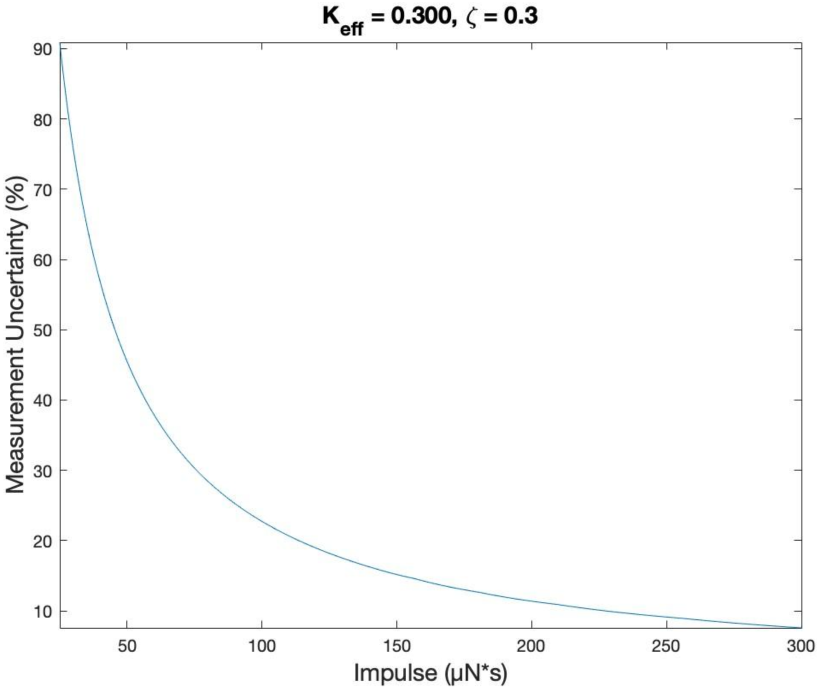


Pendulum Response Overview

- Inverted pendulum testing is limited by lever arm length and settling time requirements
- This puts a bottom line on the minimum resolvable impulse regardless of the design
  - Limited by vacuum chamber diameter
- Higher impulses will require thicker flexures to fall within resolvable limits (±5 mm)
- **For 2% settling time under 15 s with a damping coefficient $\zeta = 0.3$, $K_{eff} \geq 0.300$ N*m/rad**
- Deflection measurement uncertainty is 10 μm, and Sys. 3 and 4 define a maximum uncertainty of 50% lowest resolvable value
  - Pendulum must deflect at least 20 μm for lowest resolvable value

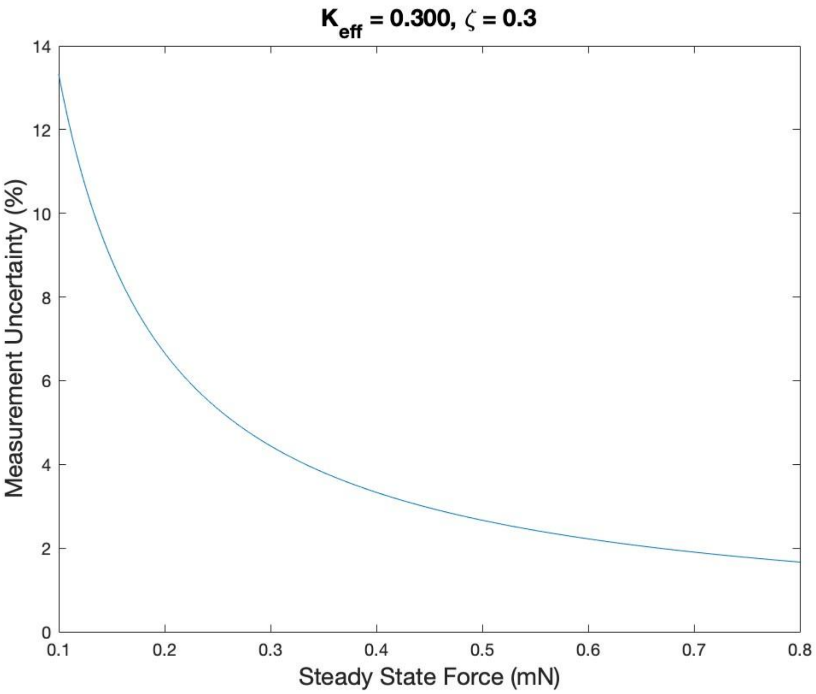
Pendulum Impulse Response Predictions

- For K_{eff} = 0.300 N*m/rad, predicted minimum resolvable impulse is 45.5 μN*s ± 50% with 20 μm deflection
  - Sys. 3 is not met
- For K_{eff} = 0.009 N*m/rad, 10 μN*s predicted to be resolved with 25 μm deflection
  - 2% settling time is predicted at 87 s for ζ = 0.3
- Given limitations on lever arm, Sys. 3 cannot be reasonably met



Pendulum Step Response Predictions

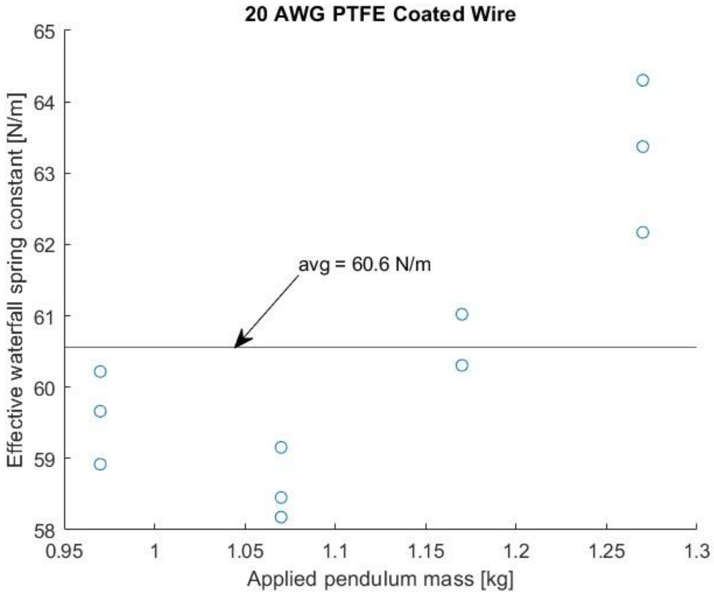
- For K_{eff} = 0.300 N*m/rad, predicted response for 0.1 mN is 134 µm deflection
  - ±13% uncertainty
- Assuming linear trend for flexure spring constant prediction, 100 mN predicted to be resolved with 1.6 mm deflection on 0.040" thick flexures
  - K_{flex} = 88.4 N/m
  - K_{eff} = 25.656 N*m/rad
- Sys. 4 is met and verified through analysis



Waterfall Characterization Test

- To estimate the effective spring constant of the waterfall, several tests were conducted with and without the waterfall attached.
- Due to the instability of the thinner flexures, only the 0.025" flexures were tested with a varyingly applied pendulum mass

- Previous tests determined:
- **33.4 N/m = K_{flex}**
- Accounting for waterfall spring effects:
- $K_{eff} = K_{flex} + K_{water}$
- **K_{eff} = 60.6 N/m**
- **K_{water} = 27.2 N/m**
- **Waterfall practically doubles the effective spring constant of the test stand**



Waterfall Characterization Future Work

The effective spring constant of the waterfall is highly dependant on:

- **Wire gauge**
- **Flexibility of wire**
  - **I.e. brand of wire**

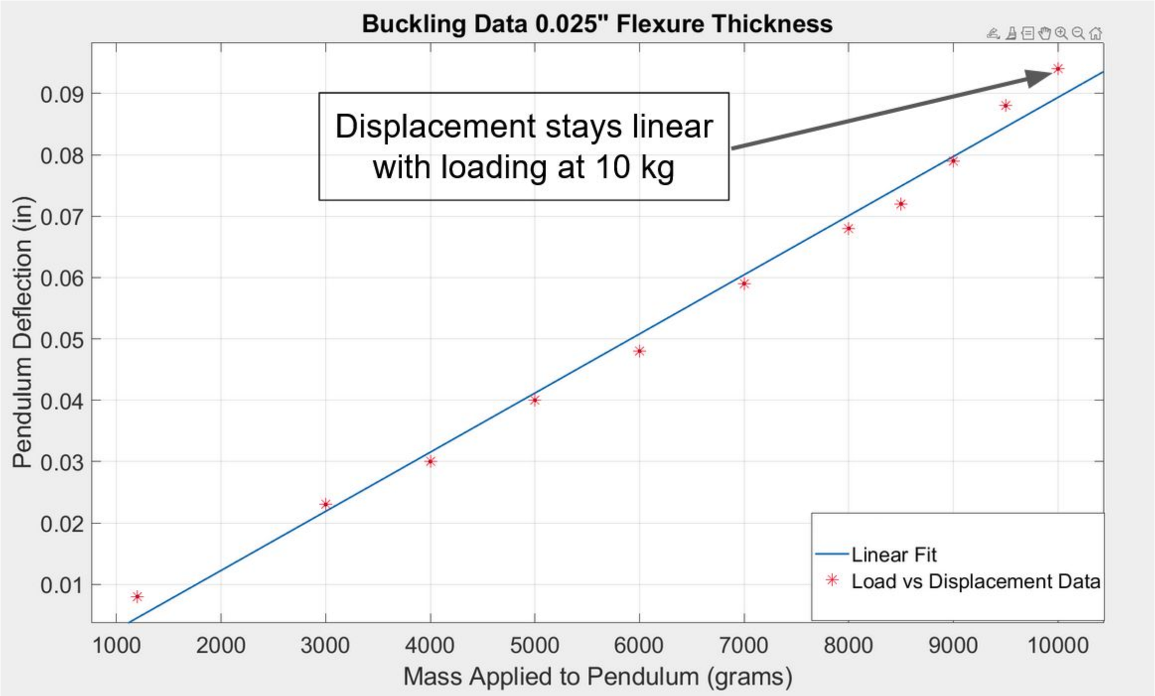
A second brief experiment was conducted with an identical wire of a different brand at the lowest pendulum mass:

- **K_{water}= 14.8 N/m**

Huge inconsistencies in effective spring constant of the waterfall.

Further testing is required to determine the effect of the type of wire on its effective waterfall spring constant.

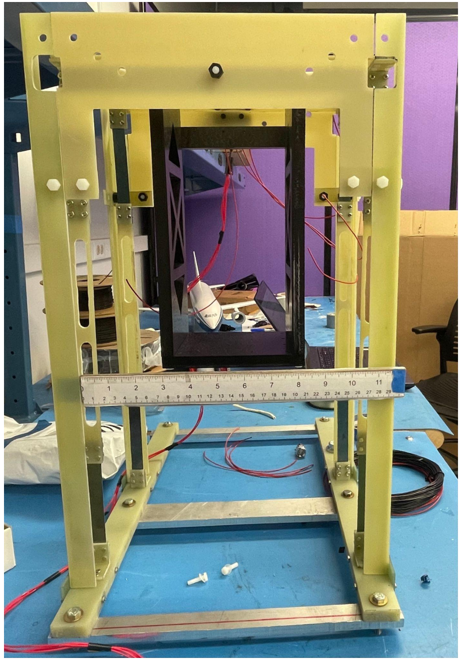
Flexure Buckling Test



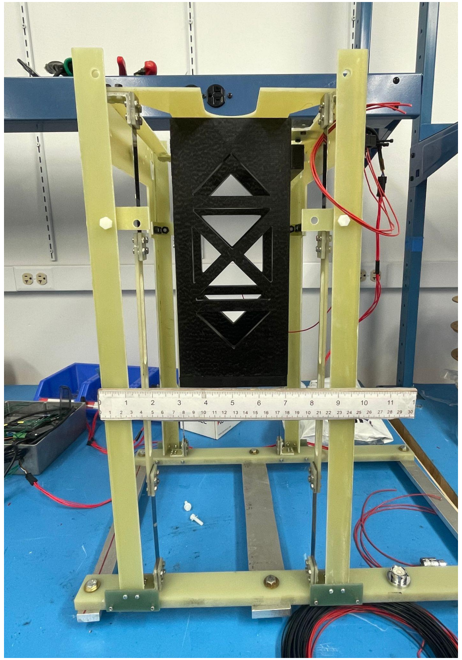
- Sys.5 - Test stand must be able to **support thrusters up to 8 kg** without buckling. Verified through testing
- Pendulum only loaded to 10kg in order to avoid plastic deformation of flexures
- Requirement Sys.5 met by test stand design with a minimum factor of safety of 1.25
- Stand becomes marginally stable at loading above 1270 grams

Thruster Size Accomodation

AD, LL



Front Thruster Clearance



Side Thruster Clearance

- Sys.6 - Test stand must accommodate **thruster diameters up to 10.0 in, and thruster lengths up to 9.1 in**
    - Verified through inspection
- Distance between pendulum legs 10.5 inches
- 5.5"x4" bolt pattern on pendulum top allows customization of PPT mount for 10 inch wide thrusters
- No obstructions for thruster length, test stand can accommodate 9.1 inch long thruster
- **Requirement Sys.6 has been verified through inspection**

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Testing Summary

Requirement Met
Requirement Not Met

AD, LL, WW

ID	Requirement	Verification Method	Met?
Sys.1	Test stand must be an **inverted pendulum style**	*Inspection*	Yes
Sys.2	Test stand shall **minimize the use of conductive materials**	*Inspection*	Yes
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 10 μN*s to 100 mN*s ± 5 μN*s** can be measured	*Analysis/Test*	No
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 0.1 mN to 0.1 N ± 0.05 mN** can be measured	*Analysis/Test*	Yes

Testing Summary

Requirement Met
De-Scoped

AD, LL, WW

ID	Requirement	Verification Method	Met?
Sys.5	Test stand must be able to **support thrusters up to 8 kg** without buckling	*Test*	
Sys.6	Test stand must accommodate **thruster diameters up to 10.0 in, and thruster lengths up to 9.1 in**	*Inspection*	
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	*Demonstration*	

Validation of 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 from 10 μN*s to 100 mN*s and with the capacity to accommodate a variety of thruster dimensions and masses

*Validated
*Not Validated

Based on our testing, our mission objective was <u>not</u> fully validated

Future Work - Chamber Interface

- Manufacturing of rubber feet covers and vibrational damping pads at pivot bearings
- Redesign (re-evaluate material and geometry) and manufacture pivot piece
- Full integration of stepper motor into chamber interface and leveling system
- Integration of chamber interface assembly into rest of test stand

Future Work - Leveling System

- Integration of motor with lower frame and longitudinal 2" garolite struts
- Testing of full system leveling process with GUI control
  - Verification of +/- 3° range of motion as originally specified
- Integration into full stand system

Future Work - Flexure Design

- Flexures of the current geometry should be manufactured with thickness of 0.030", 0.035", and 0.040"
- The effect of these flexures should be characterized to verify the predictions of the response model

Future Work - Waterfall

- Conduct additional research with a wide variety of wire brands, gauges, and coatings
- Additional testing is needed for wire sheaths or other EMI shielding hardware that might accompany the waterfall wire bundle beyond analytical verification alone

Lessons Learned

- More time was required to perfect analytical approach to verifying proper flexure sizing and necessary structural integrity
- Machinability of materials and feasibility of part manufacturing is an important consideration in design
- Manufacturing methods need careful consideration for precision and accessibility
- Detailed scheduling of all manufacturing steps and and information on manufacturing equipment status is critical to ensuring entire project is built
- There's no such thing as "enough" time for testing and data processing
- Design considerations must account for the day-to-day operation of the device
- Spec sheets and a clear nomenclature system for all parts of the design will help avoid miscommunication

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

System Requirements

LL, WW

ID	Verification Method	Met?
Sys.1	*Inspection*	*Yes*
Sys.2	*Inspection*	*Yes*
Sys.3	*Analysis*	*No (Precision Here)*
Sys.4	*Analysis*	*No (Precision Here)*

System Requirements

De-Scoped

LL, WW, KLV

ID	Verification Method	Met?
Sys.5	*Test*	*Yes*
Sys.6	*Demonstration*	*Yes*
Sys. 7	*Demonstration*	*N/A*
Sys.8	*Test*	*N/A*
Sys.9	*Demonstration*	*N/A*

CONOPS (Full System)(1/3)

NC

Setup (~7 hrs operating + 2 hrs waiting)

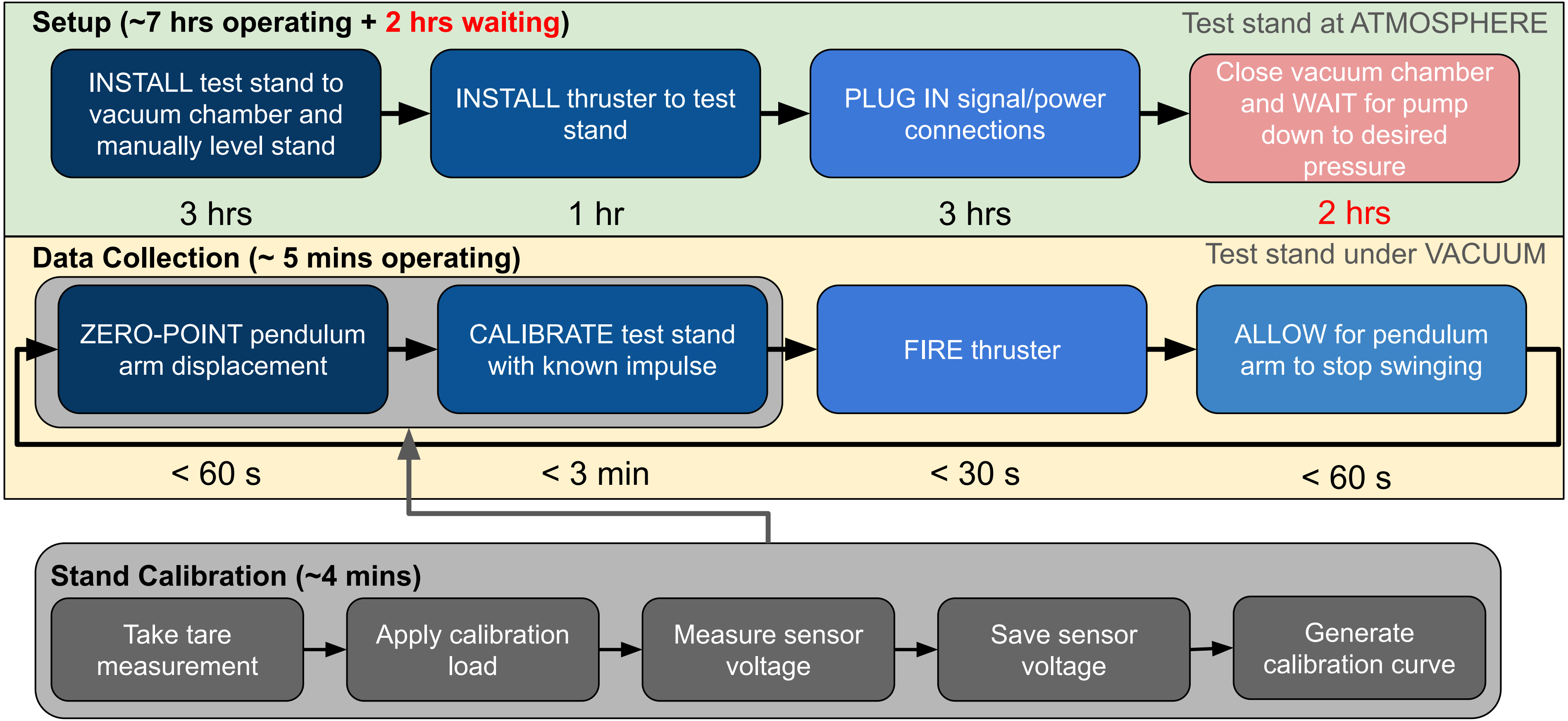
Test stand at ATMOSPHERE

INSTALL test stand to vacuum chamber and manually level stand → INSTALL thruster to test stand → PLUG IN signal/power connections → Close vacuum chamber and WAIT for pump down to desired pressure

INSTALL test stand to vacuum chamber and manually level stand	INSTALL thruster to test stand	PLUG IN signal/power connections	Close vacuum chamber and WAIT for pump down to desired pressure
3 hrs	1 hr	3 hrs	2 hrs

CONOPS (Full System)(2/3)

NC



CONOPS (Full System)(3/3)

NC

Setup (~7 hrs operating + 2 hrs waiting)

Test stand at ATMOSPHERE

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 WAIT for pump down to desired pressure — 2 hrs

Data Collection (~ 5 mins operating)

Test stand under VACUUM

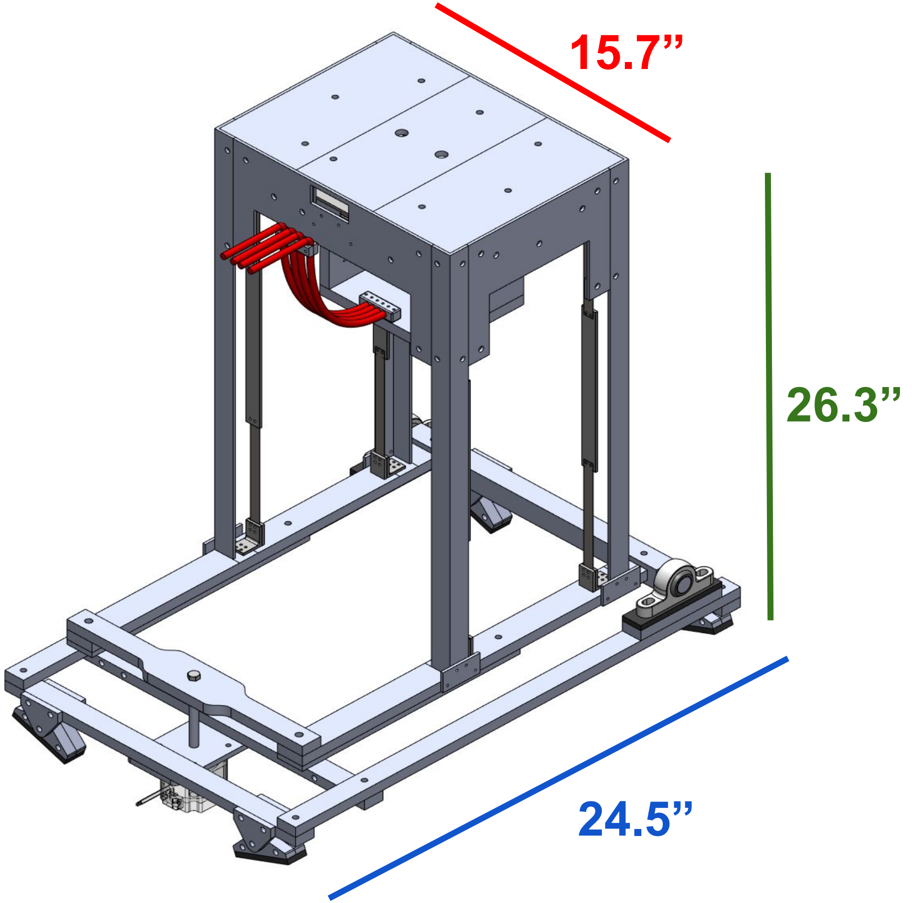
1. ZERO-POINT pendulum arm displacement — < 60 s
2. CALIBRATE test stand with known impulse — < 3 min
3. FIRE thruster — < 30 s
4. ALLOW for pendulum arm to stop swinging — < 60 s

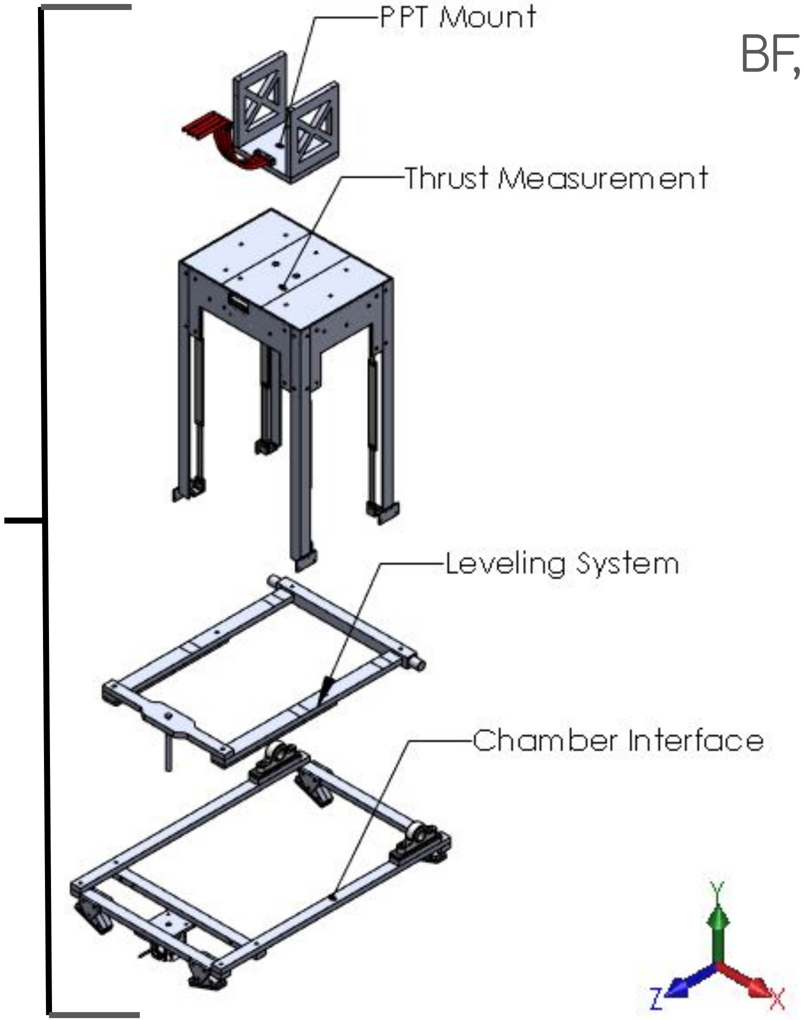
Disassembly (~4.75 hrs operating + 15 mins waiting)

Test stand at ATMOSPHERE

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

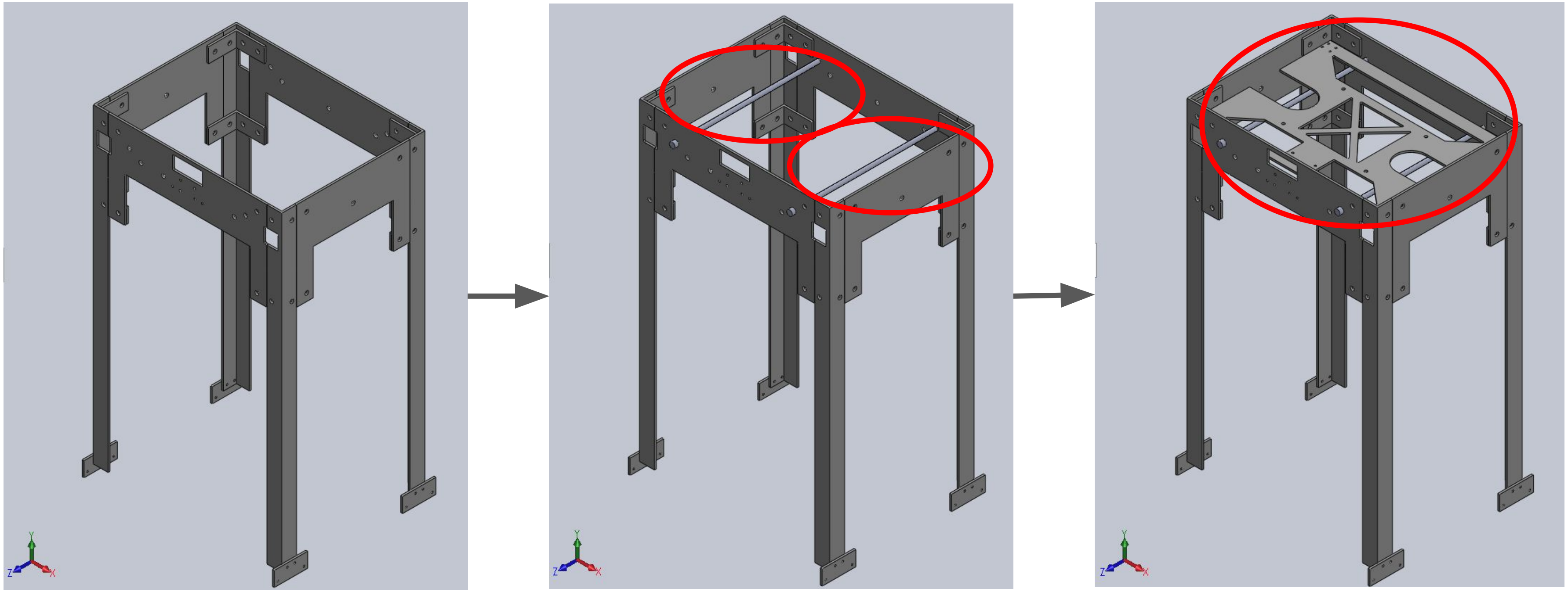




Test Setup Overview - Flexure Buckling

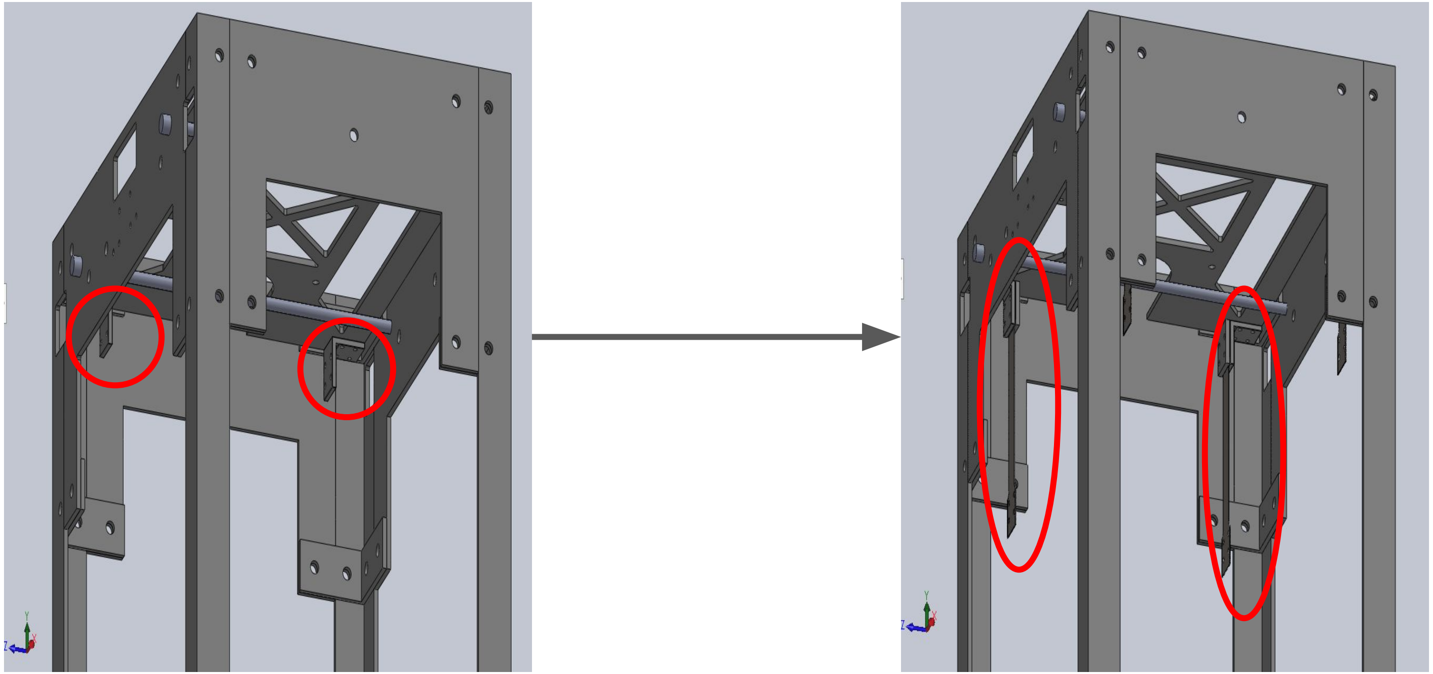
AD

- Assemble test frame per assembly instructions, leaving top 3 panels off, secure frame to base plate
- Install pendulum support pins
- Install pendulum top onto pendulum support pins



Test Setup Overview - Flexure Buckling

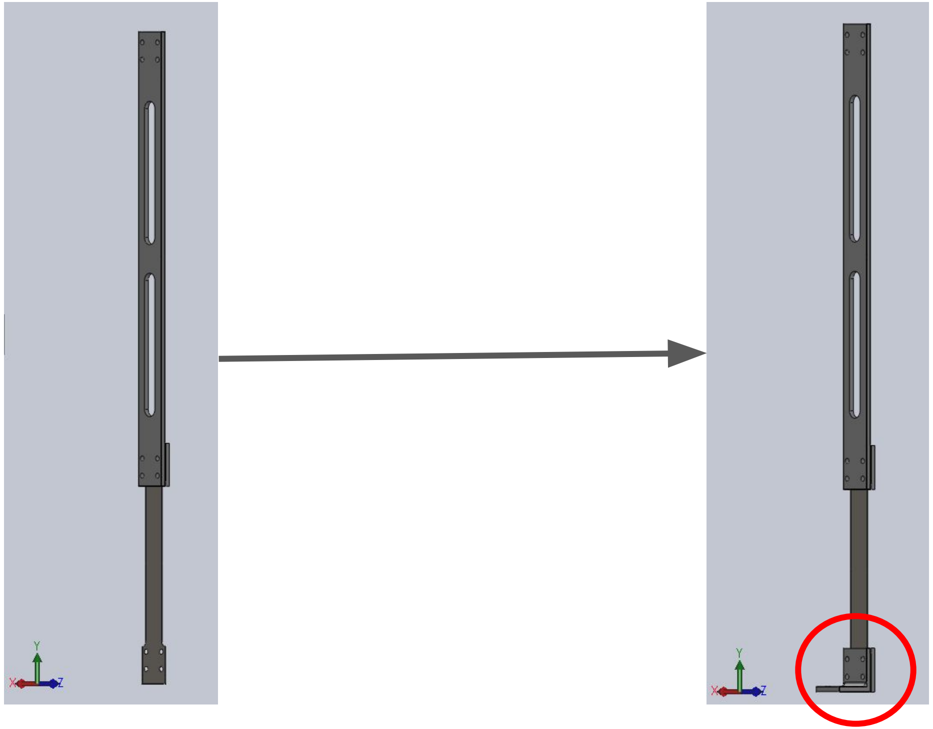
- Bolt corner brackets onto pendulum top
- Bolt flexures to be tested onto corner brackets using connector brackets



Test Setup Overview - Flexure Buckling

AD

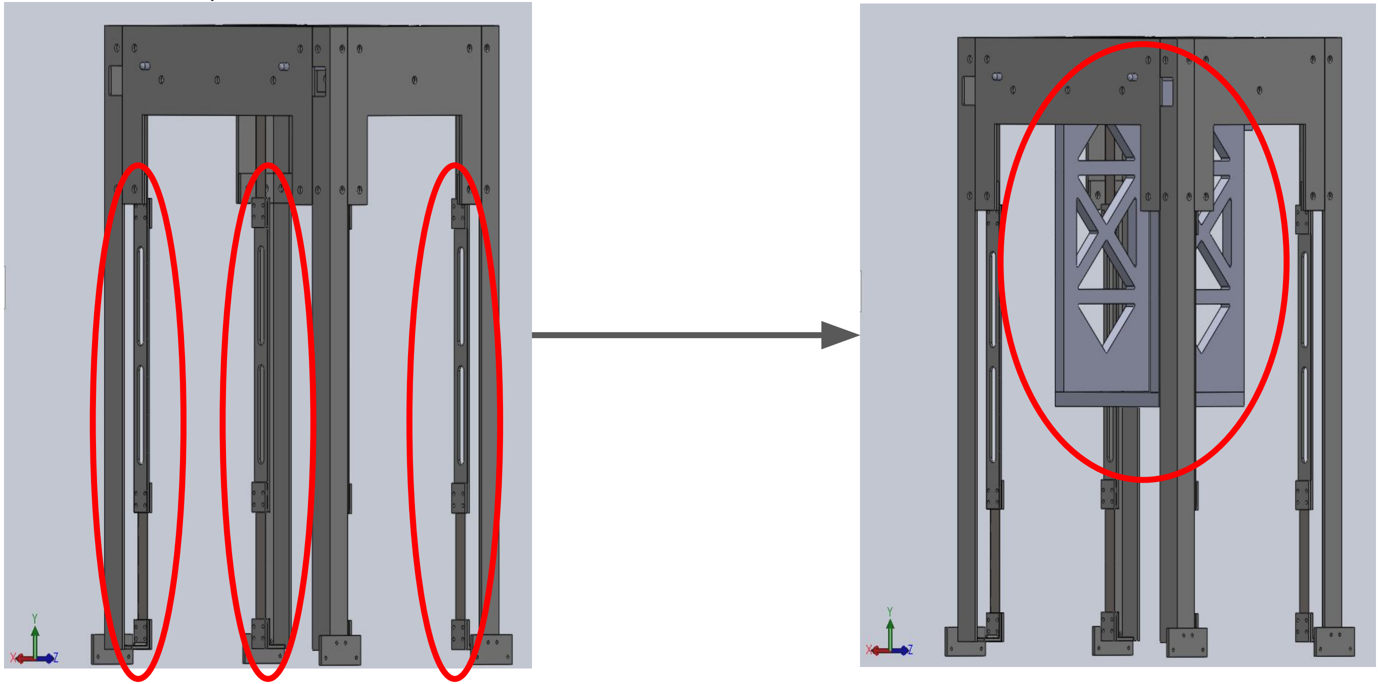
- Bolt a second set of flexures to the vertical flexure support using connector brackets
- Bolt corner brackets to flexure/vertical flexure support assemblies



Test Setup Overview - Flexure Buckling

AD

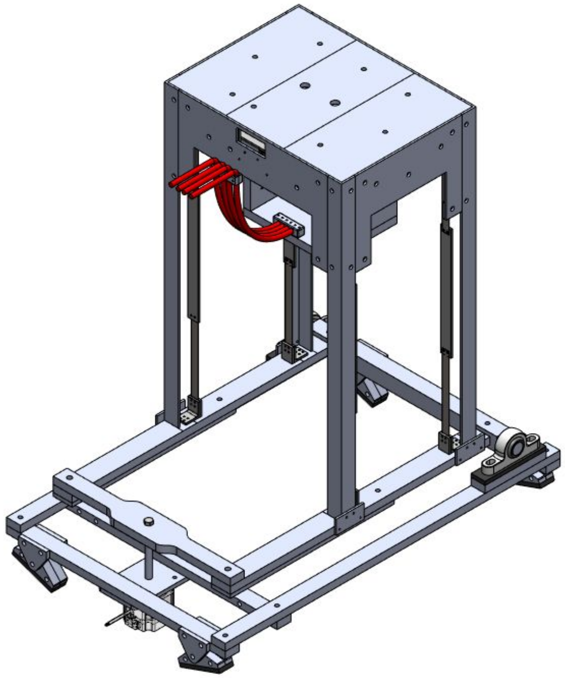
- Bolt corner bracket/flexure/vertical flexure support brackets to flexures on pendulum top using connector brackets
- Fasten lower corner brackets to base plate
- Assemble thruster shelf per assembly instructions and fasten pendulum top



Mission Overview: Anatomy

Structure

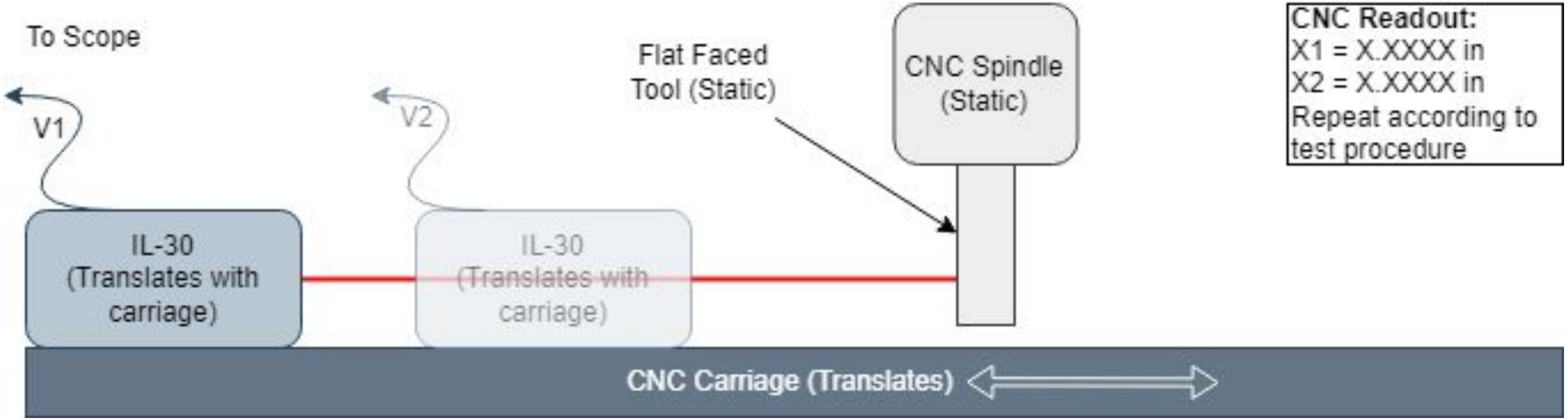
- **Measure micro quantities of thrust**
  - Electric propulsion systems have limited thrust
    - **Resolve deflections of 0.00118-0.197 in** (corresponding to impulses of 2.25 μlbf*s to 22.5 mlbf*s)
- Inverted pendulums resolve extremely low thrusts
  - Gravity acting on its center of mass **increases the stand's measurable deflection** for a given impulse



Rangefinder Hardware Test

- IL-030 tested to determine measurement error and repeatability
- Ensuring the accuracy of IL-030 is used to meet:
  - **Sys.3**: Resolve impulses ranging from 10 μN*s to 100 mN*s ± 5 μN*s
  - **Sys.4:** Resolve thrusts ranging from 0.1 mN to 0.1 N ± 0.05 mN

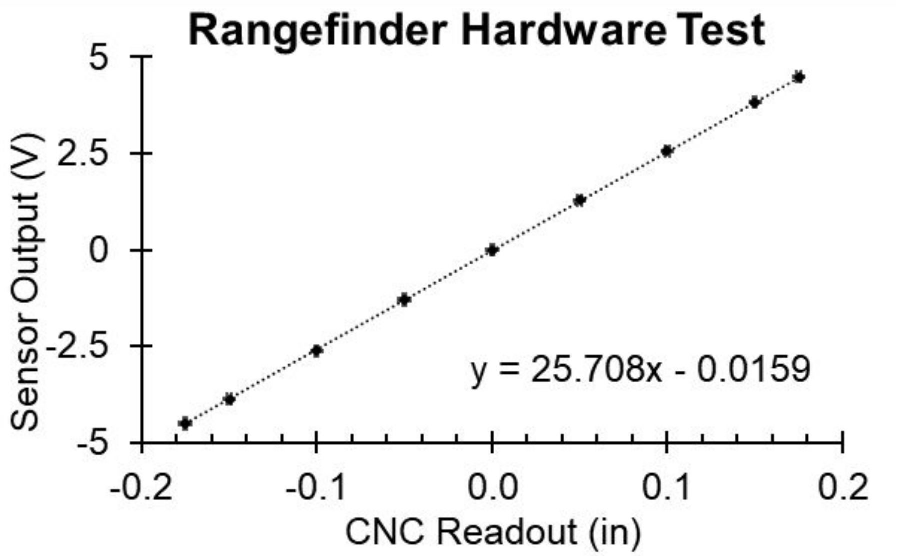
- CNC used to vary distances precisely



Rangefinder Test Setup

Rangefinder Hardware Test Results

- IL-030 tested to determine measurement error and repeatability
- Combined sensor and scope precision:
    - ±0.0269 V
- CNC precision:
    - ±0.0005 in
- Average Standard Deviation:
    - **0.002 in**



Cost Budget

Subsystem	Limit	Margin	Allocated	Used	Available
Chamber Interface	$ 200	15%	$ 170	$ 194.43	$ 5.57
Leveling System	$ 400	15%	$ 340	$ 356.96	$ 43.04
Thrust Measurement	$ 1200	30%	$ 840	$ 1147.05	$ 52.95
PPT Mount	$ 500	10%	$ 450	$ 447.15	$ 52.85
Data Analysis	$ 150	30%	$ 105	$ 103.81	$ 46.19
Multi-subsystem	$ 2250	15%	$ 1912.5	$ 2126.42	$ 123.58
Other	$ 200	15%	$ 170	$ 147.35	$ 52.65
Total	**$ 4900**	**19%**	**$ 3987.5**	**$ 4506.63**	$ 393.37

Budget - Chamber Interface

Category	Item	Cost	Total
Structure	Buna-N Rubber	$ 74.87	$ 74.87
Avionics	DB 25 Connector	$ 22.82	$ 119.56
	High Temperature Stranded Wire	$ 96.74	
			$ 194.43

Budget - Leveling System

Category	Item	Cost	Total
Structure	Ball bearing	$ 20.47	232.47
	Vibration damping sandwich mount	$ 14.29	
	Bubble level	$ 32.88	
	2" Garolite	$ 140.88	
	Delrin Rod	$ 23.95	
Avionics	Linear Stepper Motor	$ 51.19	$ 123.59
	Digital Stepper Driver	$ 20.86	
	24 V Power Supply	$ 16.99	
	Multicolored Dupont Wire	$ 6.98	
	Bud Industries CU-478 Box	$ 26.90	
	Switch	$ 0.67	
			$ 356.96

Budget - Thrust Measurement

NC

Category	Item	Cost	Total
Structure	Spring Steel 0.01", 0.02", 0.005"	$ 120.58	$ 265.02
	Tempered Spring Steel 0.01", 0.015", 0.02", 0.025"	$ 144.44	
Avionics	IL - 30 Laser	$ 348.25	$ 882.03
	IL - 1000 Transducer	$ 238.00	
	DAQ	$ 62.00	
	Connectivity AMP Connectors	$ 22.60	
	Keyence Wire Adapter	$ 12.90	
	TI DC-DC Converter	$ 49.00	
	Digikey M8 Cable	$ 29.99	
	Keyence NIB OP	$ 12.90	
	Female 10 Pcs 12V 5.5mm x 2.1mm DC Power Jack Connector	$ 7.49	
	3pcs XL4015 5A DC to DC CC CV Lithium Battery	$ 10.49	
	Assorted Connectors	$ 97.41	
			$ 1147.05

Budget - PPT Mount

NC

Category	Item	Cost	Total
Structure	Magnet	$ 0.58	$173.40
	Aluminum plate	$ 7.08	
	.5" Delrin	$ 165.74	
Avionics	4 Pin Connector kit	$ 7.35	$ 273.75
	4 Pin Connector kit (2)	$ 16.54	
	M8 circular mount	$ 11.89	
	PTFE Stranded Wire	$ 97.91	
	Delrin Rod	$106.08	
	M8 Female Connector	$33.98	
			$ 447.15

Budget - Data Analysis

Category	Item	Cost	Total
Software	1 TB Hard Drive	$ 63.15	$ 103.81
	USB to USB A Cable	$ 6.06	
	Arduino	$ 27.60	
	Arduino 2.0 USB Cable	$ 7	
			103.81

Budget - Multi-subsystem

Category	Item	Cost	Total
Structure	Fiberglass screws	$ 12.50	$ 2126.42
	Nylon screws	$ 13.44	
	Steel screws	$ 29.98	
	.5" garolite	$ 390.26	
	.125" garolite	$ 98.85	
	PETG plastic	$ 55.14	
	Vacuum epoxy	$ 130.37	
	Nitrile gloves	$ 26.38	
	Garolite angle, 1"	$ 774.16	
	Garolite angle, 2"	$ 238.98	
	Assorted nuts & bolts	$114.24	
	Steel 3D printer nozzle	$ 29.69	
	Abrasive garnet	$ 212.33	
			$ 2126.42

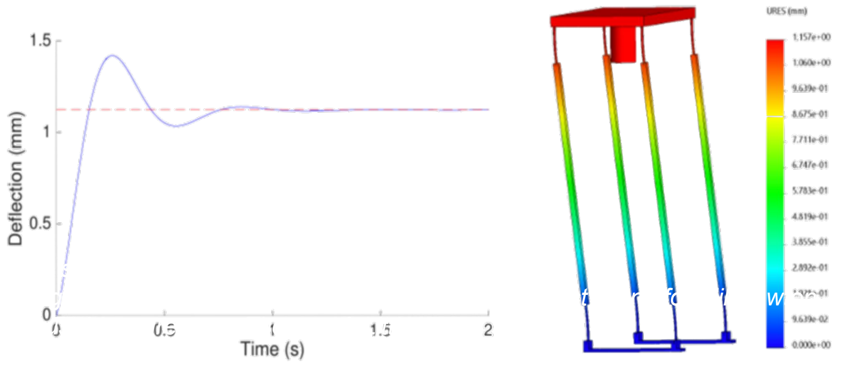
Mass Budget - measure when we take apart stand

Subsystem	**Limit (kg)**	**Margin**	**Allocated (kg)**	**Used (kg)**	**Available (kg)**
Chamber Interface	2	15%	1.7		
Leveling System	2	15%	1.7		
Thrust Measurement	3.3	30%	2.3		
PPT Mount	3	30%	2.1	1.4	
Data Analysis	1	10%	.9		
Total	**11.3**	**20%**	8.7		

Mission Overview: Operation

Deflection Measurement

- **Measure micro quantities of thrust**
  - Electric propulsion systems have limited thrust
    - **Resolve deflections of 0.00118-0.197 in** (corresponding to impulses of 2.25 μlbf*s to 22.5 mlbf*s)
- Inverted pendulums resolve extremely low thrusts
  - Gravity acting on its center of mass **increases the stand's measurable deflection** for a given impulse



Nominal Inverted Pendulum Impulse Deflection

Image Credit: [1]