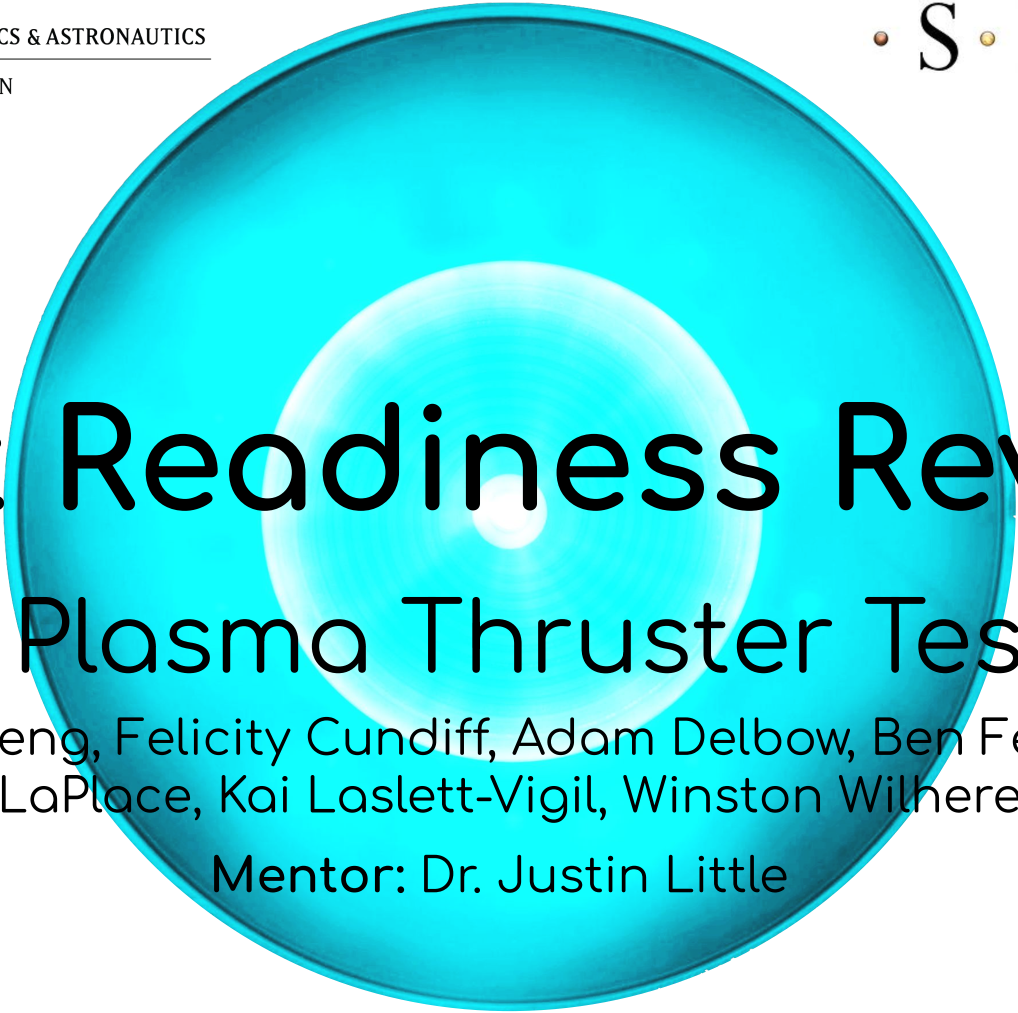
WILLIAM E. BOEING
DEPARTMENT OF AERONAUTICS & ASTRONAUTICS
UNIVERSITY of WASHINGTON

S·P·A·C·E



Test Readiness 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

Important Announcement: TRR De-Scope

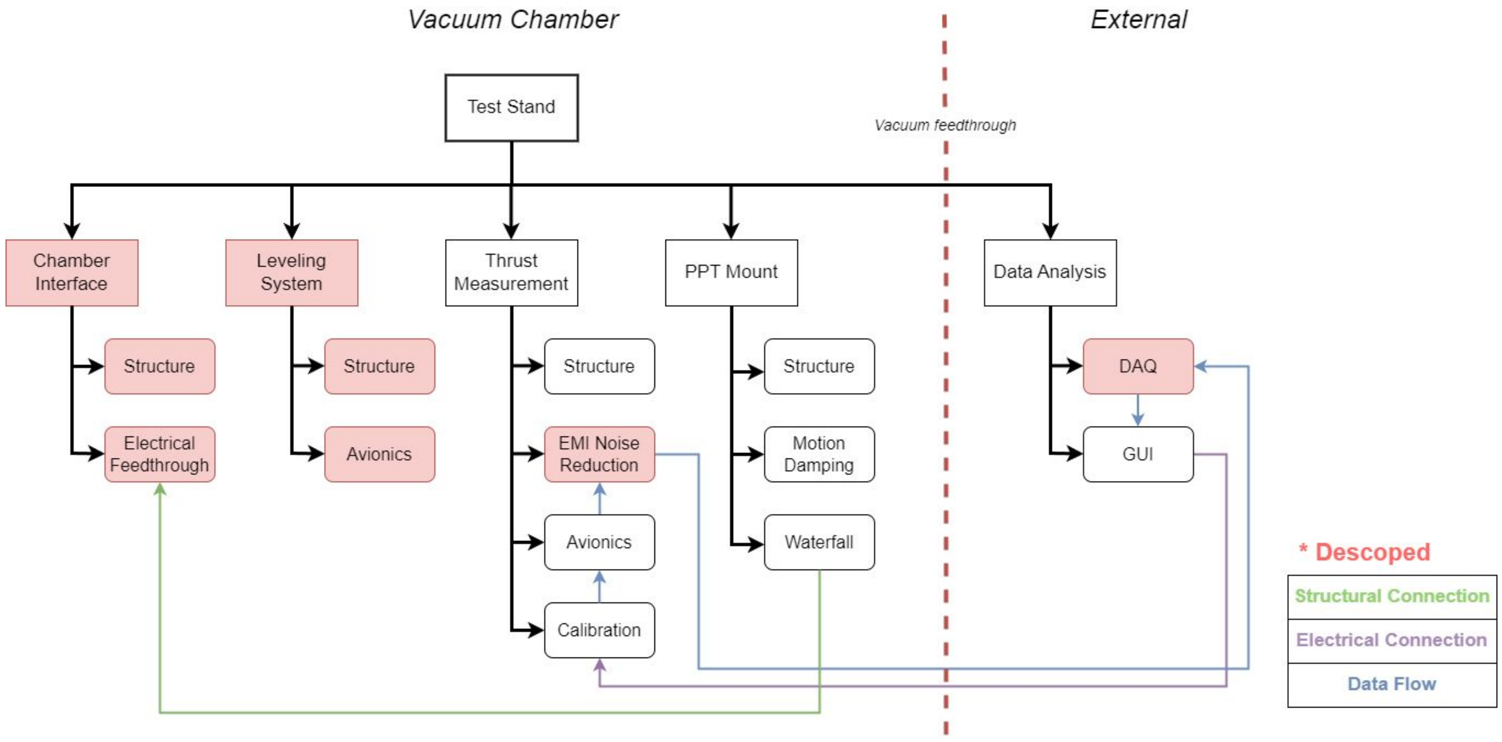
Due to SPACE Lab test scheduling and manufacturing delays, the current project will be **delaying the manufacturing of the chamber interface and leveling system not testing the full system under vacuum**

Implications:

- System test will **no longer occur in the designated vacuum chambers**
- The system calibration process will transition from utilizing the Dawgstar PPT as a known impulse to **using a weighted pendulum to strike the test stand**
- All vacuum interface and EMI shielding related subsystems will additionally be **de-scoped for later testing**

BF, NC, LL

Important Announcement: TRR De-Scope



Agenda

- **Mission Objective, CONOPS Review, Systems Requirements, V&V Matrix**
- Integrated System Overview
- Subsystems & Integration Test Results
- Test Procedure Review
- Test Plan Review
- Safety
- Schedule
- Conclusions

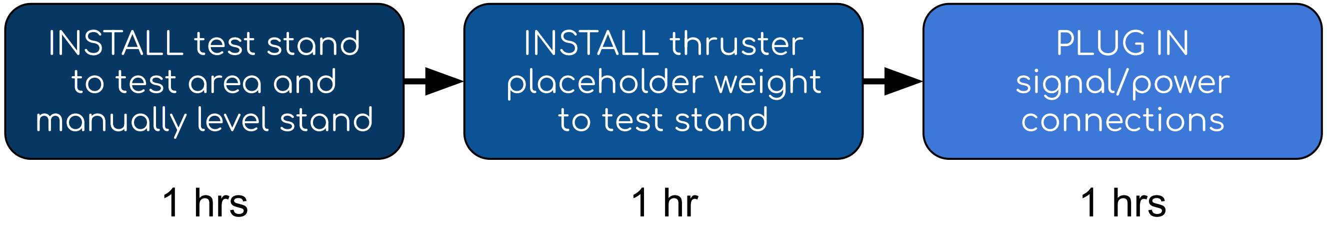
Mission Objective

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**

CONOPS (Descoped) (1/3)

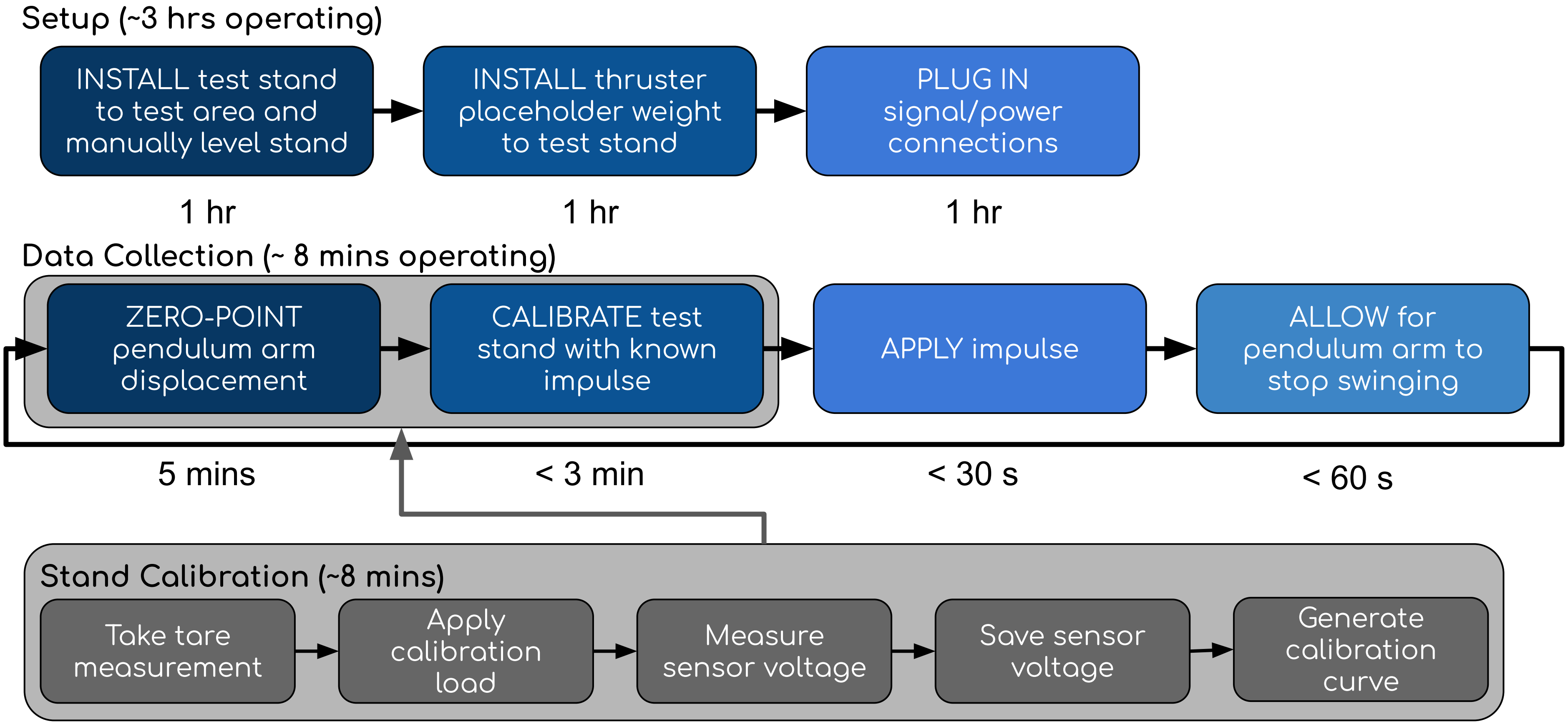
NC

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

Disassembly (~2 hrs operating)

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

System Requirements

WW

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	*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*

System Requirements

De-Scoped for TRR

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**	*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	*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*	*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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NC, WW

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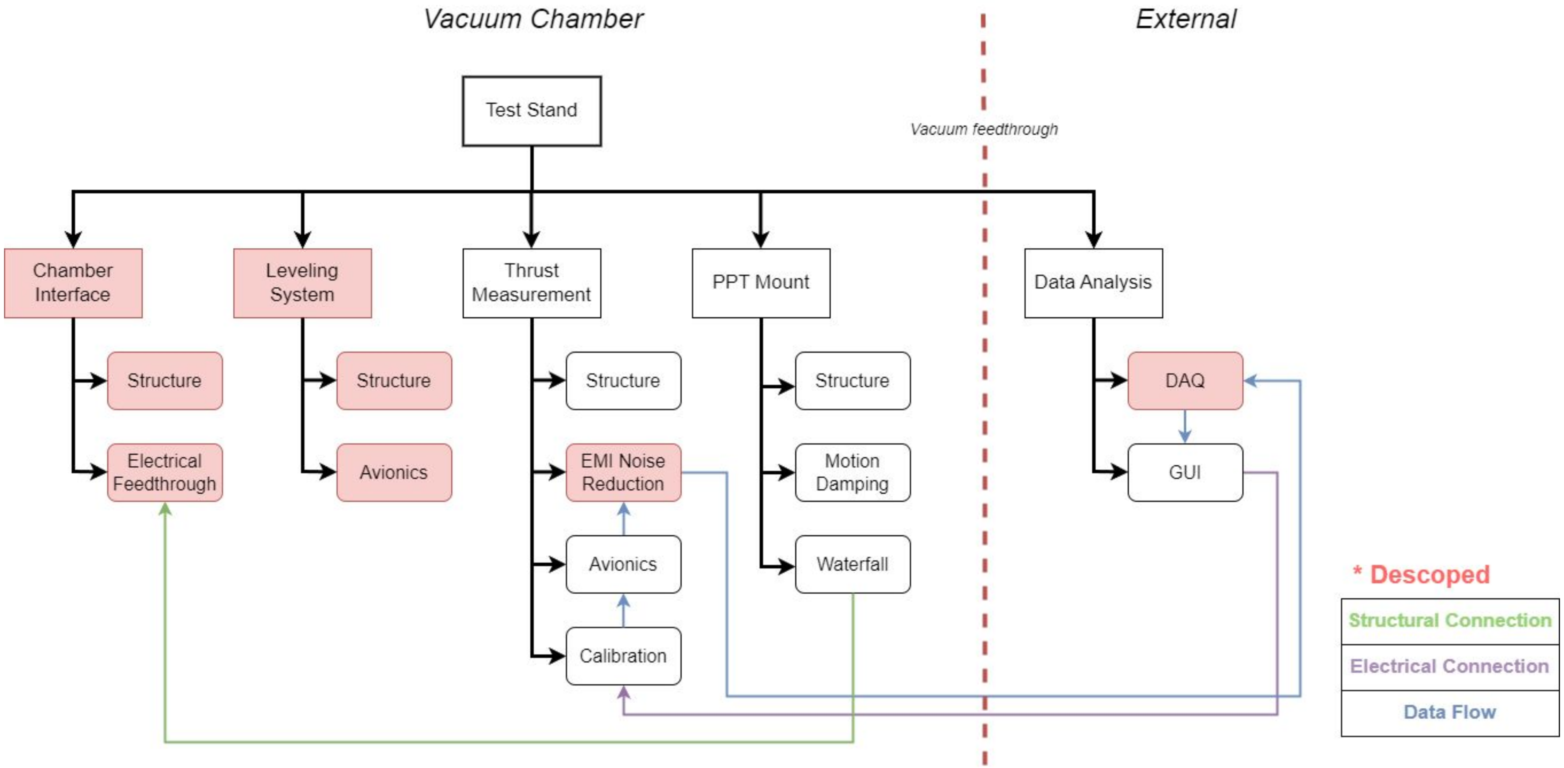
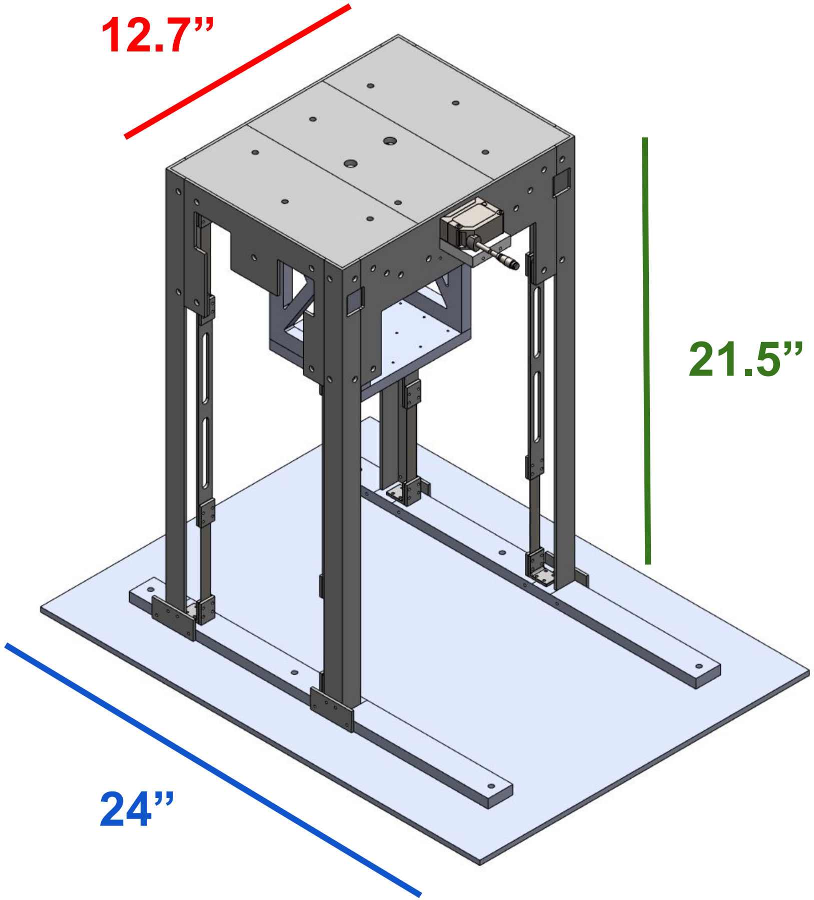
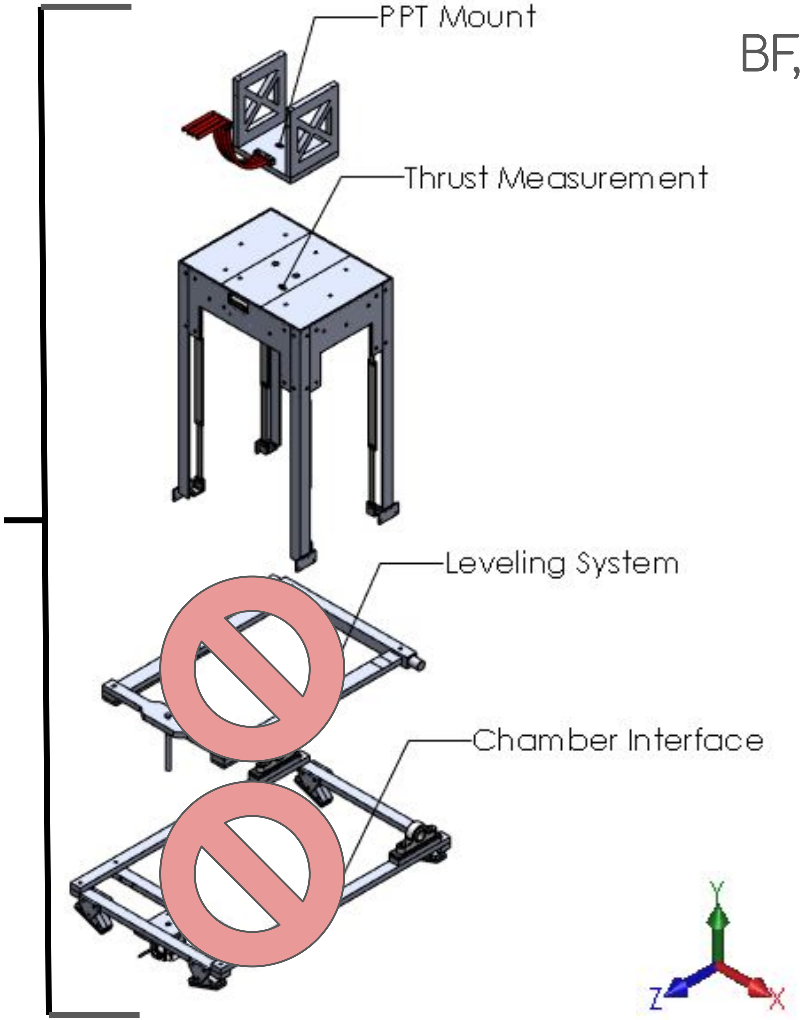
System Architecture



Assembly Overview (Descoped)

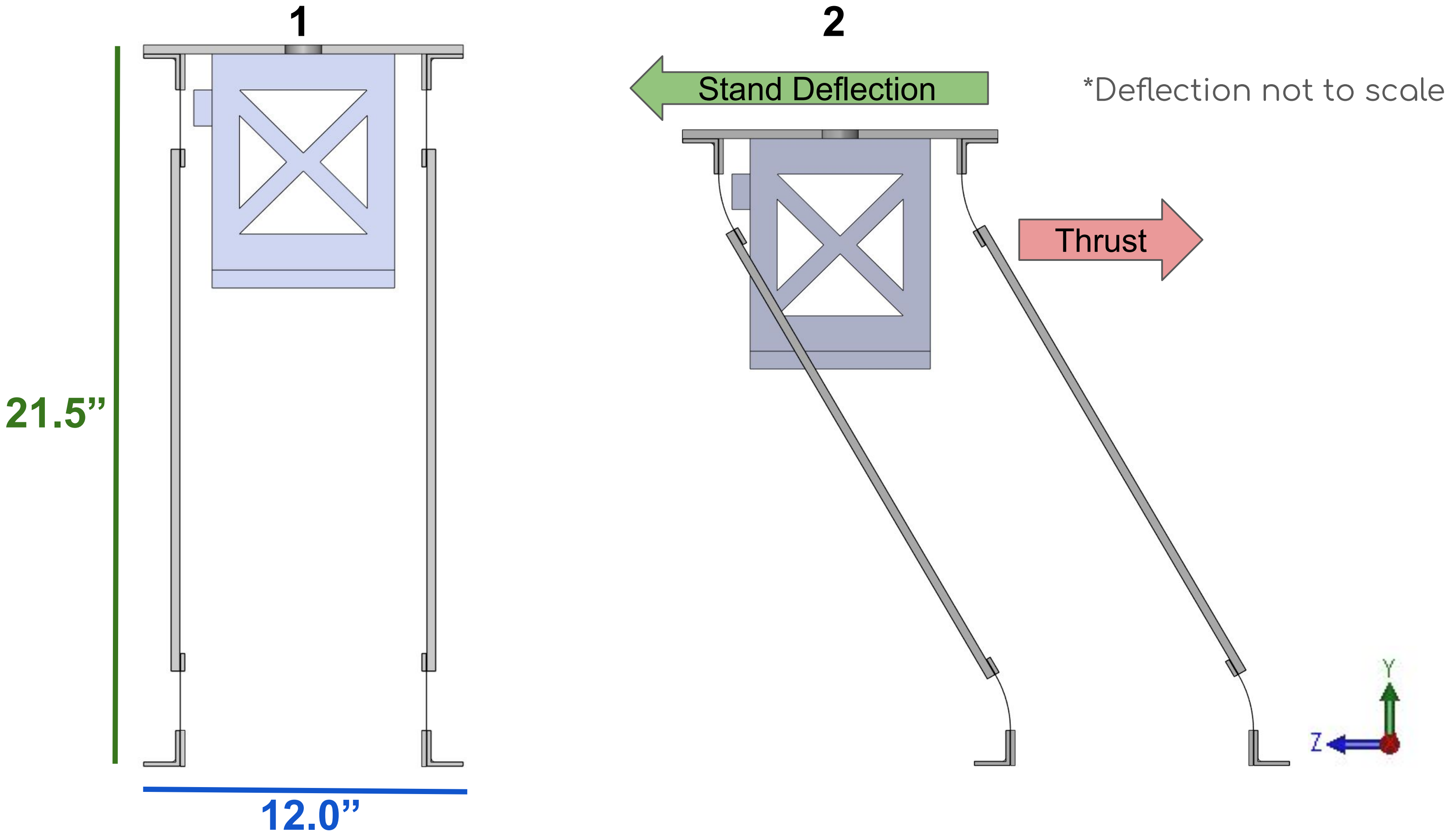
BF, NC





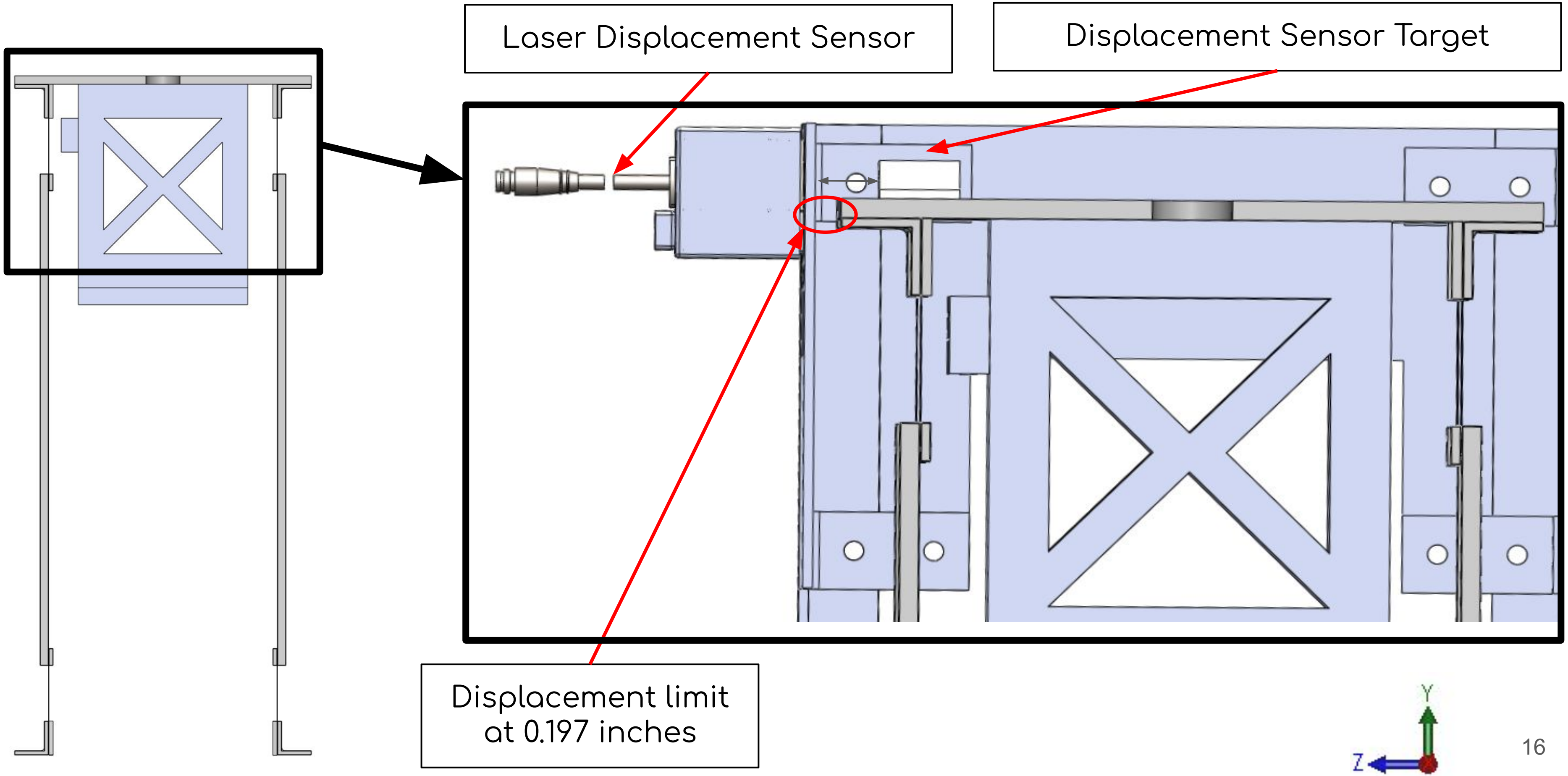
Function - Stand Deflection

BF, NC



Function - Data Capture

BF, NC



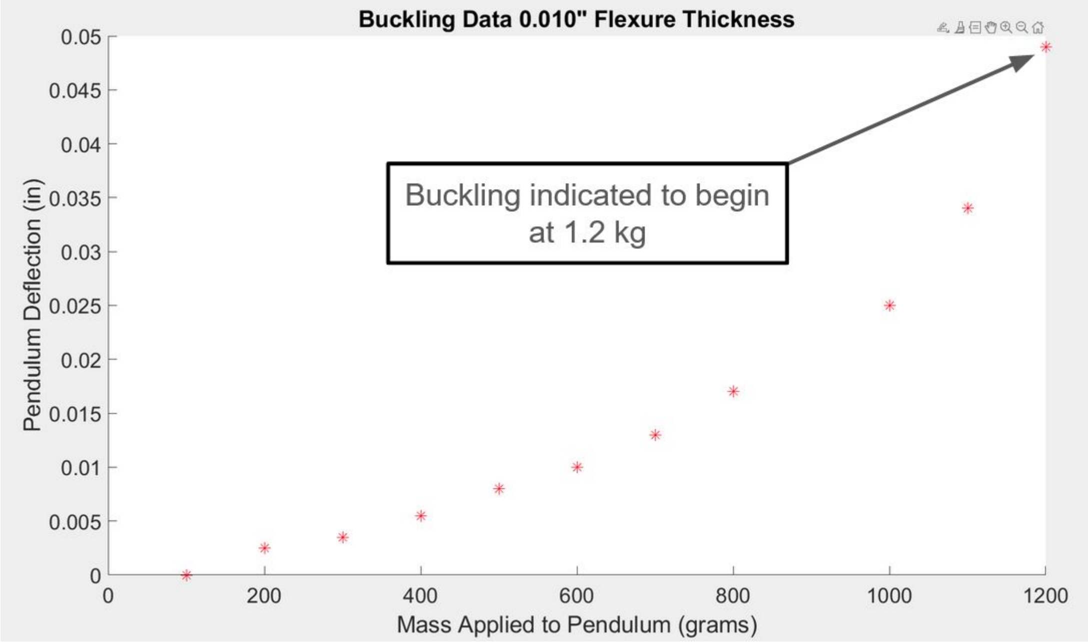
Subsystem Test Setups Overview

NC, BF, KLV, FC

Test	Description	Equipment
Flexure Buckling	Verify that flexure sets are capable of supporting thruster masses indicated in REF-IFS1	• Digital scale with gram precision • Calibrated masses • 0:0.001":1" dial indicator • Descoped test stand
Rangefinder	Verify the repeatability and error of measurements	• CNC Mill and Flat Tool • Rangefinder • Oscilloscope
GUI and Motor	Verify motor receives GUI input and characterize motor response for GUI calibration.	• Computer with GUI • IL-030 and IL-1000 • Oscilloscope • Stepper motor

0.010" Flexure Buckling Results

AD, WW

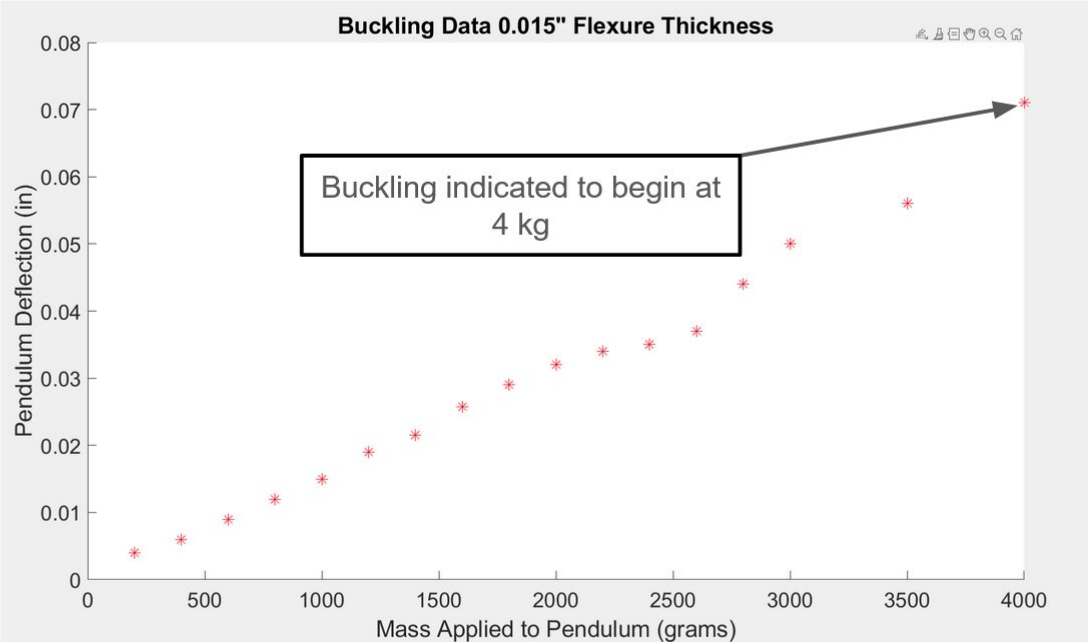


**Note: thruster shelf removed*

- Thruster shelf t**oo heavy for smaller thruster measurements,** needs separate shelf design
- Shelf and thruster maximum mass of 1 kg gives a **FoS of 1.13**
- Updated response model to account for buckling → stand predicted to resolve 55E-6 ± 50% uN*s at **FoS of 1.10**

0.015" Flexure Buckling Results

AD, WW



Note: thruster shelf removed

- Thruster shelf **too heavy for smaller thruster measurements,** needs new shelf design
- Shelf and thruster maximum mass of 3.2 kg gives a **FoS of 1.22**
- Updated response model to account for buckling → stand predicted to resolve 300E-6 ± 50% uN*s at **FoS of 1.10**

Flexure Buckling Tests

AD, LL

- Buckling tests for 0.020" and 0.025" flexures **not yet completed**
- Tests **to be completed** Tuesday, May 21 in AERB 139
- Each individual test takes 1 hour; **total testing time is 2 hours**
- Test Procedure: https://docs.google.com/document/d/15yM5jC-WfB1lkUnyY28MM1jgY2zfB1NzjpleRV7ITJ4/edit#heading=h.90rcyr7qucak

Pendulum Leg Assembly

Flexure Buckling Tests

- Expected result for 0.020" flexure using Euler's buckling equation: **buckling starts at approximately 8 kg** with thruster shelf installed, to be verified through testing
- Expected results for 0.025" flexure using Euler's buckling equation: **buckling starts at approximately 17 kg** with thruster shelf installed, to be verified through testing
- Larger mass tests completed using sand weighed out with a scale
- This subsystem test will test for **verification of requirement Sys.5**

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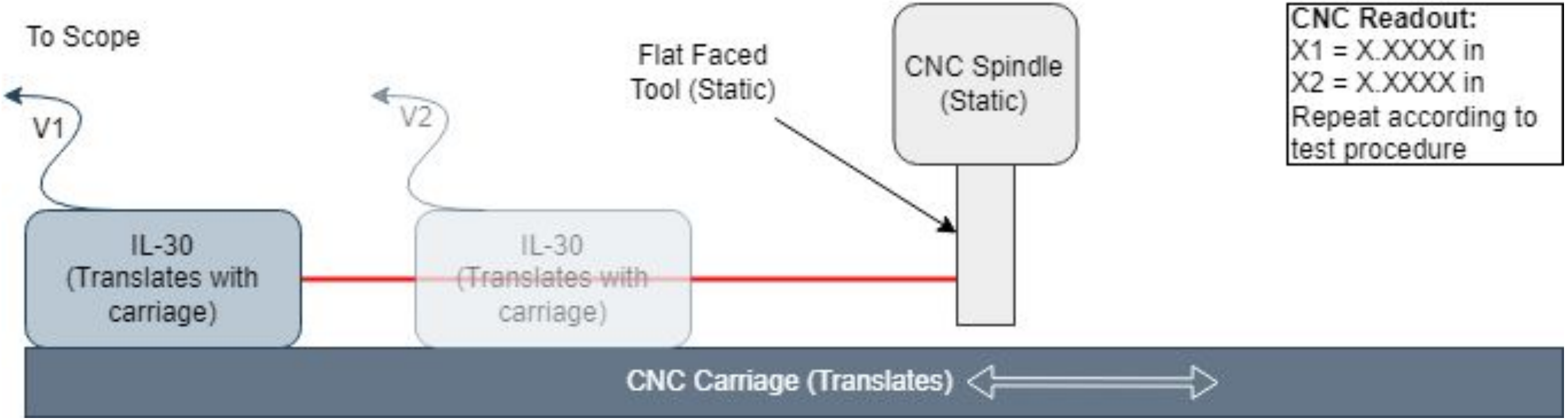
Rangefinder Hardware Test

- 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

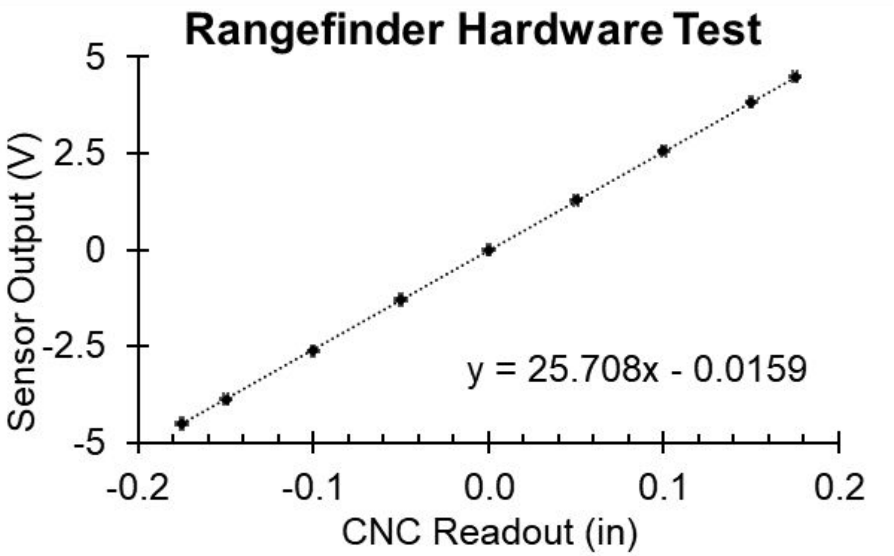
- CNC used to vary distances precisely



Rangefinder Test Setup

Rangefinder Hardware Test Results

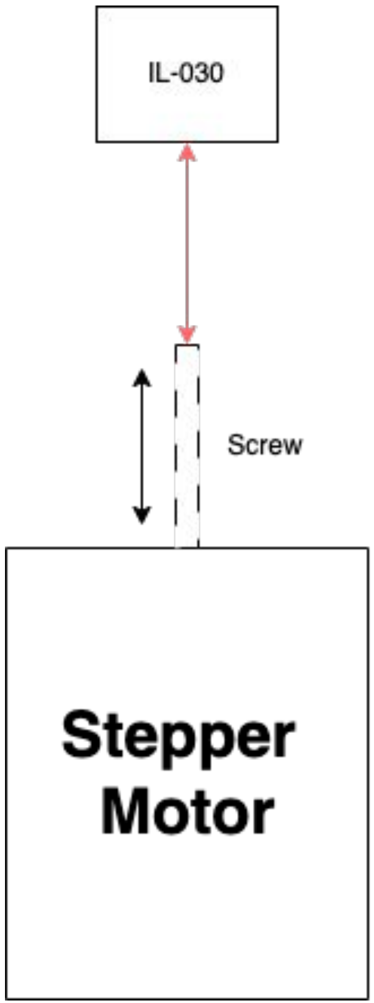
- IL-030 tested to determine measurement error and repeatability
- Combined sensor and scope precision:
  - ±0.0269 V
- CNC precision:
  - ±0.0005 in
- Average Standard Deviation:
  - **0.002 in**



Stepper Motor and GUI Test Plan

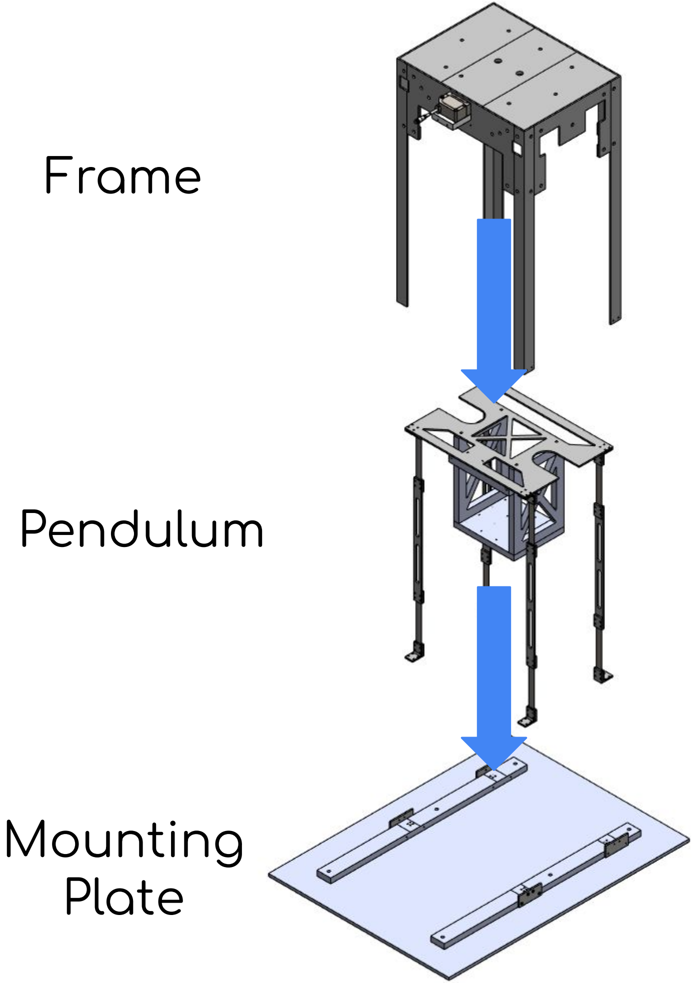
- Stepper motor and GUI tests **not yet completed**

- Tests **to be completed Tuesday May 21** in AERB 139
  - Approximately 30 minutes to complete
  - Demonstrate motor response to GUI input
  - Characterize screw actuation per motor step to properly calibrate GUI

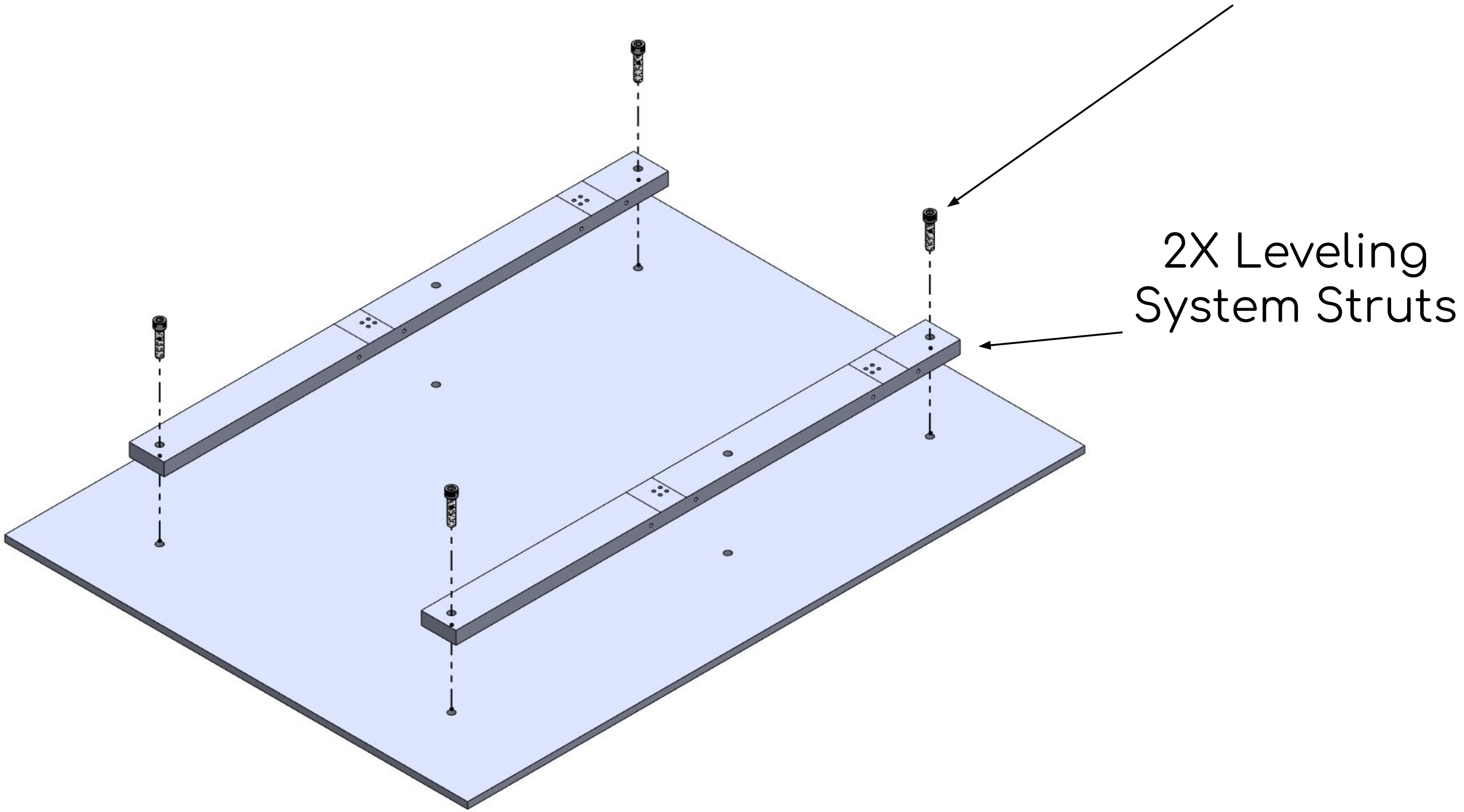


BF, LL

Structures Integration Overview

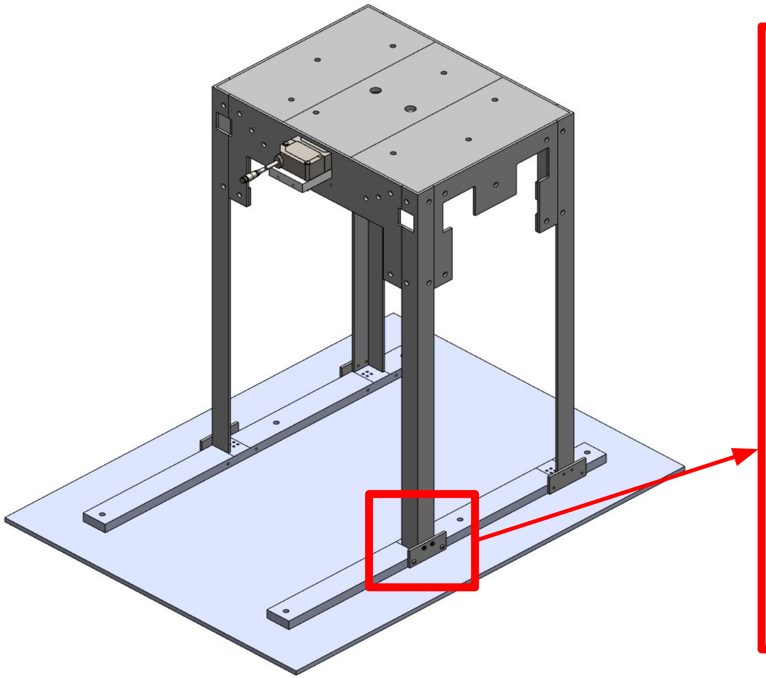


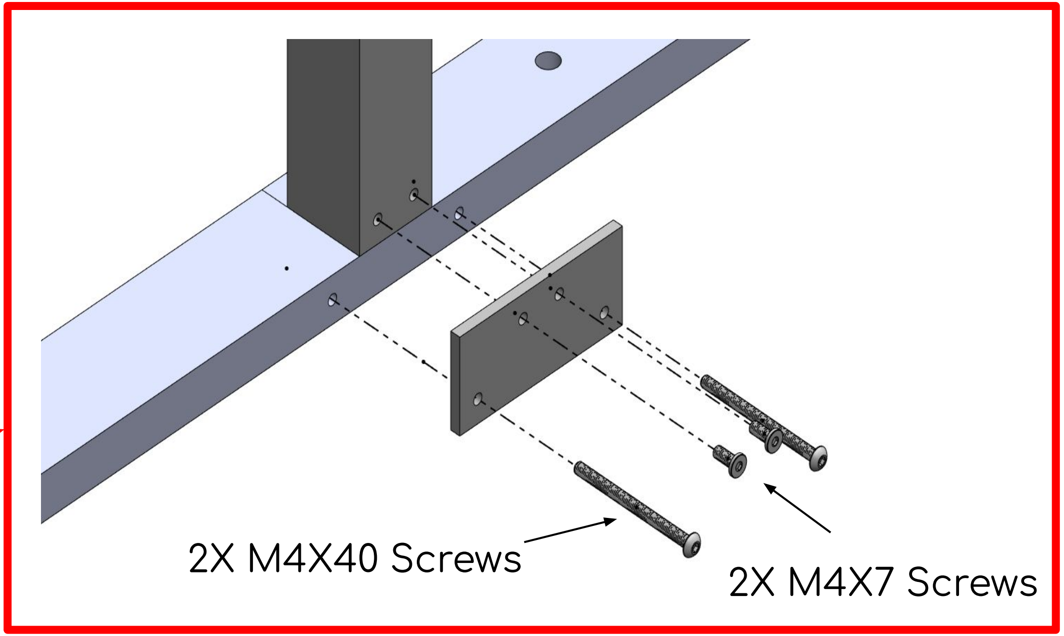
Mounting Plate Integration



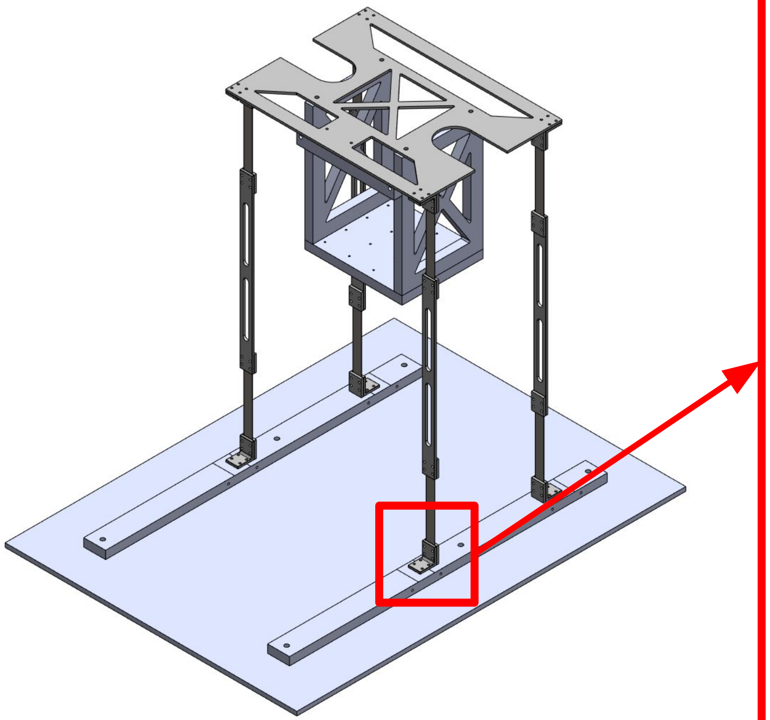
Frame to Mounting Plate Integration

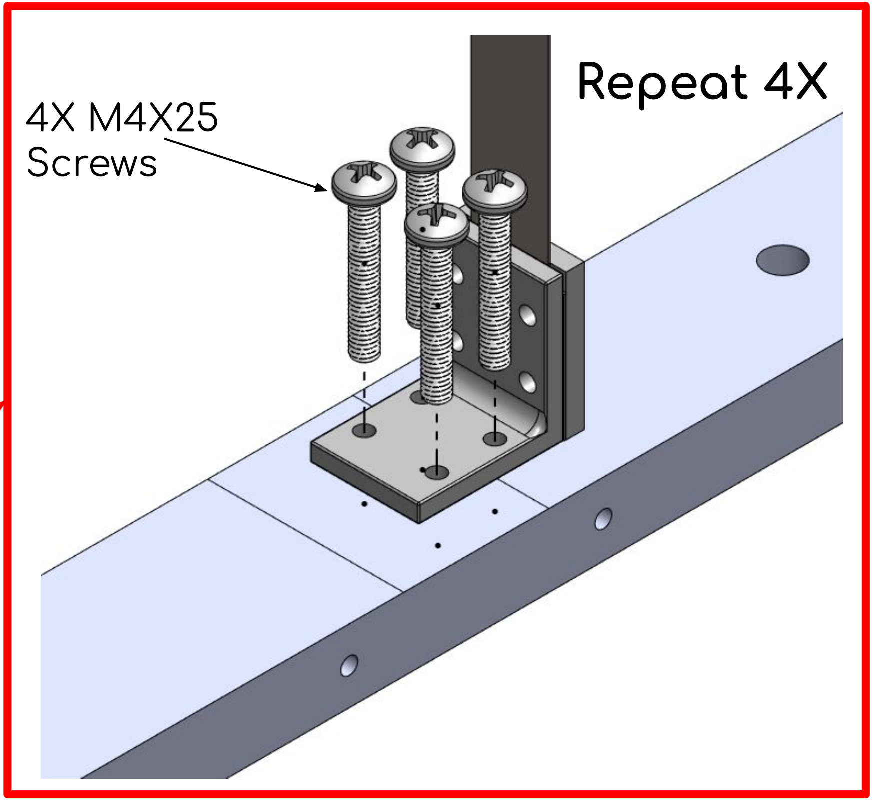
BF, LL



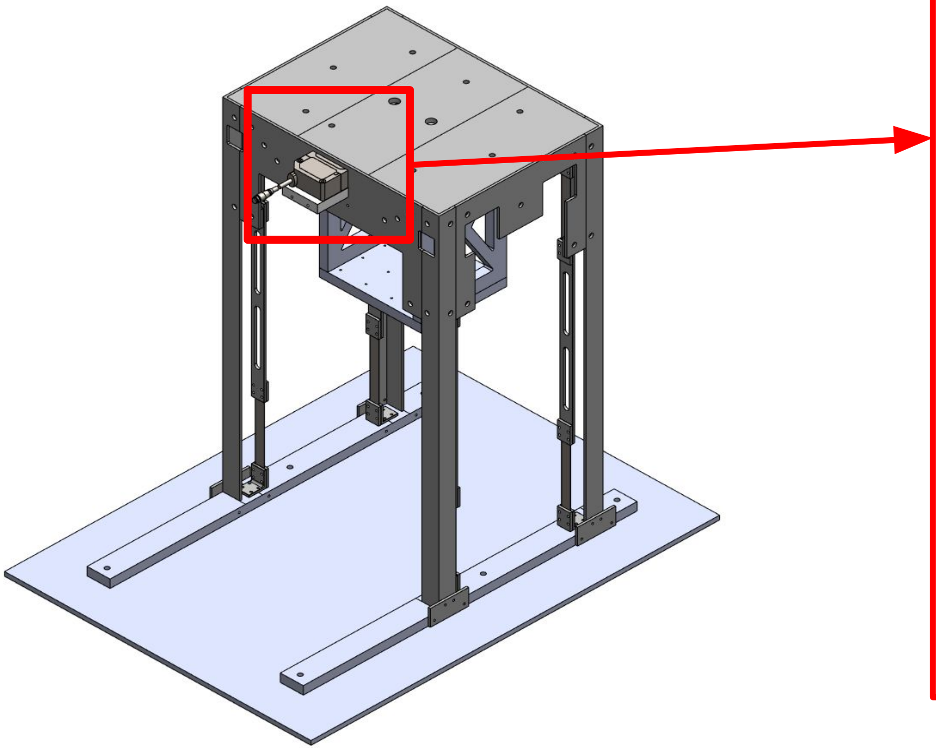


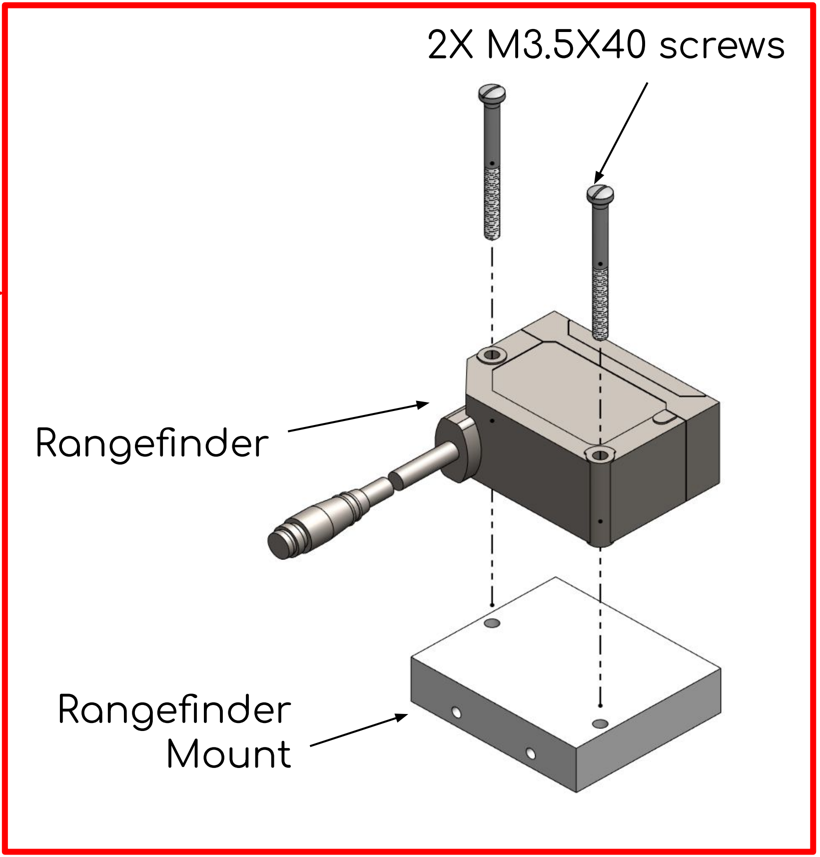
Pendulum to Mounting Plate Integration





Avionics Integration





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NC, WW

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System Test Overview

Equipment	Location	Notes
De-scoped Test Stand Assembly	AERB 139	Default Configuration (with flexure set FX2)
Flexure Sets	AERB 139	8 flexures per set: FX1, FX2, FX3, FX4
Thruster placeholder weights	AERB 139	0 - 10 kg
Oscilloscope	SPACE Lab	Supplied by SPACE Lab
Computer	-	
Bubble Level	AERB 139	Concentric
Masking Tape Roll	-	

System Test Overview

Equipment	Location	Notes
Calibration Pendulum Frame	SPACE Lab	Supplied by SPACE Lab
Calibration Weight	-	1 g (washer/nut)
Roll of string/fishing line	SPACE Lab	~0.245 g/m
Slow motion camera	-	iPhone, 240 fps slow motion
Ruler	-	Must include cm markings
Protractor	-	
Digital Mass Scale	-	0.1 g resolution

System Test Procedure & Plan Preview

Modified system test due to de-scoping constraints:

- Full system test with Dawgstar PPT no longer feasible
- System calibration to show proof of concept
- Use calibration to verify Sys. 3 & Sys. 4
- Waterfall and dampener tests rolled into system calibration

Steps to verify Sys. 3:

- Full system test calibration
- Employ use of SPACE Lab calibration pendulum

Steps to verify Sys. 4:

- Analysis of system test calibration data to check 0.5x resolution of minimum and maximum recorded thrust & impulse values

Test Procedure & Test Plan Review

NC, WW

Links to system test procedure and test plan

Test procedure:
https://docs.google.com/document/d/19LgM8vZmldS-nUuxWhPQhSV5jrzaEgmahgzZCXV9uUg/edit?usp=sharing

Test Plan
https://docs.google.com/document/d/19vuNhTcxJRtio_r66dI3BWF0MB6F-_Tjd1TSr84EqdU/edit?usp=sharing

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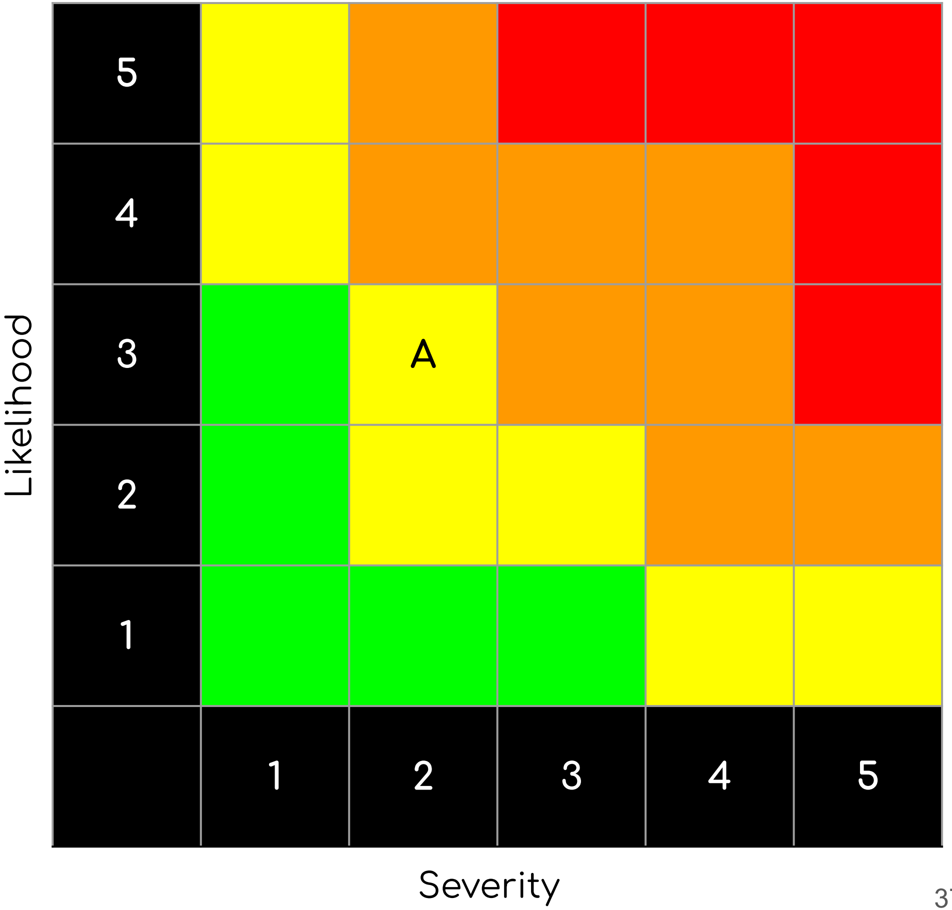
Risks & Safety

NC, FC, LL

Risk Assessment

Item	Label	Mitigation strategy
Contact with G10 fiberglass dust during manufacturing	A	Wearing proper PPE, avoiding touching jagged ends, using vacuum to collect dust particles



Agenda

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- **Safety**
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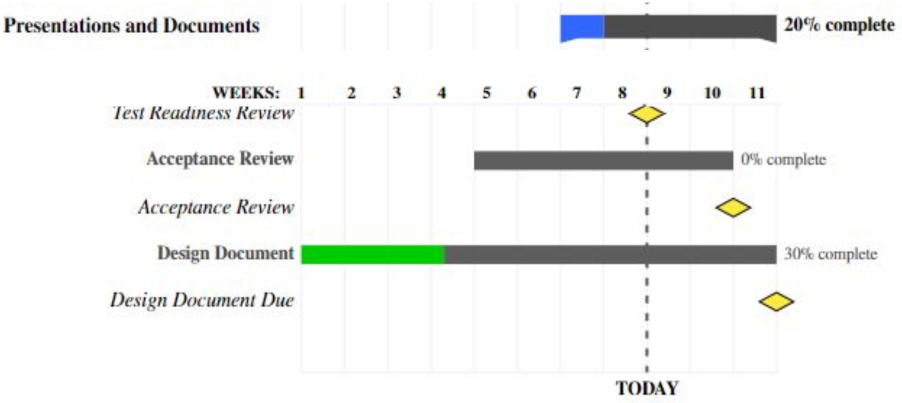
Schedule


WEEKS: 1 2 3 4 5 6 7 8 9 10 11
Purchasing
90% complete
Thrust Measurement
90% complete
PPT Mount
95% complete
Data Analysis
100% complete
Manufacturing
80% complete
Thrust Measurement
90% complete
PPT Mount
90% complete
Data Analysis
100% complete
Testing
70% complete
Thrust Measurement
80% complete
PPT Mount
80% complete
Data Analysis
100% complete


Presentations and Documents
20% complete
WEEKS: 1 2 3 4 5 6 7 8 9 10 11
Test Readiness Review
Acceptance Review
0% complete
Acceptance Review
Design Document
30% complete
Design Document Due
TODAY

Agenda

NC, WW

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- Schedule
- **Conclusions**

Conclusions

- The system **cannot be fully tested** due to manufacturing delays
- In the meantime, a **proof of concept calibration** will be completed to demonstrate the test stand's ability to satisfy **SYS 3 & 4**
- **Buckling test** to be completed by Tuesday 5/21
- **Laser rangefinder verification** test completed
- **System testing** to begin Thursday 5/24
- Planning for **4 days of system testing,** 1 day each test configuration
- **System testing** to be completed Tuesday 5/28

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

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

3 hrs

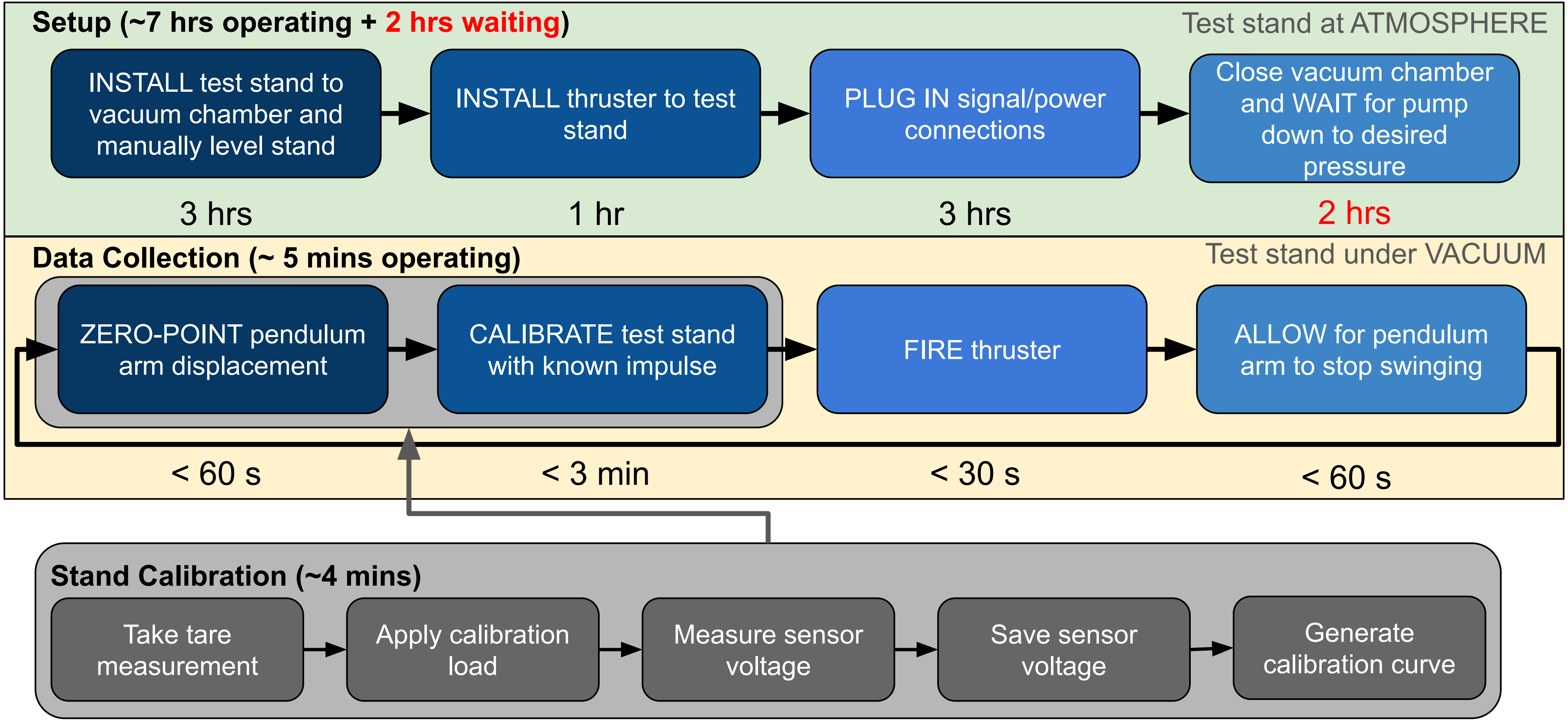
1 hr

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

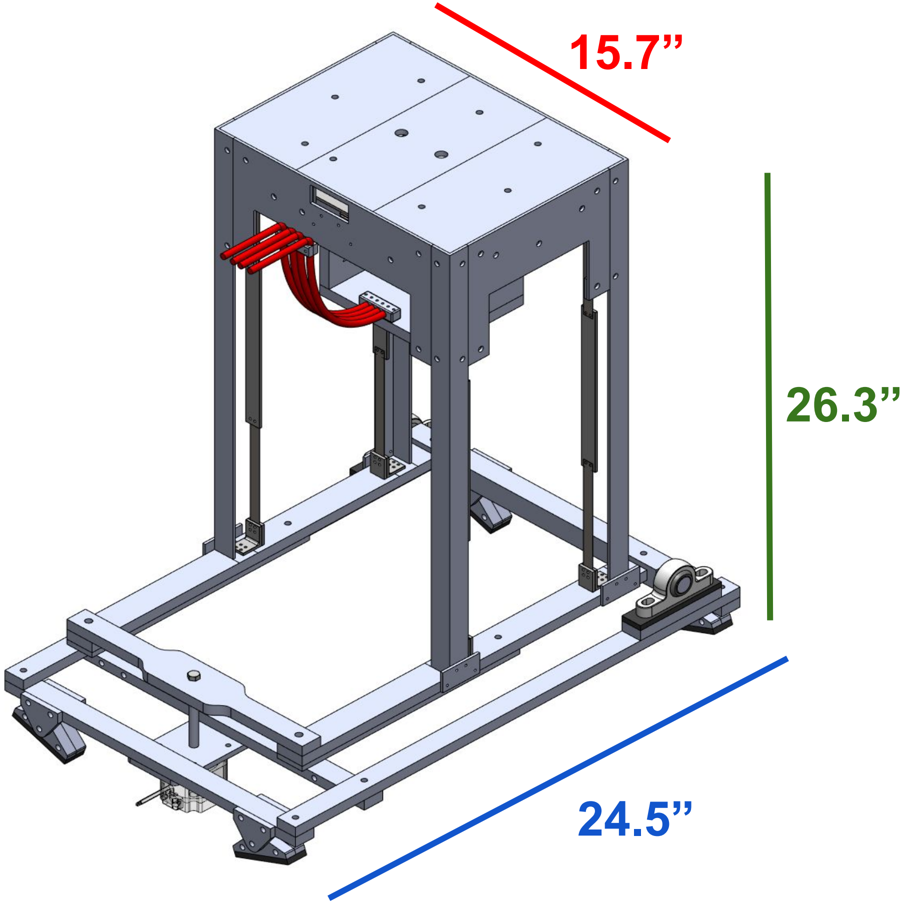
1. ZERO-POINT pendulum arm displacement — < 60 s
2. CALIBRATE test stand with known impulse — < 3 min
3. FIRE thruster — < 30 s
4. ALLOW for pendulum arm to stop swinging — < 60 s

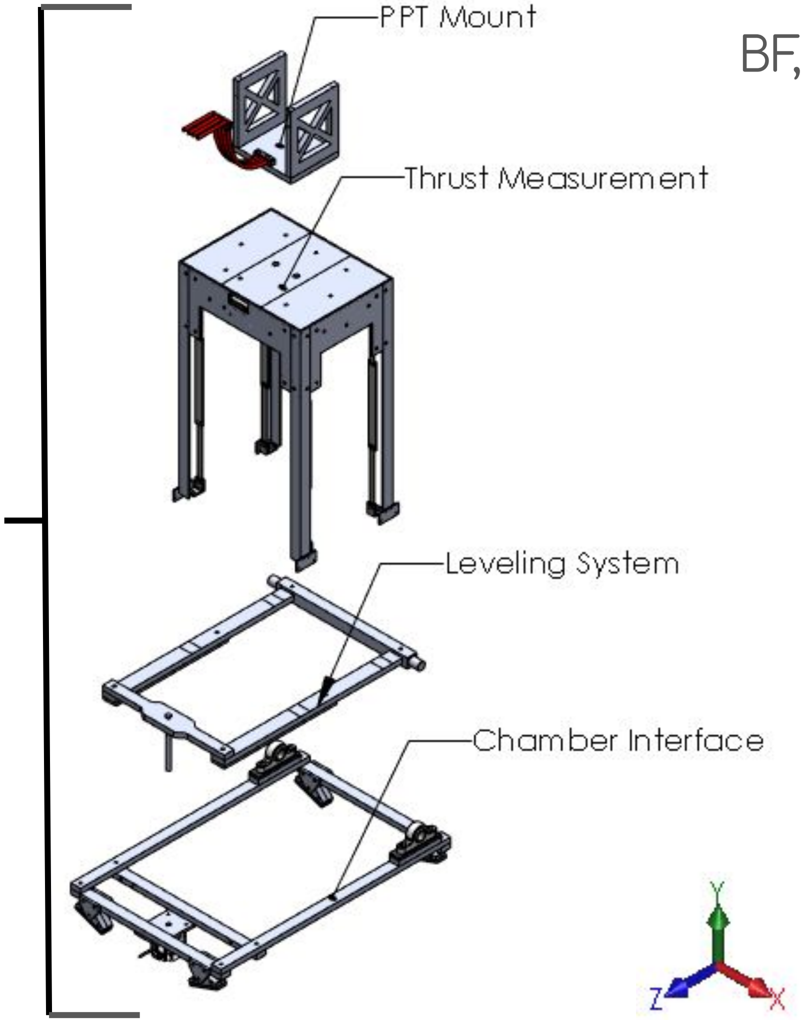
Disassembly (~4.75 hrs operating + 15 mins waiting)

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

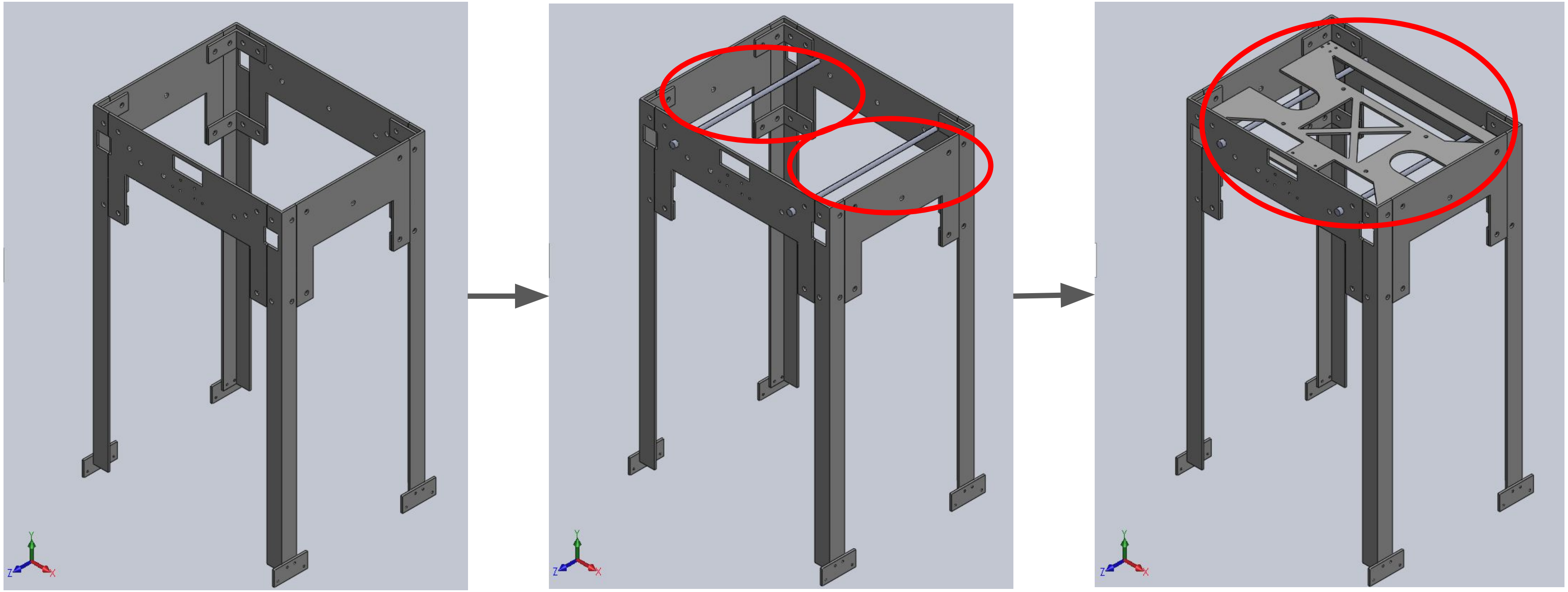




Test Setup Overview - Flexure Buckling

AD

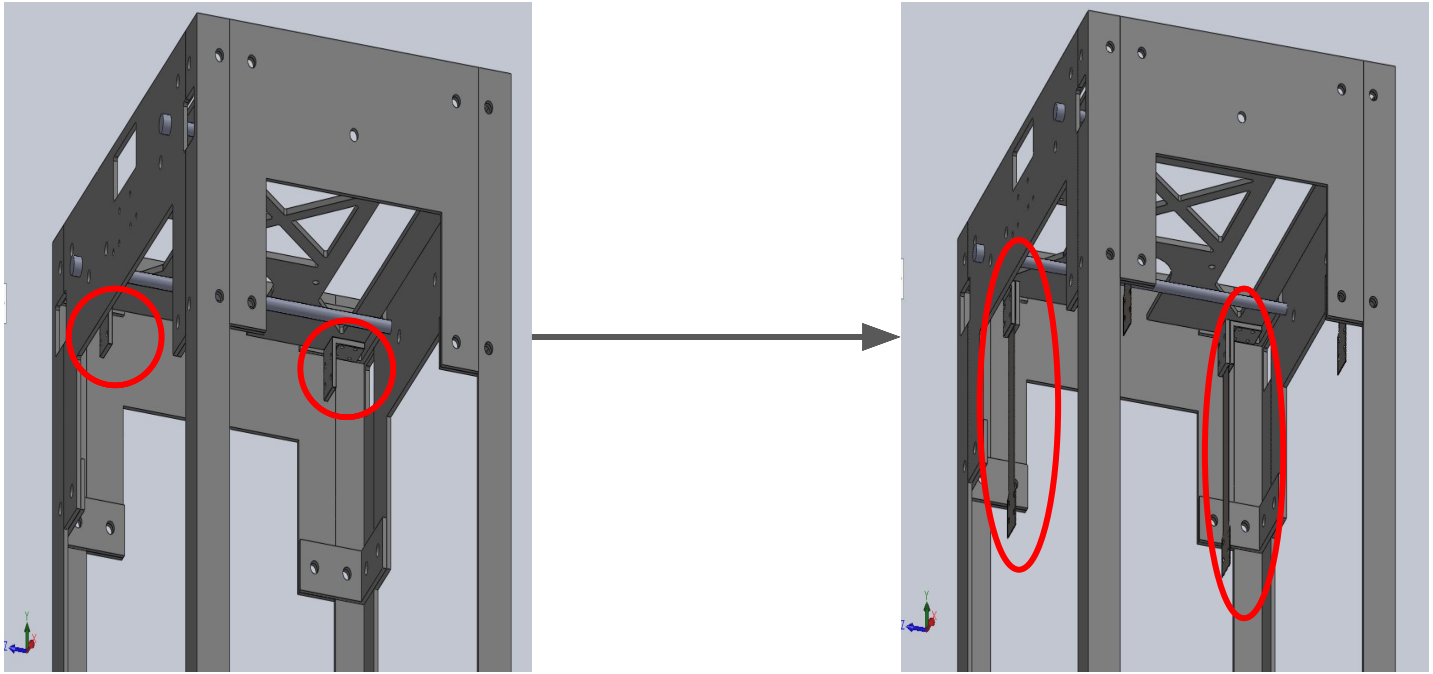
- Assemble test frame per assembly instructions, leaving top 3 panels off, secure frame to base plate
- Install pendulum support pins
- Install pendulum top onto pendulum support pins



Test Setup Overview - Flexure Buckling

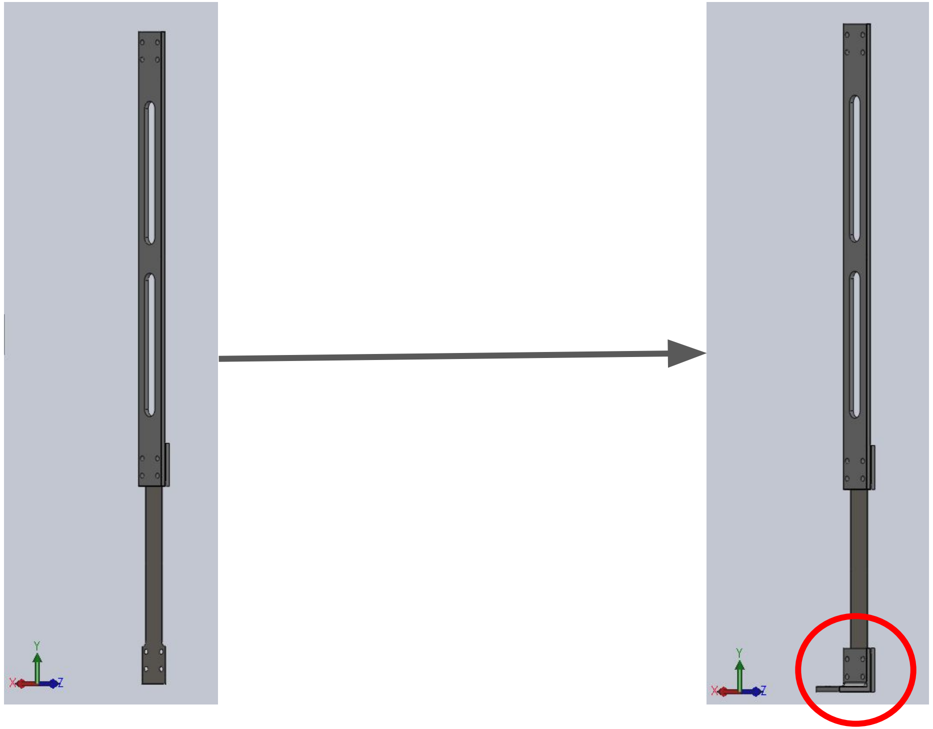
AD

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



Test Setup Overview - Flexure Buckling

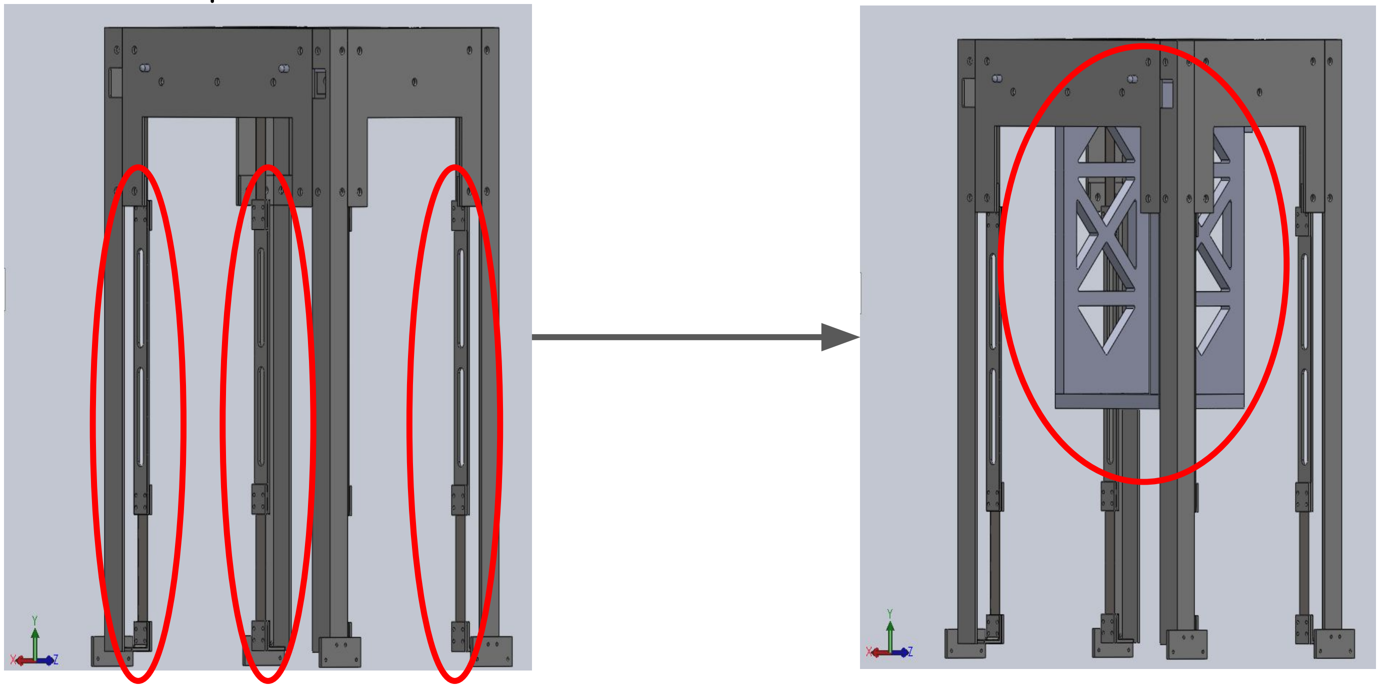
- Bolt a second set of flexures to the vertical flexure support using connector brackets
- Bolt corner brackets to flexure/vertical flexure support assemblies



Test Setup Overview - Flexure Buckling

AD

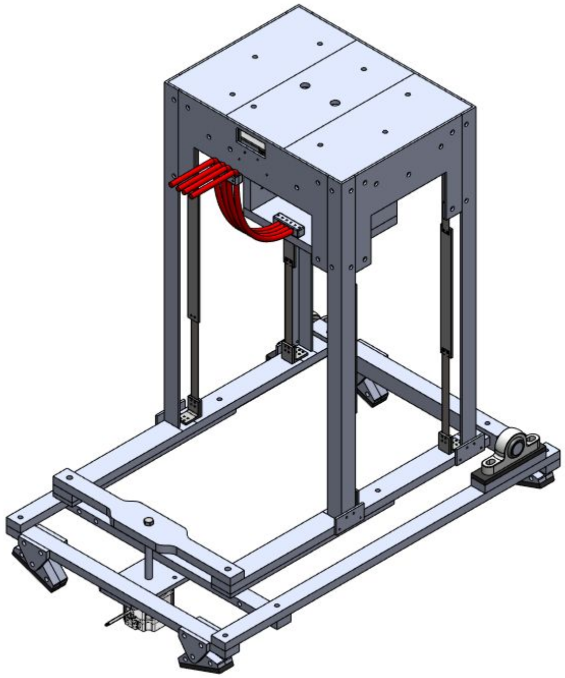
- Bolt corner bracket/flexure/vertical flexure support brackets to flexures on pendulum top using connector brackets
- Fasten lower corner brackets to base plate
- Assemble thruster shelf per assembly instructions and fasten pendulum top



Mission Overview: Anatomy

Structure

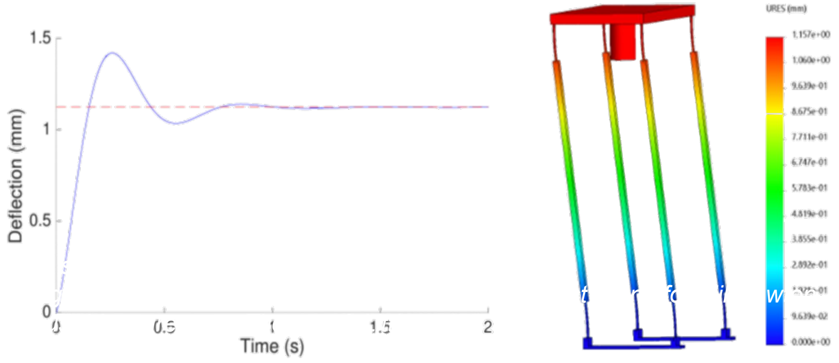
- **Measure micro quantities of thrust**
  - Electric propulsion systems have limited thrust
    - **Resolve deflections of 0.00118-0.197 in** (corresponding to impulses of 2.25 μlbf*s to 22.5 mlbf*s)
- Inverted pendulums resolve extremely low thrusts
  - Gravity acting on its center of mass **increases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



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]

Project Timeline

Next Steps

NC, LL

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