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A.S.T.R.A.

Atmospheric – Satellite – Trajectory – Repositioning Attachment

Preliminary Design Review (PDR)

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Nathan Stephens, Control Systems
Clayton Cannella, Mechatronics
Evan Thompson, Mechatronics
Jimmy Maskill, Electronics
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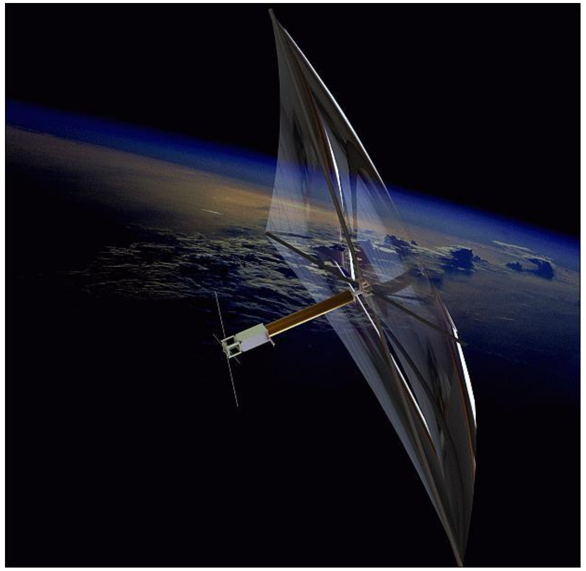
GSA: Kian Jamal
Professor: Dr. Irmak
Faculty Advisor: Dr. Rios
Industry Mentor: TBD
Capstone Coach: TBD

1.0 Executive Summary

- Expandable and retractable CubeSat attachment capable of modulating drag force to perform orbital maneuvers.
- Addresses growing space debris concerns and enables maneuvering without the use of propulsion.
- Key stakeholders include Dr. Rios and space agencies such as SpaceX, Spire Global, and Planet Labs.



InflateSail. [6]

[6] ESA / Surrey Space Centre, "InflateSail".

2.1 Problem Statement

Most CubeSats do not have the ability to perform orbital maneuvers.

- Once deployed, typically constrained to initial trajectory with no means of change.
- It is estimated that 90% of all CubeSats do not have any means of propulsion due to cost, mass, and complexity. [1]
- The lack of control limits mission flexibility and contributes to the challenge of safe and sustainable operations.

PROBLEM

Project A.S.T.R.A enables orbital maneuvers via controlled drag modulation.

- By varying drag area of the attachment the CubeSat will be able to engage in formation flight, debris avoidance, and targeted reentry.
- The concept offers a low mass, low cost, and low complexity alternative to chemical or electric propulsion systems.

SOLUTION

[1] Hebden, K., “Innovative Design Could See CubeSats ‘Steam-Powered’ ”

Liam Pettit, Project Manager

2.2 Objectives

Objective #	Objective Text	Objective Rationale
OBJ-01	The team shall design a mockup CubeSat-compatible attachment capable of modulating its cross-sectional area relative to direction of motion.	The modulation of the drag force will allow for the CubeSat to alter attitude and altitude allowing it to perform orbital maneuvers such as debris avoidance and controlled deorbiting.
OBJ-02	The team shall design a mockup CubeSat to be used in testing the attachment created in OBJ-01.	The mockup CubeSat shall serve as a validation method for compatibility between the prototype attachment and a CubeSat.
OBJ-03	The team shall demonstrate a proof of concept that the designed CubeSat-compatible attachment reliably functions while in simulated orbital conditions.	Proving the attachment can reliably function while in simulated orbital conditions demonstrates design concept viability for real-world orbital maneuver applications.

Morgan Lee, Systems Engineer

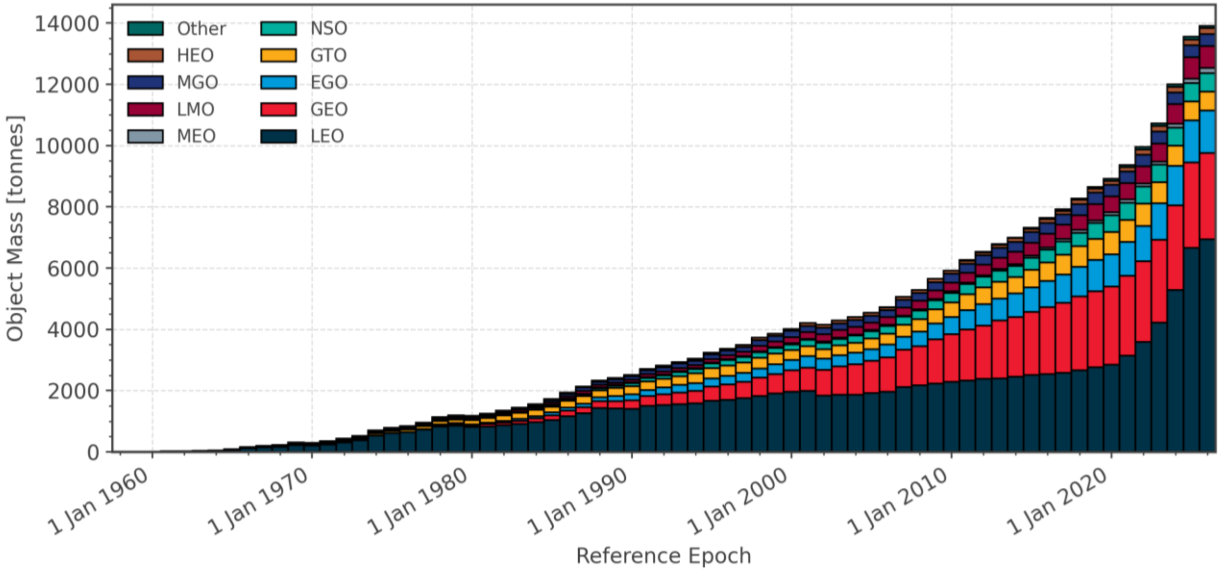
2.3 Deliverables - Documentation and Analysis

Deliverable
All documentation required by the Senior Design courses
Drag attachment prototype
Mock-up CubeSat
Validation and analysis for structures, mechatronics, electronics, and control subsystems
Rationale, validation and analysis for material selection
CAD models for the entire system
Testing and analysis plans
User manual for our finalized model

Clayton Cannella, Mechatronics Lead

2.4 Broader Impact

- The quantity of debris in LEO is rapidly increasing
    - ➢ Increases collision risk for satellites
- Many satellites have no way of changing their orbit
    - ➢ Some satellites use propulsion; however, this adds weight, complexity, and cost
- It will become increasingly more important for satellites to have high maneuverability



Mass evolution by object orbit. [8]

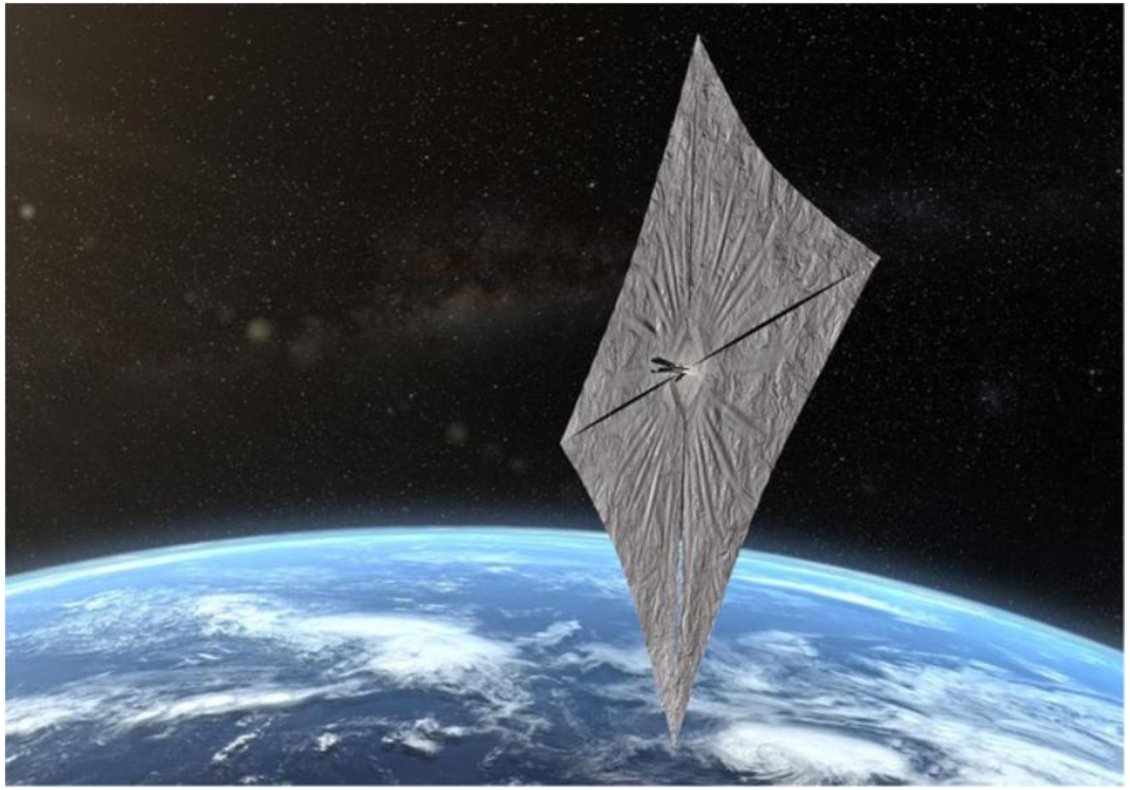
[8] European Space Agency, "Space Environment Statistics".

Jimmy Maskill, Electronics Lead

2.4 Broader Impact

- In 2022, the Federal Communications Commission adopted a new rule changing deorbit time from 25 years to 5 years [10].
- Single-use drag sails on satellites are effective in LEO. [11]
- Single-use sails cannot be used to change orbit since they cannot be modulated.

Project A.S.T.R.A. will serve as a proof of concept for a drag modulation device used to perform orbital maneuvers



Single Use Satellite Drag Sail [11]

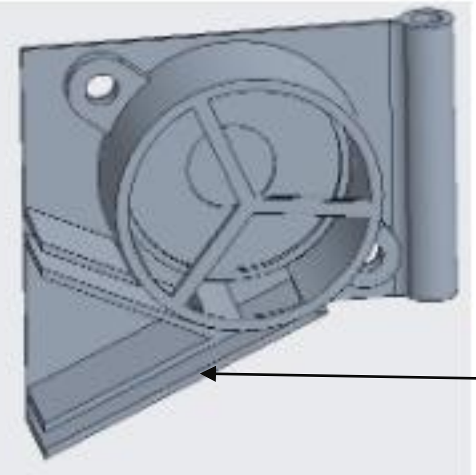
[10] Federal Communications Commission, "FCC Adopts New '5-Year Rule' for Deorbiting Satellites".
[11] Space: Science & Technology, Overview and Key Technology of the Membrane Drag Sail for Low Earth Orbit Satellite Deorbit

Jimmy Maskill, Electronics Lead

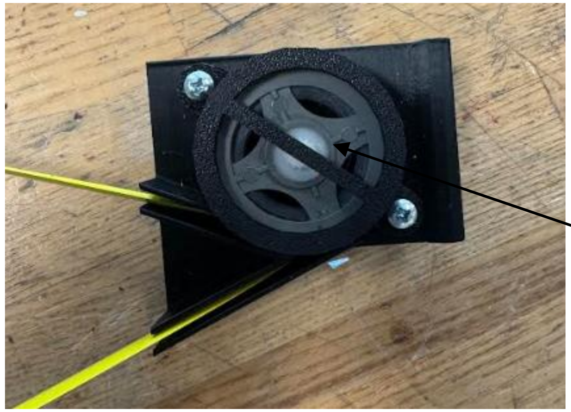
3.0 Concept of Operations

Deployment

Application of a resistor and burn-wire to hold booms



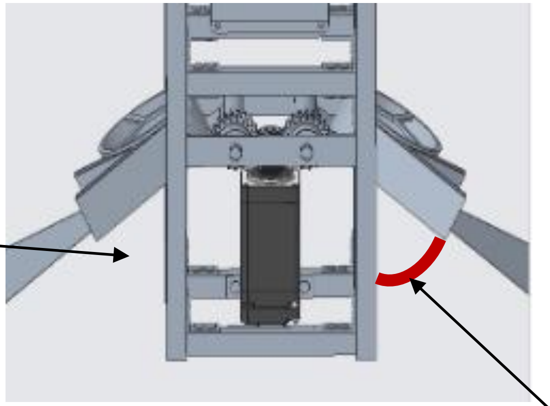
Once deployed, booms are guided via railing

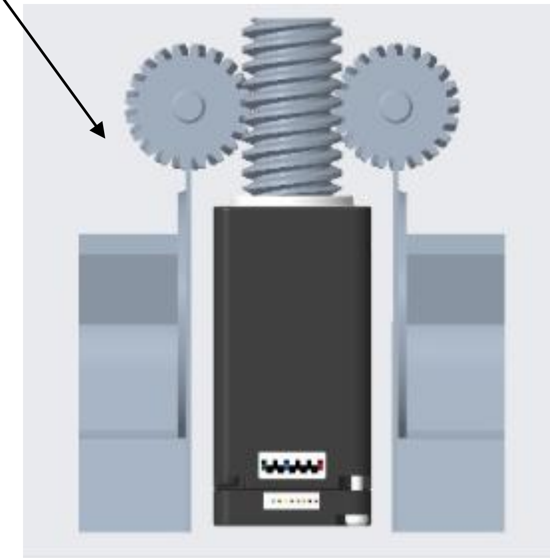


Stored energy of the tape spring to deploy the booms with sail attached

Modulation

Stepper motor drives worm gear to modulate deployment angle





Sail deployment angle changed along path, based on command

Cole Schumacher, Controls Lead

3.1 External Interfaces

- Parent CubeSat
  - Receives and transmits commands to the attachment
  - Supplies power to the attachment
- Launch Adapter
  - Clasps CubeSat and attachment during Rocket ascension
  - Aids in injection of CubeSat and attachment into orbit
- Ground Control
  - Sends commands to parent CubeSat to transmit to attachment
  - Receives data concerning deployment success

Cole Schumacher, Controls Lead

4.0 Level 1 System Requirements

Requirement #	Requirement Text	Requirement Rationale	Verification Method	Verification Strategy
SYS.01	The attachment shall be fully contained within a 2U (1U = 10cmx10cmx10cm) size before initial deployment.	A 2U attachment provides standardized sizing that is compatible with various other CubeSats.	Inspection	Demonstrate volume compliance in a CAD model and inspect physical prototype to ensure compliance.
SYS.02	The attachments material selection shall comply with Inter-Agency Space Debris Coordination Committee space debris mitigation guidelines. [4]	The attachment material must allow the design to burn up on reentry within appropriate guidelines.	Analysis	Use NASA's DAS to model the attachment materials to ensure full compliance. [5]
SYS.03	The attachment's surface area at any time shall be able to be measured with an accuracy of 7.5% [16] per user input.	The attachment's total cross-sectional area must be known for computing total drag on the device.	Test	Test and compare measured surface area with computed surface area
SYS.04	The attachment shall be able to obtain a minimum cross-sectional area of 0.5 m2 [17].	Reaching the mentioned cross-sectional area will exemplify the attachments' ability to utilize drag forces in LEO.	Test, Analysis	Measurements of cross-sectional area

Nathan Mulford, Structures Lead

4.0 Level 1 System Requirements

Requirement #	Requirement Text	Requirement Rationale	Verification Method	Verification Strategy
SYS.05	The attachment shall be able to fit within the NanoRacks [13] CubeSat Deployer while integrated with a CubeSat.	Compatibility with the NanoRacks [13] CubeSat deployer allows for the attachment to be used on diverse applications and missions.	Inspection, Demonstration	A model of the adapter will be manufactured and fitted to the attachment.
SYS.06	The attachment shall be within a total mass of 2.66 kg. [18]	To comply with CubeSat launcher standards the attachment must not exceed a specified weight.	Inspection	Measure the mass of the entire attachment.
SYS.07	The magnetic signature of the attachment shall be provided to the stakeholder.	Provision of the measured magnetic signature will allow for the operators of the parent CubeSat to calibrate necessary equipment to account for the attachments magnetic signature.	Test	Materials will be selected to minimize their magnetic signature; an analysis will be conducted to quantify said magnetic signature.
SYS.08	The attachment's power consumption shall be no more than 20 Watts. [20]	The power used by the attachment should not exceed the unused power of the parent CubeSat, so it does not interfere with mission operations.	Test, Analysis	A test will be conducted in order to determine electrical current used in deployment and retraction operations.

Evan Thompson, Mechatronics

5.1 System Design

- Full Design Compacted within 2U
- Single Actuator
- Booms and Sail Deploy using stored energy
- Total mass at 2kg
- 0.5 m^2 total sail area
- Capable of deorbit from 400 km in 12 days

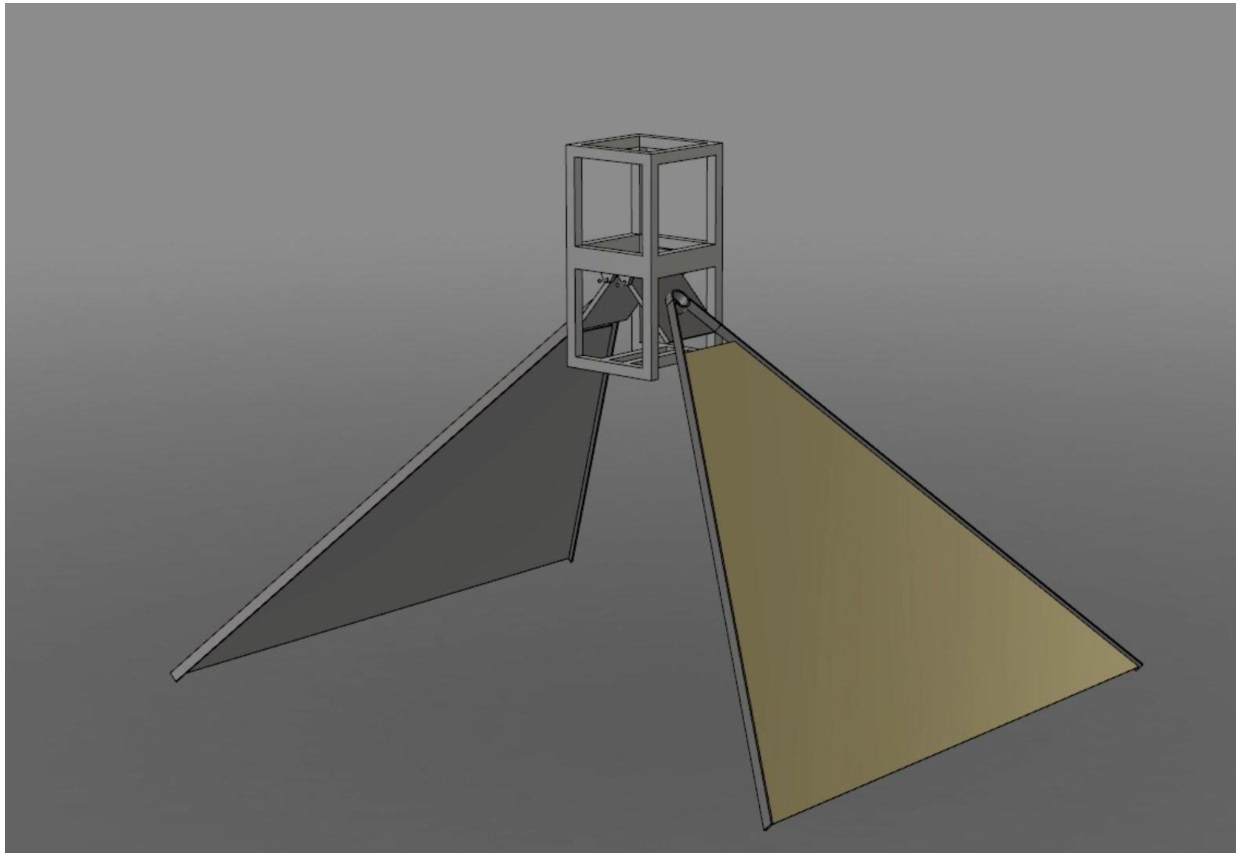
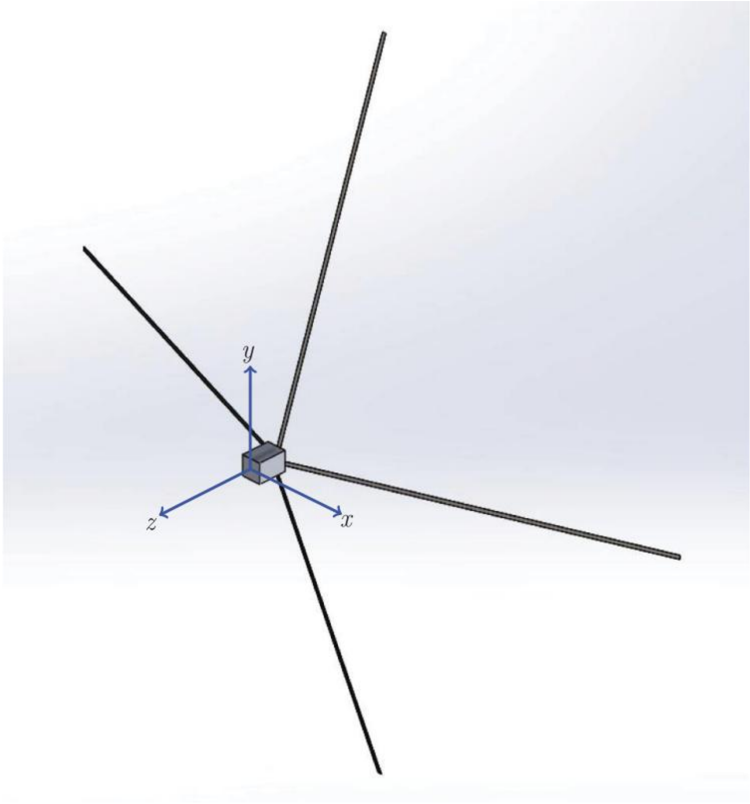


Image will be updated to latest full CAD model with dimensions as we approach PDR.

Liam Pettit, Project Manager

5.1.1 System Design Approach and Alternatives Considered

- Dr. Rios' previous design concept (D3 System)
  - Retractable tape booms – Fits in 1U
  - 4 Actuators
  - Complex Deployment/Retraction
- A design like above concept but with added sail between booms
  - Shorter Booms but still retractable
  - 4 Actuators
- One time deployment booms with sail between them
  - Two variations considered, telescoping booms vs tape spring
  - Full Sail Assembly can rotate 0°- 90°
  - 1 Actuator



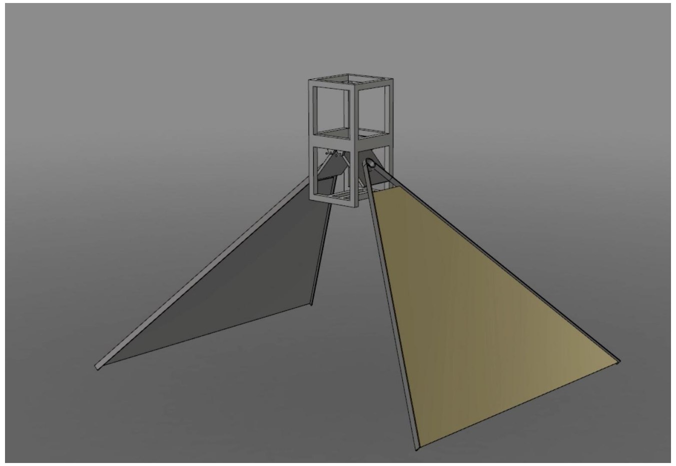
D3 System – Camilo A. Riano, R, Et. Al [#]

5.1.1 System Design Approach and Alternatives Considered

System Design - Pugh Matrix					
			Solution Alternatives		
Concept Selection Legend Better + Same S Worse - **Key Criteria**	***Importance Rating (1-5)***	Dr. Rios' D3 System	**Simlair to Dr. Rios D3, sail added between booms**	**Single Deployment with Tape Springs - Sail Assembly Rotates**	**Single Deployment with Telescoping Booms - Sail Assembly Rotates**
Price	**3**		-	S	S
Design Simplicity (# of actuators, moving parts, etc)	**5**		-	-	-
Ability to Obtain Area	**5**		+	+	+
Ability to be Fully Contained before Deployment	**5**		S	S	S
Ability to be Reduce CSA	**4**		S	-	-
Frame Compatibility	**5**		S	S	S
Deployment/Retraction Reliability	**5**		-	+	+
Ability to Achieve Passive Stability	**4**		S	+	+
Overall Weight	**3**		+	+	+
		Sum of Positives	2	4	4
		Sum of Negatives	3	2	2
		Sum of Sames	4	3	3
		Weighted Sum of Positives	8	17	17
		Weighted Sum of Negatives	13	9	9
		TOTALS	**-5**	**8**	**8**

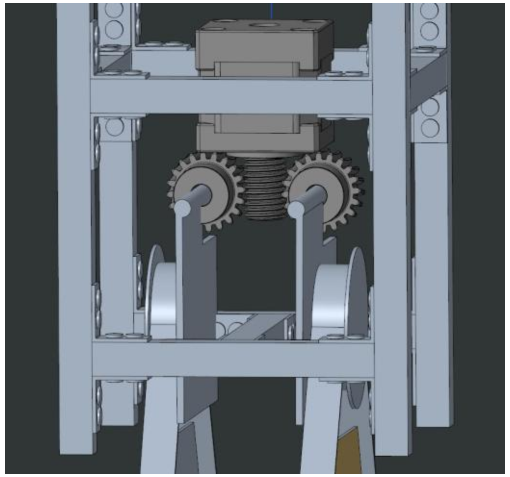
Liam Pettit, Project Manager

5.1.3 A.S.T.R.A Design Evolution

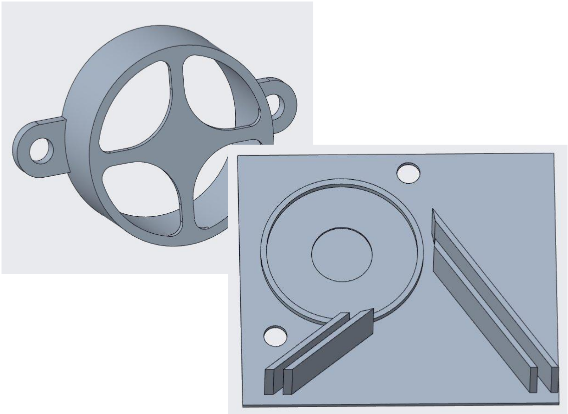


First initial design concept

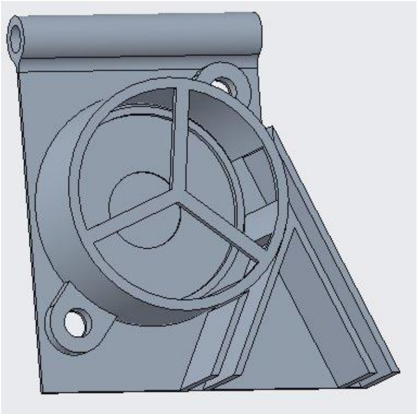
Frame Development



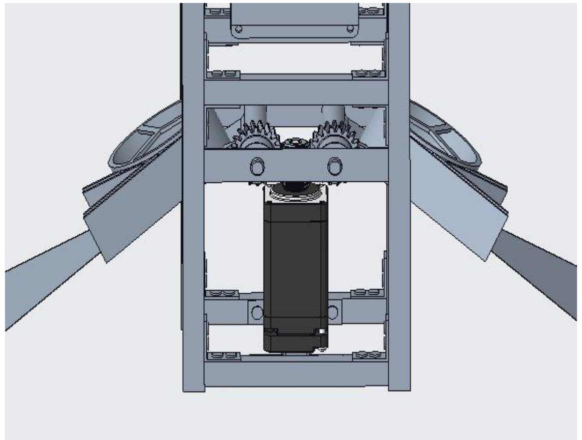
Rotating Assembly Development



Base Plate Early Prototyping



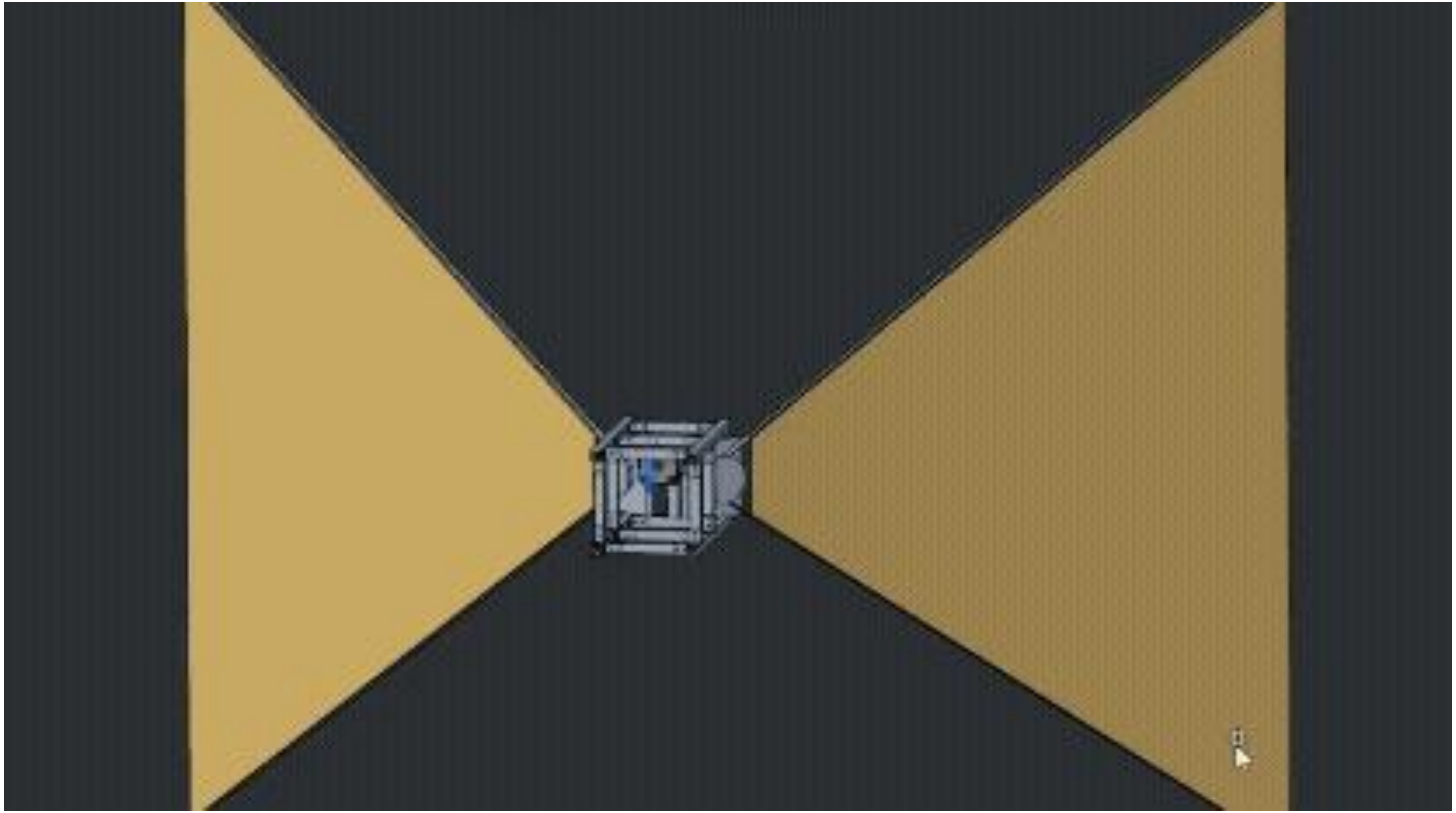
Full Base Plate initial Prototype



Integration

Liam Pettit, Project Manager

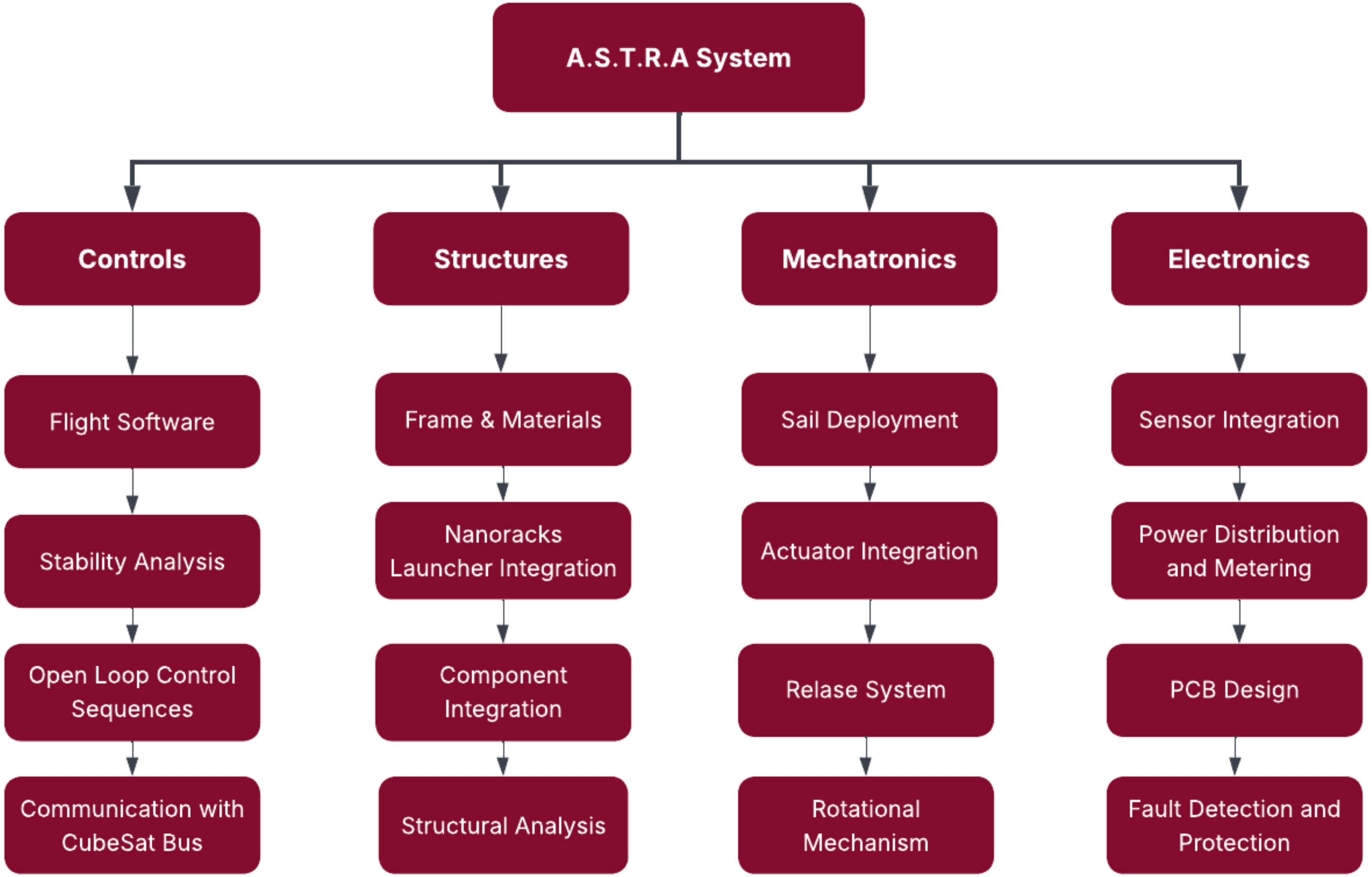
5.1.3 Full System Deployment Animation



More up to date animation will be placed here.

Morgan Lee, Systems Engineer

5.2 System Architecture



Morgan Lee, Systems Engineer

6.1.1 Structures Subsystem Requirements

Requirement #	Requirement Text	Parent Requirement	Requirement Rationale	Verification Method	Verification Strategy
STR.01	The design shall have a minimum factor of safety of 1.5.	OBJ.03	A minimum factor of safety of 1.5 ensures the design can withstand all loads and conditions consistent with launch and deployment conditions.	Analysis	The factor of safety will be calculated and verified through simulations.
STR.02	The frame shall be able to withstand stresses consistent with launch conditions.	OBJ.03	The system must be able to function after loading from increased G-forces during launch.	Analysis	Perform stress analysis consistent to launch loading to demonstrate structural integrity.
STR.03	The team shall provide a simulation that proves the device will withstand vibrations consistent with launch conditions.	OBJ.03	The design must survive vibrations in launch conditions to function reliably in orbit.	Test	Simulate vibrations consistent with launch conditions in FEA simulations.
STR.04	The design shall be able to withstand 13,500 drag modulation cycles.	OBJ.03	Cyclic fatigue testing ensures reliable and consistent repeatable deployment and modulation.	Analysis	Utilize FEA software to simulate cyclic loading conditions.

Nathan Mulford, Structures

6.1.1 Structures Subsystem Requirements

Requirement #	Requirement Text	Parent Requirement	Requirement Rationale	Verification Method	Verification Strategy
STR.05	The design shall be able to survive all stresses induced from initial deployment.	OBJ.03	Survival of all induced stresses during initial deployment ensures the design will later be able to modulate drag.	Analysis	Utilize FEA software to simulate stresses induced from initial deployment.
STR.06	The frame shall be fully contained in a 2U (10 x 10 x 20 cm) volume, with the design being fully contained.	SYS.05	Proving the design fits in a 2U ensures that the design fits in the ISISPACE launch adaptor.	Inspection	Visually measuring that the frame does not exceed the 2U (10 x 10 x 20 cm) volume, with the design being fully contained.
STR.07	The mass of the frame shall not exceed 0.3 kilograms.	SYS.08	A mass budget for the supporting structure allows for mass to be allocated to other subsystems.	Inspection	Weigh the model and demonstrate the mas in CAD.

Alvaro Cameo, Structures

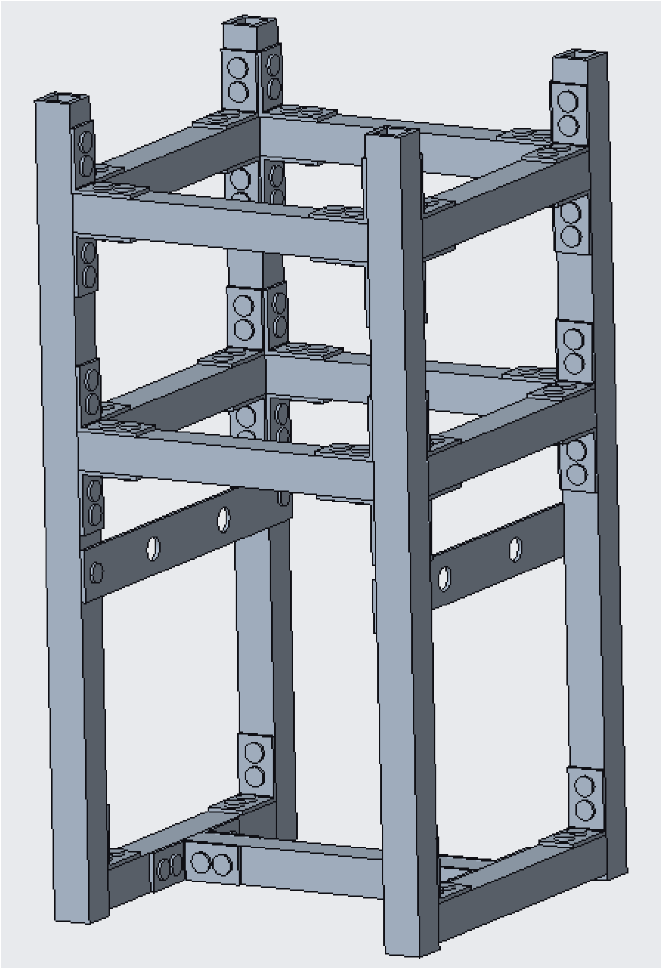
6.1.2 Structures Trade Study: Frame Materials

Frame Material Selection	Weight	Aluminum 6061-T6		Aluminum 7075-T6		CFRP		Stainless Steel 316L	
		Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Cost	20%	5	1	4	0.8	1	0.2	3	0.6
Fabrication Ease	10%	5	0.5	4	0.4	2	0.2	2	0.2
Density	20%	4	0.8	4	0.8	5	1	1	0.2
Strength	15%	1	0.15	3	0.45	5	0.75	3	0.45
Thermal Range	10%	5	0.5	5	0.5	3	0.3	5	0.5
Magnetic Signature	10%	5	0.5	5	0.5	5	0.5	3	0.3
Thermal Conductivity	15%	5	0.75	4	0.6	1	0.15	1	0.15
Total Score	100%		**4.2**		**4.05**		**3.1**		**2.4**

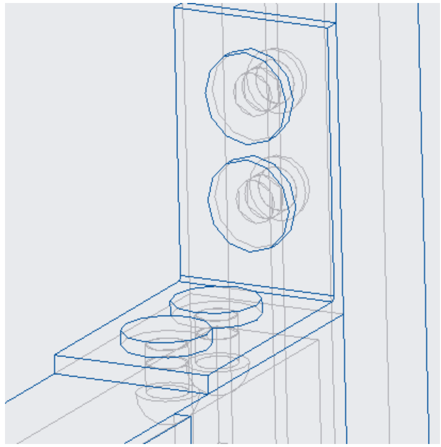
- Aluminums outperform steel and CFRP in most categories
- Al6061-T6 was chosen because of its low cost and fabrication ease

Nathan Mulford, Structures

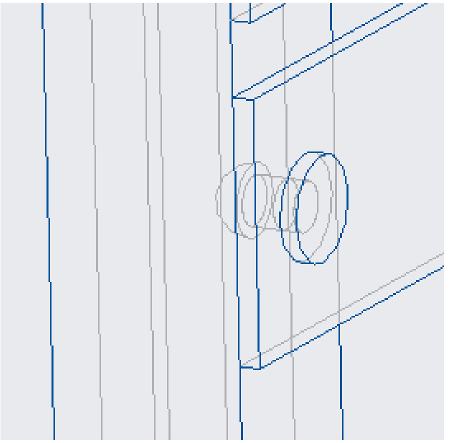
6.1.3 Frame Design & Assembly



Full Assembled Frame



L-Shaped Connection



Vertical Connection

STR.07	The mass of the frame shall not exceed 0.3 kilograms.

Subsystem Requirement STR.07

Component Type	90 Degree Angles	Long Rectangular Tubes	Short Rectangular Tubes	Rivets	Horizontal Plate
Required Number / Length	40 x 0.03125 ft	4 x 0.656168 ft = 2.63 ft	11 x 0.265583 ft = 2.93 ft	2 x 164	2 x 0.3281 ft x 0.04167 ft
Purchasing Number	1 x 2ft	1 x 6ft		2 x 250	0
Price	5.45 $	21.29 $		25.46 $	HSDC
Total Price	52.20 $				

- Extremely affordable frame
- Estimated total mass is 0.28188 kg, displaying virtual compliance Subsystem Requirement STR.07

Alvaro Cameo, Structures

6.1.5.1 Structures Testing: FEA – Frame Launch Loading

Table 4.3.1-1: Launch Load Factors Envelope

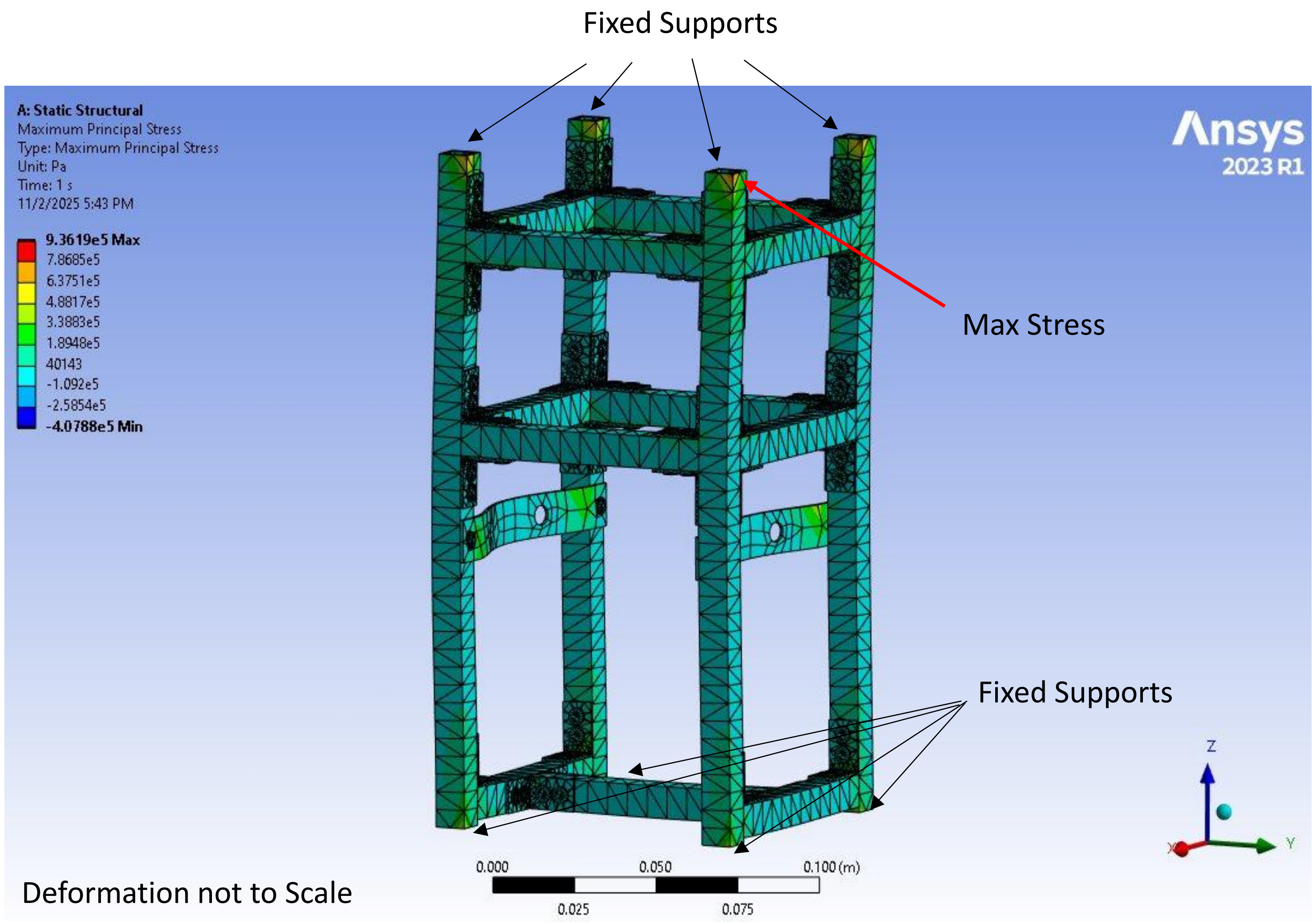
	Nx (g)	Ny (g)	Nz (g)	Rx (rad/sec^2)	Ry (rad/sec^2)	Rz (rad/sec^2)
Launch	+/- 7.0	+/- 4.0	+/- 4.0	+/- 13.5	+/- 13.5	+/- 13.5

Note: The RSS of Ny and Nz is +/-1.8 g, which can be applied one axis at a time in combination with the Nx load.

Requirement from NanoRacks CubeSat Deployer (NRCSD) Interface Definition Document (IDD) [2]

- NanoRacks outlines specific launch load conditions that the design must survive
- This includes gravitational loading and angular accelerations

6.1.5.1 Structures Testing: FEA – Frame Launch Loading



Material:	Aluminum 6061-T6
Yield Stress:	276 MPa
Poisson's ratio:	0.33
Young’s Modulus:	68.9 GPa
Max Stress:	0.936 MPa
Max Deformation:	0.0028 mm
Nodes:	135109
Elements:	55986

Factor of Safety: 294.81 (STR.02)

Because the frame must comply with launcher compatibility specifications and enable component mounting, it cannot easily be optimized for a lower factor of safety.

Nathan Mulford, Structures

6.1.5.2 Structures testing: FEA – Rail Static Loading

4.3.5 Integrated Loads Environment

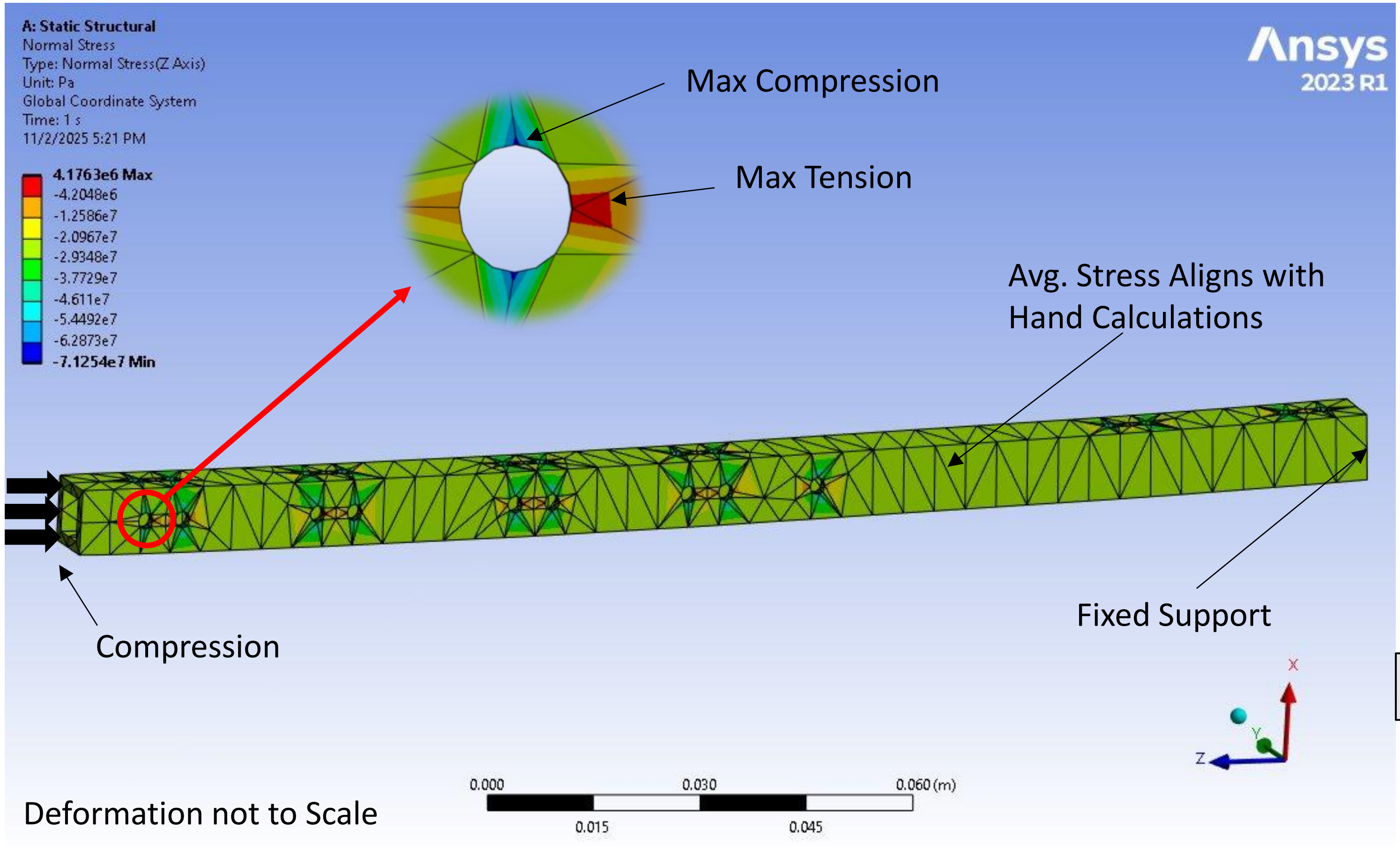
The CubeSat shall be capable of withstanding a force of 1200N across all rail ends in the Z axis.

Note: This number is conservative and will be refined based on qualification testing and further analyses by NanoRacks.

Requirement from NanoRacks CubeSat Deployer (NRCSD) Interface Definition Document (IDD) [2]

- NRCSD outlines an additional load requirement for the rails
- Assume worst case of 1200 N on a single rail
- Verify using FEA and hand calculations

6.1.5.2 Structures testing: FEA – Rail Static Loading



Material:	Aluminum 6061-T6
Yield Stress:	276 MPa
Poisson's ratio:	0.33
Young's Modulus:	68.9 GPa
Max Stress:	71.25 MPa (compression)
Max Deformation:	0.075 mm
Nodes:	4199
Elements:	1863

$$\sigma_{avg} = \frac{F}{A} = \frac{1200\ N}{50.4\ mm^2} = 23.81\ MPa$$

Factor of Safety: 3.87 (STR.02)

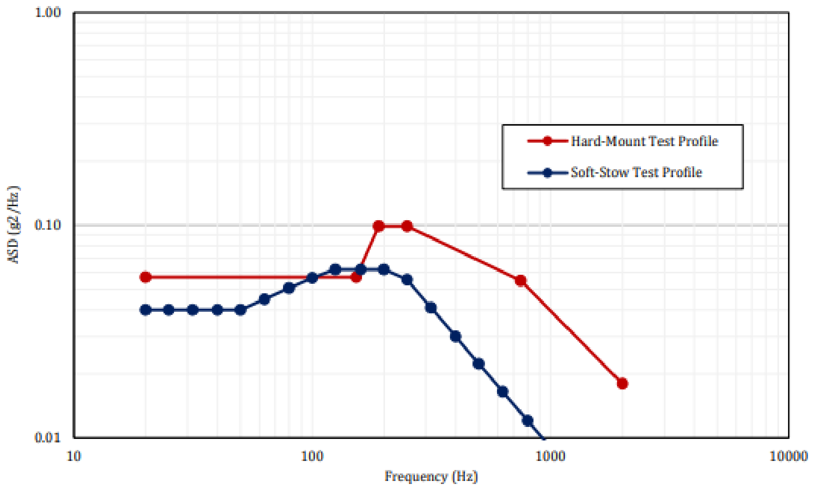
Because the rail geometry must comply with launcher compatibility specifications, it cannot easily be optimized for a lower factor of safety.

Nathan Mulford, Structures

6.1.5.3 Structures testing: FEA – Random Vibrations

4.3.2.1 Random Vibration Test Options

Since the NRCSD launches in the soft-stow configuration (wrapped in bubble wrap and secured in a foam-lined CTB, as outlined in Section 3.4.2.7), the satellites contained within the NRCSD are exposed to a soft-stow random vibration launch environment. This allows the payload developer to test in a flight equivalent configuration if desired. The acceptable random vibration test options for CubeSat payload developers are outlined below.



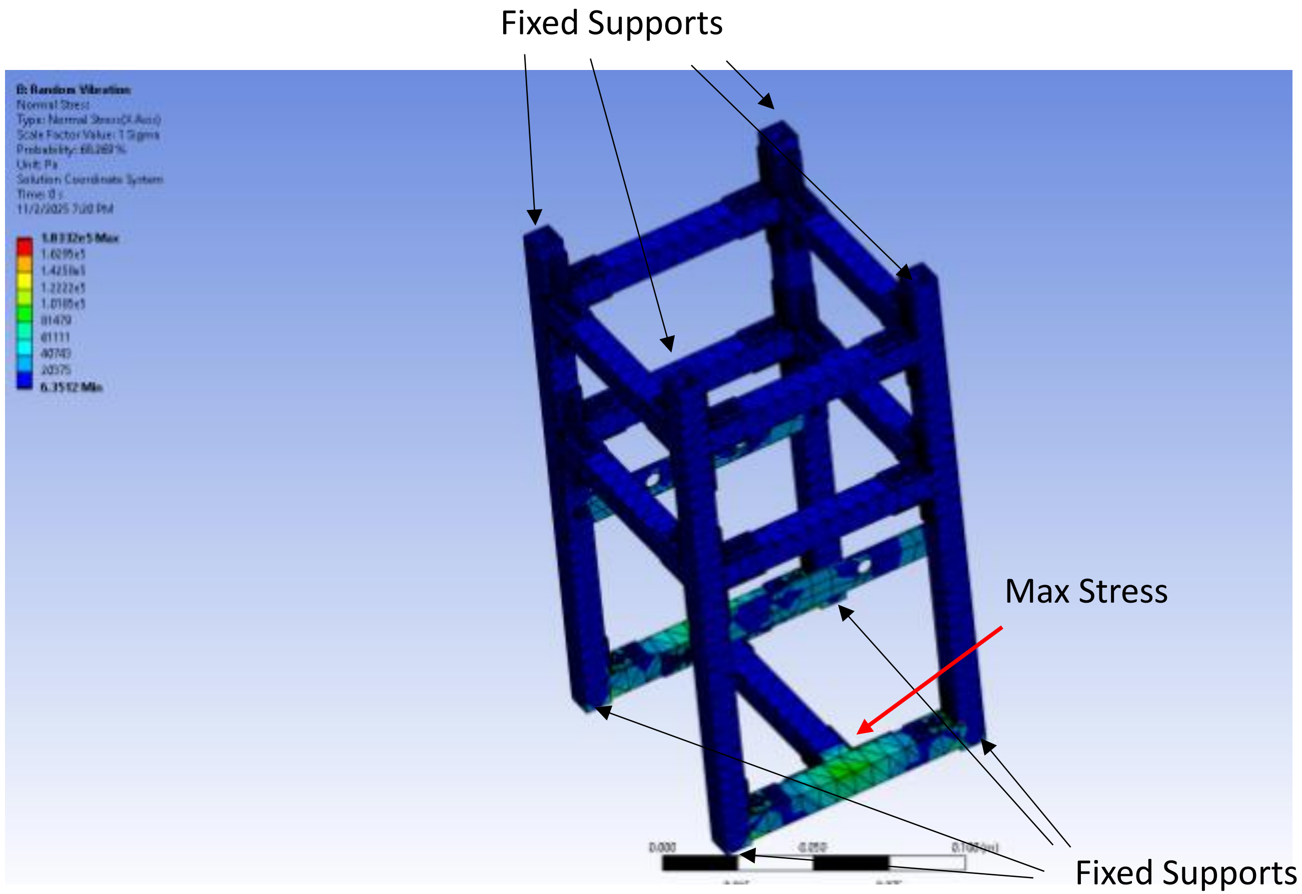
Hard-Mount Test Profile	
Frequency (Hz)	**ASD (g^2/Hz)**
20	5.700E-02
153	5.700E-02
190	9.900E-02
250	9.900E-02
750	5.500E-02
2000	1.800E-02
grms	**9.47**
Duration (sec)	**60**

Figure 4.3.2.1-1: Random Vibration Test Profiles

Requirement from NanoRacks CubeSat Deployer (NRCSD) Interface Definition Document (IDD) [2]

- NanoRacks outlines specific random vibrations that the design must survive
- Selected test profile is Hard-Mount

6.1.5.3 Structures testing: FEA – Random Vibrations

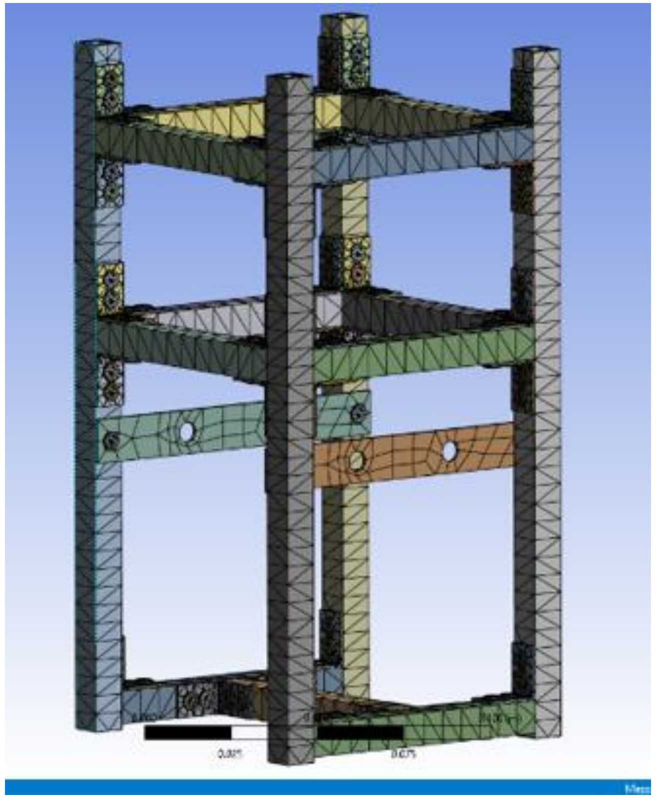


FEA Results for Random Vibrations Testing under Hard-Mount Test Profile

Material:	Aluminum 6061-T6
Yield Stress:	276 MPa
Poisson's ratio:	0.33
Young’s Modulus:	68.9 GPa
Avg Stress (1σ):	0.183.3 MPa
Max Stress:	0.550 MPa
Nodes:	135109
Elements:	55986

Factor of Safety: 501.85 (STR.02)

6.1.5.4 Structures testing: FEA – Modal Vibrations



Mesh for Modal Survey of ASTRA Attachment

Mode	Frequency [Hz]
1	801.44
2	807.57
3	1332.4
4	1341.3
5	1558.2
6	1886.7
7	2125.9
8	2176.2
9	3172
10	3174.1

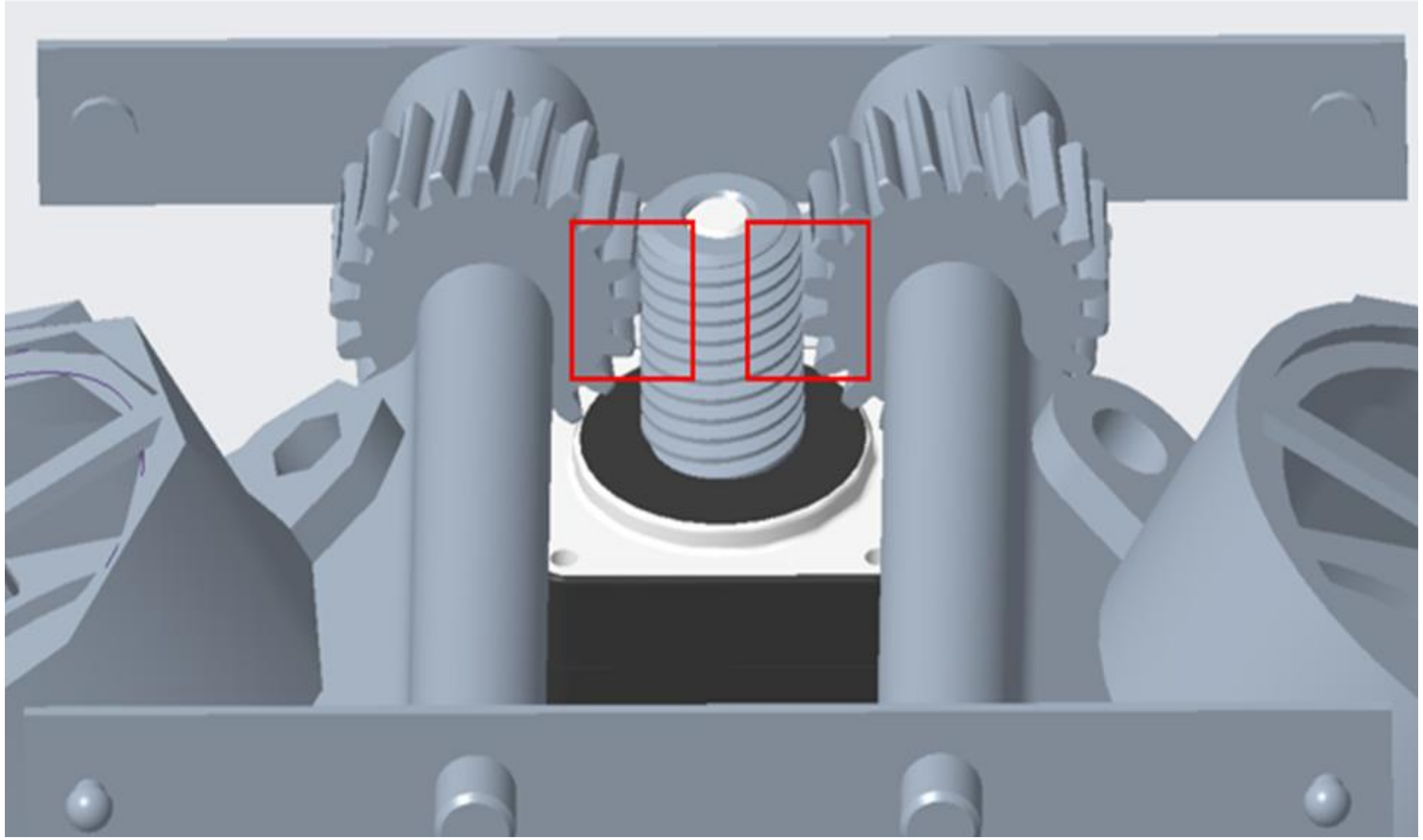
First 10 Natural Frequencies of ASTRA Attachment

Material:	Aluminum 6061-T6
Yield Stress:	276 MPa
Poisson's ratio:	0.33
Young's Modulus:	68.9 GPa
Min Frequency:	801.44 Hz
Nodes:	135109
Elements:	55986

Nasa states: "The low-frequency launch environment is typically defined up to 100 hertz (Hz)" [x]

Alvaro Cameo, Structures

6.1.5.5 Structures testing: FEA – Drag Modulation Cycles



Modulation Mechanism CAD Model

- Cyclic Fatigue Requirement: 13,500 Cycles
- Failure is most likely at gear contact points
- Stress amplitude will be determined through FEA
- Basquin's Law will be used to determine the cycles to failure

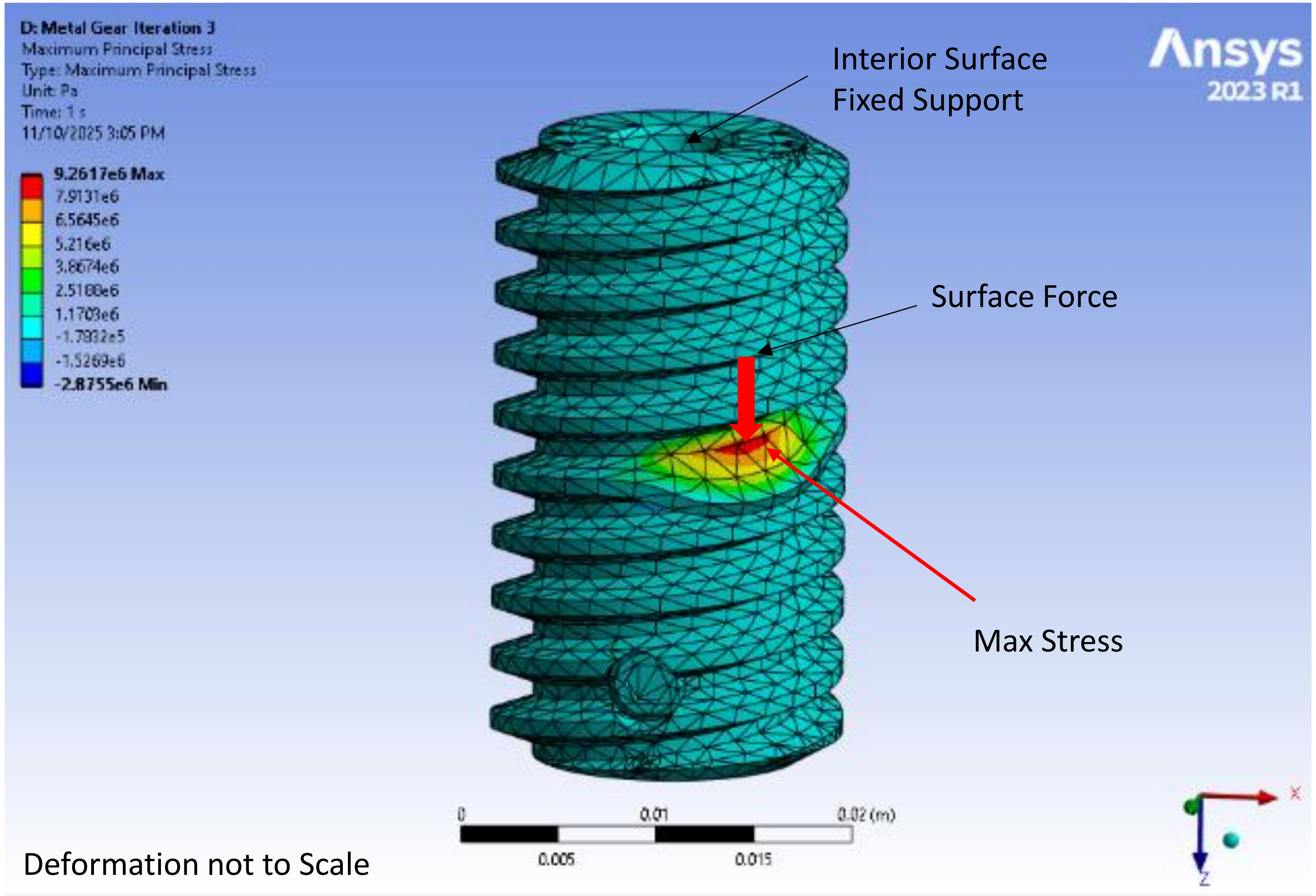
$$F = \frac{\tau}{r} = \frac{0.14\ Nm}{0.008\ m} = 17.5\ N$$

$$F_{eff} = \frac{F}{\sin(\alpha)} = \frac{17.5\ N}{\sin(20°)} = 51.17\ N$$

Handbook of Gear Design [12]

Nathan Mulford, Structures

6.1.5.5 Structures testing: FEA – Drag Modulation Cycles



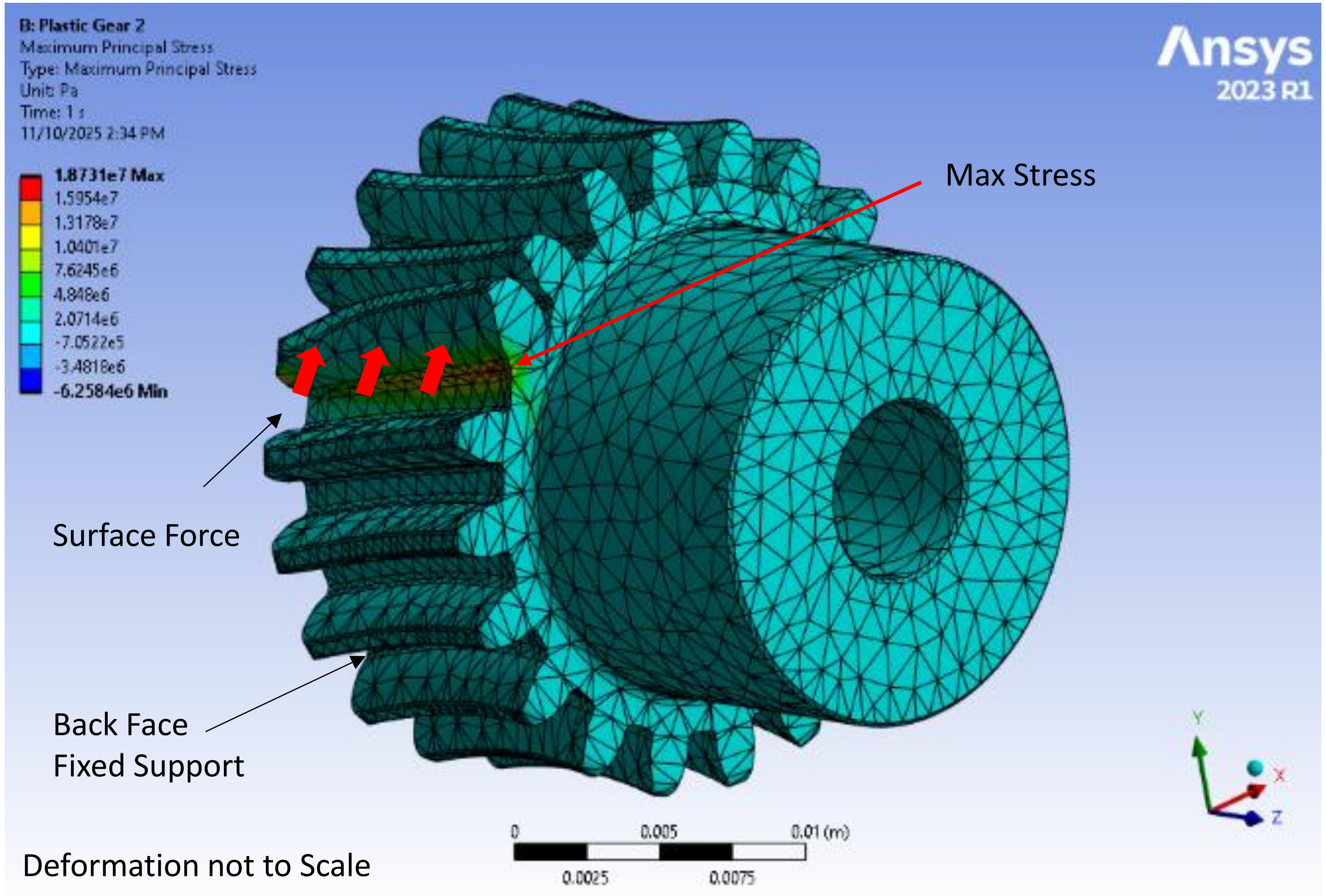
Material:	303 Stainless Steel
Yield Stress:	205 MPa
Young's Modulus:	193 GPa
Fatigue Strength Coefficient:	950 MPa
Fatigue Strength Exponent:	-0.095
Max Stress:	9.26 MPa (Tension)
Min Stress:	-2.88 MPa (Compression)
Nodes:	16918
Elements:	8909

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} = \frac{(9.2617\ MPa) - (-2.8755\ MPa)}{2} = 6.07\ MPa$$

Mechanical Engineering Design [13]

Nathan Mulford, Structures

6.1.5.5 Structures testing: FEA – Drag Modulation Cycles



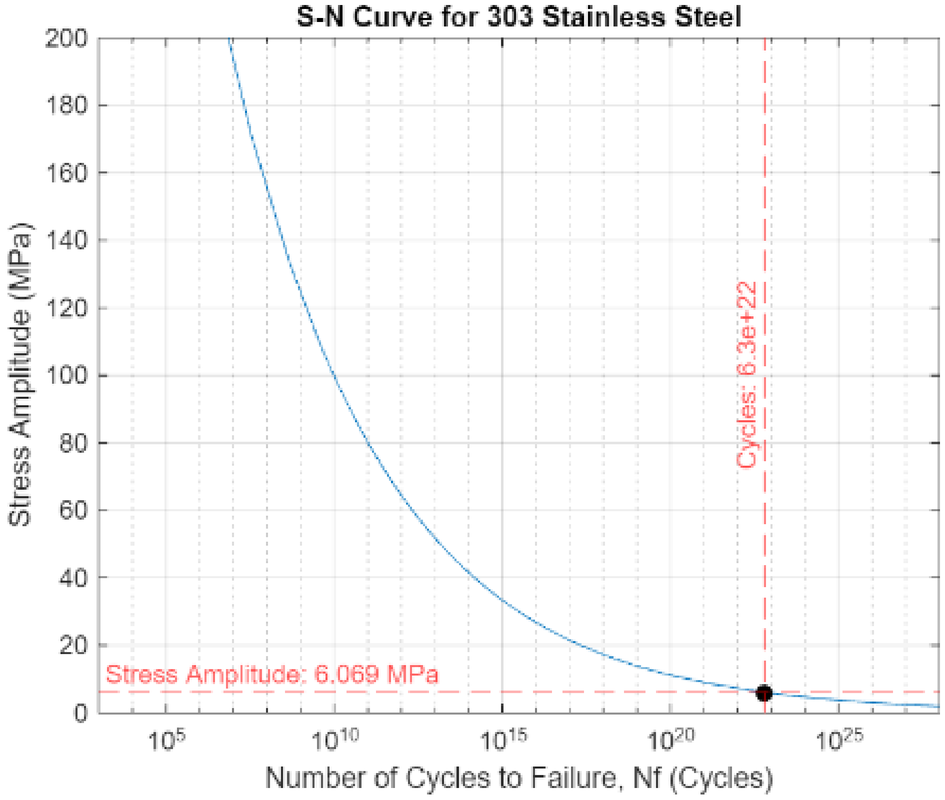
Material:	PA66 (Nylon)
Yield Stress:	70 MPa
Young's Modulus:	3.3 GPa
Fatigue Strength Coefficient:	31.45 MPa
Fatigue Strength Exponent:	-0.016
Max Stress:	18.73 MPa (Tension)
Min Stress:	-6.26 MPa (Compression)
Nodes:	42979
Elements:	24210

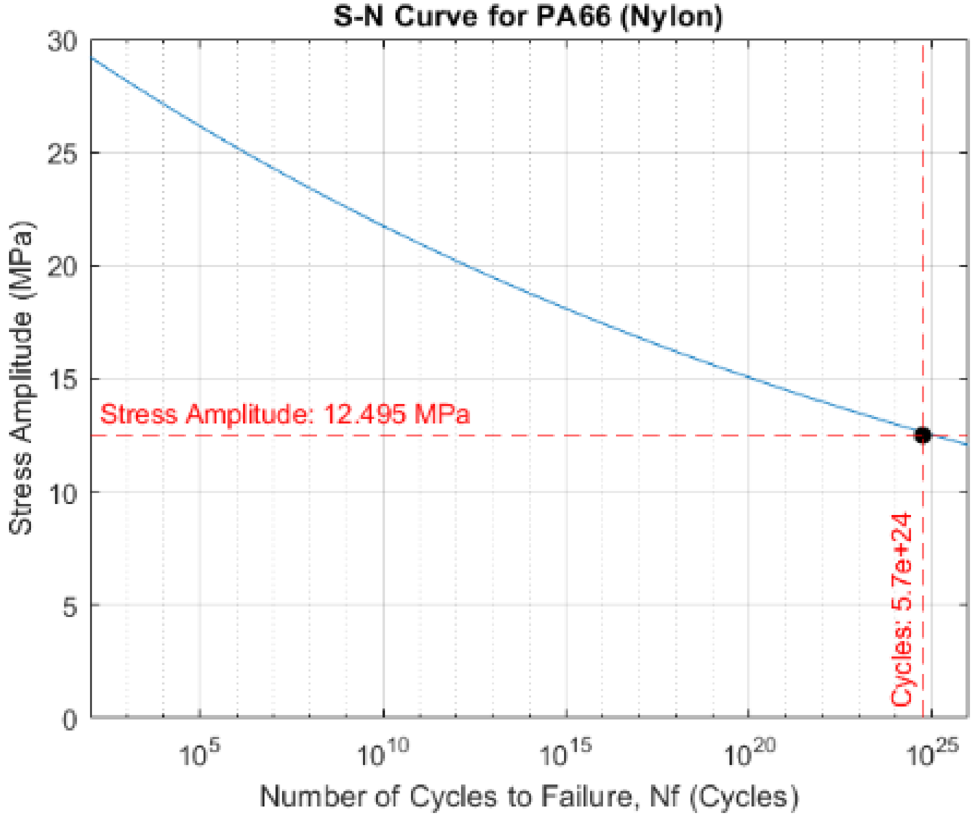
$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} = \frac{(18.731\ MPa) - (-6.258\ MPa)}{2} = 12.49\ MPa$$

Mechanical Engineering Design [13]

Nathan Mulford, Structures

6.1.5.5 Structures testing: FEA – Drag Modulation Cycles





$$N_f = \frac{1}{2}\left(\frac{\sigma_a}{\sigma_f{}'}\right)^{\frac{1}{b}} = \frac{1}{2}\left(\frac{6.0686}{950}\right)^{\frac{1}{-0.095}} = 6.32 * 10^{22}\ cycles$$

$$N_f = \frac{1}{2}\left(\frac{\sigma_a}{\sigma_f{}'}\right)^{\frac{1}{b}} = \frac{1}{2}\left(\frac{12.49}{31.45}\right)^{\frac{1}{-0.016}} = 5.66 * 10^{24}\ cycles$$

Equations from Mechanical Engineering Design [13]

6.2 Mechatronics Subsystem Requirements

Requirement #	Requirement Text	Parent Requirement	Requirement Rationale	Verification Method	Verification Strategy
MECH.01	The mechatronics subsystem shall be able to survive a temperature range of -10 °C to 50 °C.	OBJ.03	The subsystem must be able to operate after experiencing int ernal temperatures consistent with LEO.	Analysis	The team shall perform analysis via ANSYS Maxwell and Mechanical on the motor and internal mechanisms to ensure reliability in the expected temperature range
MECH.02	The mechatronics subsystem shall be able to survive 4 thermal cycles of -10 °C to 50 °C of 2700 seconds.	OBJ.03	While in orbit, the attachment will receive a cyclical heating, consistent with its orbital period	Analysis	The team shall perform analysis via ANSYS Mechanical on the internal mechanisms to ensure longevity under thermal cycles
MECH.03	Each stored drag sail shall fit within a 2U space within the attachment.	SYS.01	The subsystem should not exceed the allocated volume allowances.	Inspection	Inspect the physical prototype to ensure the sail meets volume requirements.
MECH.04	The attachment shall reach its maximum CSA from its minimum CSA in less than 150 seconds.	SYS.04	The connected CubeSat must be able to act multiple times within one orbit at 400km.	Test	Measure the time from the minimum to the maximum CSA.

6.2.1 Mechatronics Trade Studies

image

image

Actuation Method

Worm Gear Selected
- Chosen for simplicity due to few parts
- Vertical symmetry
- Volumetrically efficient

Gear Material

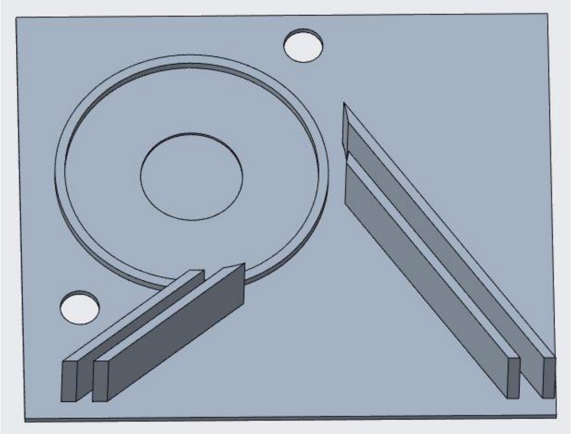
Nylon Selected
- Chosen primarily for its accessibility in terms of cost and customization of sizes
- Low strength and durability are less important for low loads and short missions
- No risk of cold welding

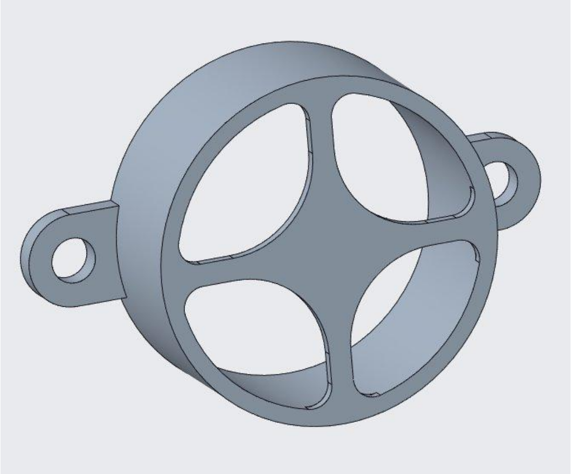
Stepper Motor

11HS2-00674-ME1K Selected
- Chosen for its smaller size, NEMA 11 vs 14
- Higher torque in favor of rotational speed
- Built-in encoder to simplify assembly

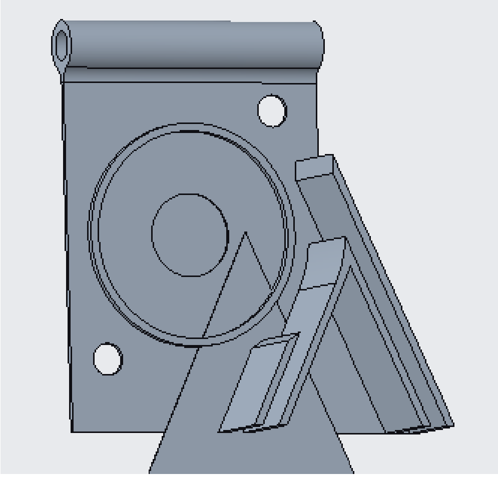
6.2.2.1 Deployer Design Evolution

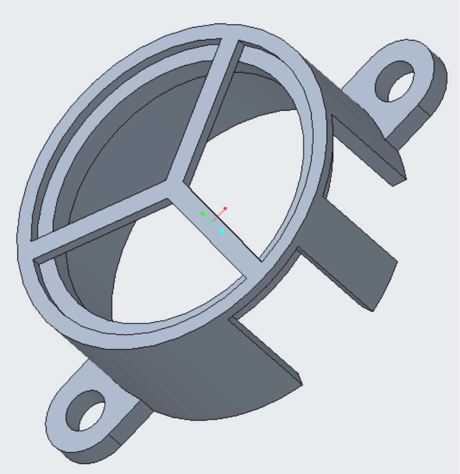
1st Prototype





2nd Prototype

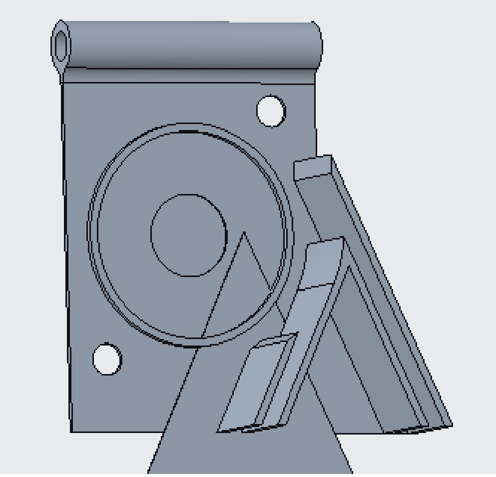


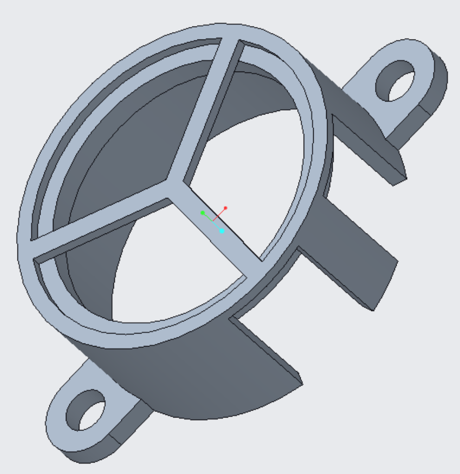


- Made changes to better integrate with CubeSat
- Set sail angle to 50 degrees for drag analysis
- Added a brake to the spool cover to slow deployment and reduce jamming

6.2.2.1 Deployer Design Evolution

2nd Prototype





- Reconfigured spools to center the sail
- Removed the retaining bar to increase the consistency of brake pressure and aid in winding
-

3rd Prototype

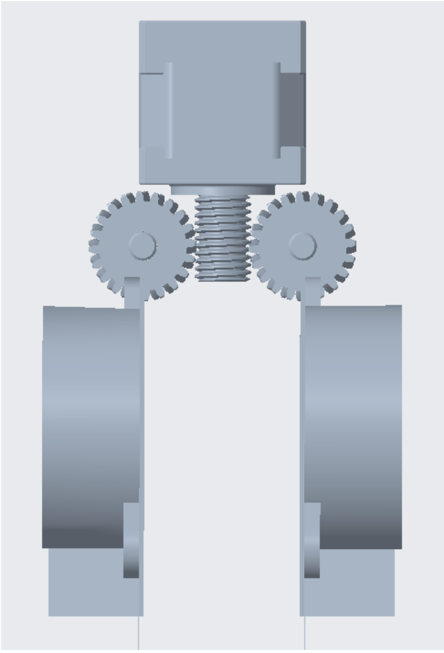
Small spool base

Small spool

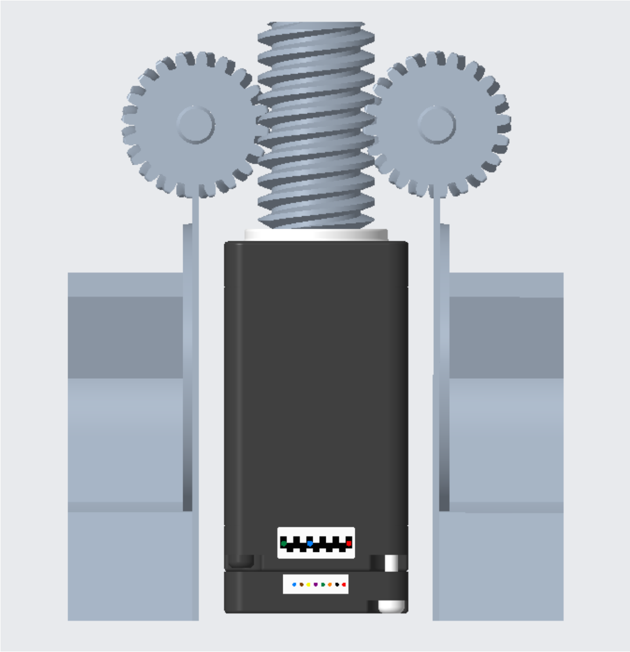
Small spool cover

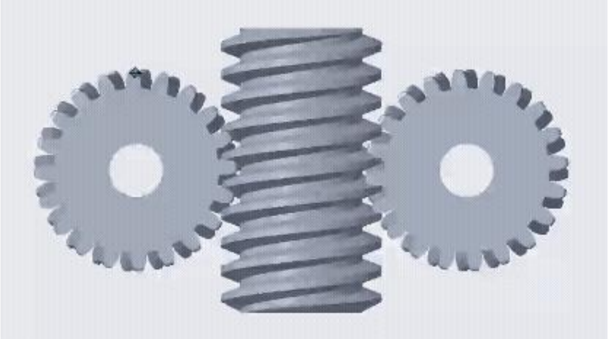
6.2.3 Actuation Design

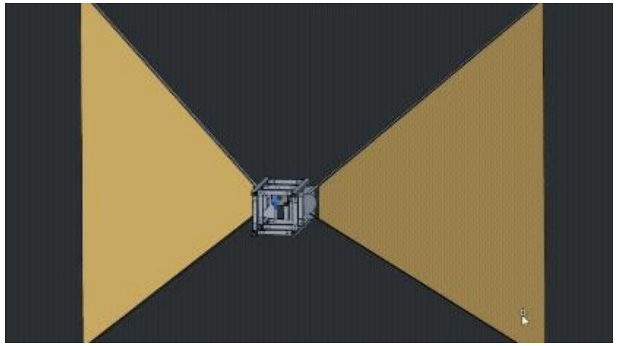
1st Iteration



2nd Iteration







Speed not to scale

- Moved stepper motor below
- Taller/thinner stepper motor
- Replaced worm gear
    - Better meshing and less slipping

6.2.4 Hand Calculations

- typed equations, free body diagram, from expected loads from gravity

6.3 Controls Subsystem Requirements

Requirement #	Requirement Text	Parent Requirement	Requirement Rationale	Verification Method	Verification Strategy
CS.01	The team shall provide software capable of rotating the attachment’s sails.	OBJ.01	Rotation of the devices sails through software input demonstrates viability to the proof of concept.	Analysis, Testing	Run actuation testing to ensure proper rotation corresponding to software input.
CS.02	The attachment’s code shall execute the deployment of the sails as a function of a user-inputted time.	OBJ.01	The deployment of the sails as a function of time aligns with industry-based orbital maneuvering and telemetry applications.	Analysis, Testing	Time actuation tests to ensure proper deployment time of the sails.
CS.03	The attachment’s code shall rotate the attachment's sails as a function of user-inputted time.	OBJ.01	The rotation of the sails as a function of time aligns with industry-based orbital maneuvering and telemetry applications.	Testing, Analysis	Time actuation tests to ensure proper rotation time of the actuators.

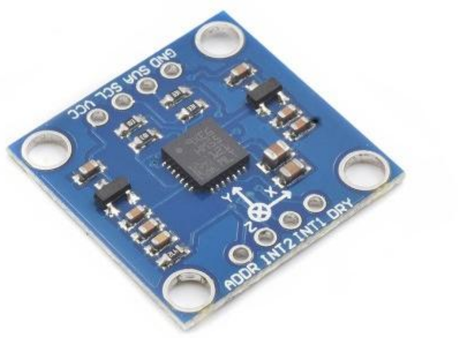
Cole Schumacher, Controls

6.3 Controls Subsystem Requirements

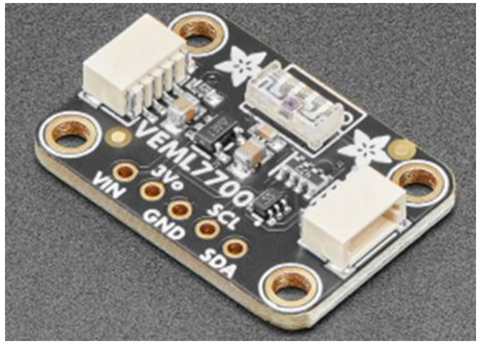
Requirement #	Requirement Text	Parent Requirement	Requirement Rationale	Verification Method	Verification Strategy
CS.04	The attachments code shall provide an algorithm that outputs the measured cross-sectional area within 0.0375 m^2 of the expanded drag sail, as a function of rotated angle.	SYS.03	The provision of a measurement algorithm supports possible mission-based data collection.	Inspection	Physically measure the area of the sails and compare with software output.
CS.05	The attachment shall have a minimum I2C clock speed of 400 Kbits/s with the Mockup CubeSat computer. [#]	SYS.03	Faster communication speed allows for lower response times between input and device activation.	Inspection, Analysis	Log the Baud rate of the system prior to usage of the OBC to ensure consistency.
CS.06	The attachments code shall execute a low-power functionality (sleep mode), per user unput.	ES.04	Enabling sleep mode as a function of user input aligns with industry like space vehicle functions.	Testing, Analysis	Run tests executing the respective command and measuring power consumption as a result.

Cole Schumacher, Controls

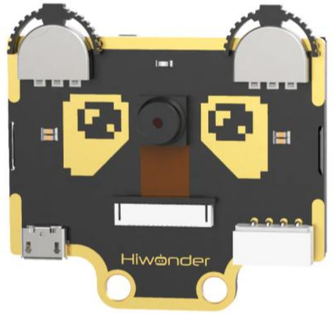
6.3.1 Controls Trade Study – Deployment Verification



Accelerometer [#]
Measures changes in acceleration during deployment



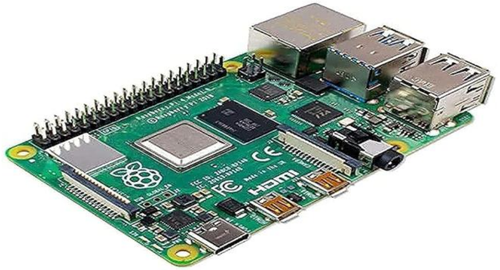
Sun Sensor [#]
Detects panel orientation using solar incidence



Camera [#]
Visually confirms deployment

- Evaluated using the priorities: Accuracy/Viability, Power, Cost, and Certainty of Full Deployment
- Sun Sensors had the highest total score (4.2). Chosen due to high accuracy, low power, and reliable deployment confirmation

6.3.1 Controls Trade Study CubeSat Flight Computer



Raspberry Pi 4 [#]

A low-cost, general-purpose single-board computer widely used for embedded and educational projects

Jetson Nano [#]

An NVIDIA single-board computer designed for high-performance computing and AI/vision processing.

Tinker Board 2S [#]

An ASUS single-board computer offering balanced performance and I/O for compact embedded applications.

- Highest weights: Cost, I2C/UART compatibility, and Power Consumption
- Raspberry Pi 4 scored highest (4.5). Chosen for best compatibility, low cost, and low power usage

6.3.1 Controls Design

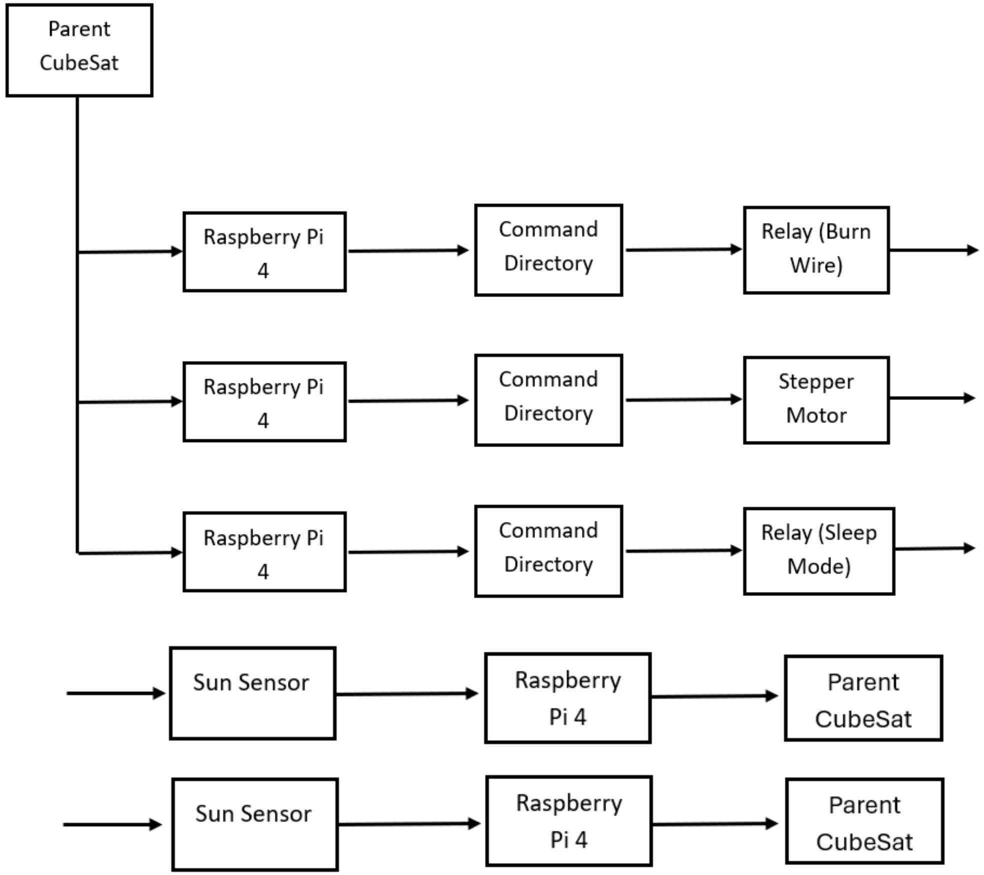
Associated Components

- Raspberry Pi 4
- Stepper Motor
- Sun Sensors
- Encoder (inclusive in motor)
- Relays

Key Functionalities

- Control of deployment
- Control of modulation (deployment angle)
- Sleep Mode
- Deployment Verification
- Sail angle feedback

Open- Loop Architecture



Cole Schumacher, Controls

6.3.3 Monte Carlo Simulation CD + Orbital Decay

- Analysis of full satellite (1U parent + 2U Attachment)
- Theory derived from thesis titled "Satellite Drag Analysis using Direct Simulation Monte Carlo (DSMC)" [5]
- Utilizes Sentman's Flat Plate theory derived to include influence of sail deployment angle
  - Accounts for molecular weight/speed of LEO atmosphere
- Monte Carlo portion runs for 20,000 cases with errors in area, mass, deployment angle, velocity, temperature, and diffusion.
- Utilizes NRLMSISE-00 Atmospheric Model

6.3.3 Monte Carlo Simulation CD + Orbital Decay

Initial Conditions and FBD:

$A_{attach.} = 0.5\ m^2$ $\sigma_{A_{sail}} = 0.02\ m^2$

$A_{parent} = 0.01\ m^2$

$M_{tot} = 3.33\ kg$ $\sigma_{M_{tot}} = 0.15\ kg$

$V_{rel.} = 7500\ \frac{m}{s}$ $\sigma_{V_{rel.}} = 150\ \frac{m}{s}$

$T_\infty = 300\ K$ $\sigma_{T_\infty} = 10\ K$

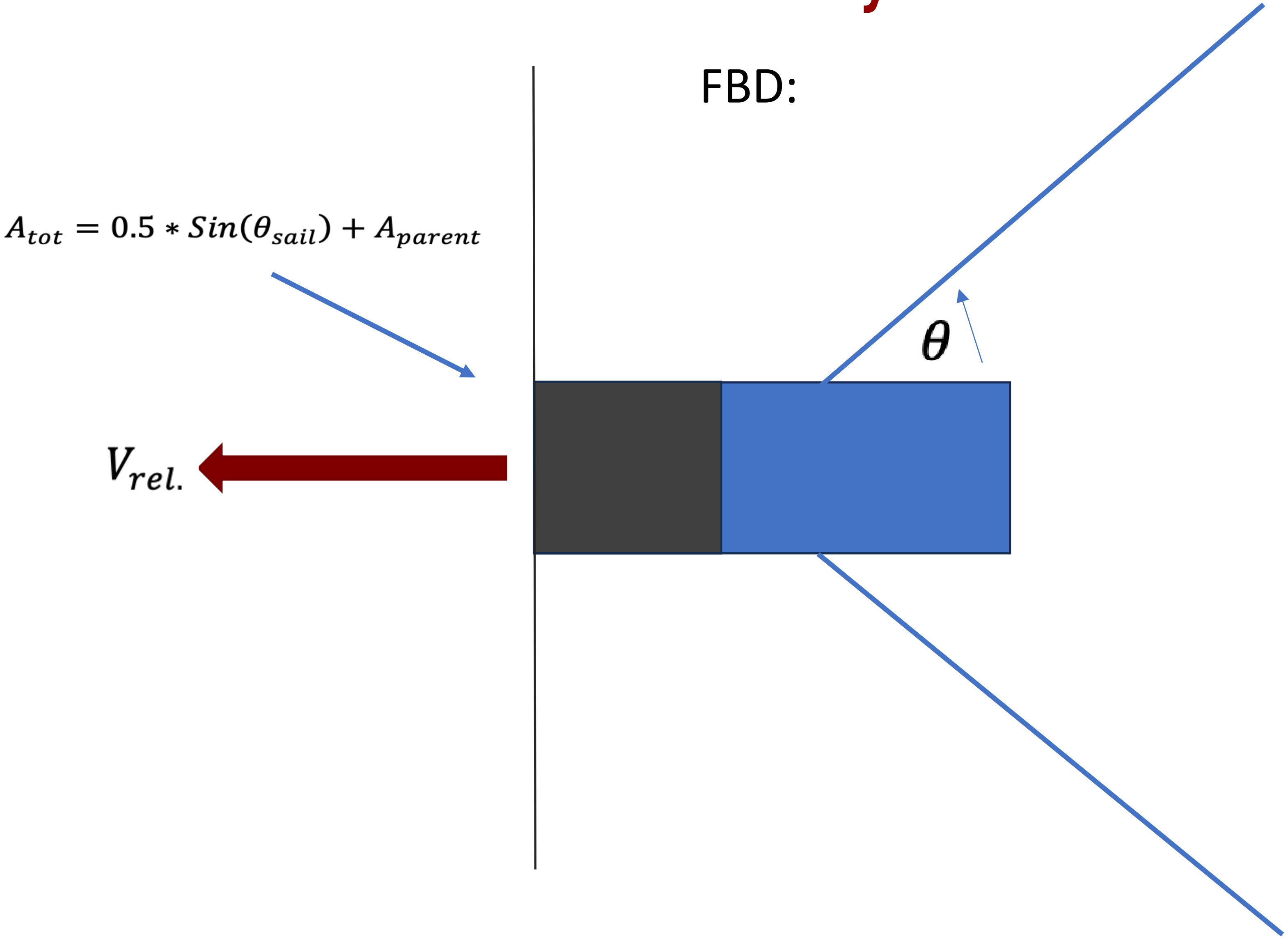
$T_w = 298\ K$ $\sigma_{T_w} = 10\ K$

$\alpha = 0.9$ $\sigma_\alpha = 0.05$

$\theta_{sail} = 0^\circ - 90^\circ$ $\sigma_{\theta_{sail}} = 2^\circ$

$H_{start} = 400\ km$, $H_{end} = 120\ km$, $\Delta H = 2\ km$

FBD:



6.3.3 Monte Carlo Simulation CD + Orbital Decay

Sample Calculation:

- Results line up with what is expected, Cd = 2.4
- Validates simulation results

Coefficient of Drag:

[5] $v_{mp} = \sqrt{\frac{2*k_B*T_\infty}{m_g}} = \sqrt{\frac{2*(1.38*10^{-23})*300}{(16*(1.66*10^{-27}))}} = 558.34\,\frac{m}{s}$

[5] $s = \frac{7500}{v_{mp}} = \frac{7500}{558.34} = 13.43$

[5] $T_k = (1-\alpha)*\left(\frac{m_g V_{rel.}^2}{3*k_b}\right) + \alpha * T_w = (1-0.9)*\left(\frac{\left(16*(1.66*10^{-27})\right)(7500^2)}{3*(1.38*10^{-23})}\right) + (0.9*298) = 3876.9\,K$

[6] $C_D(\theta) = \frac{2}{s\sqrt{\pi}} e^{-s^2*\sin^2(\theta)} + \frac{\sin(\theta)}{s^2}(1+2s^2)\,\mathrm{erf}(s*sin(\theta)) + \frac{\sqrt{\pi}}{s} * \sin^2(\theta) * \sqrt{\frac{T_k}{T_\infty}}$

$C_D(75°) = \frac{2}{(13.43)\sqrt{3.14}} e^{-13.43^2*\sin^2(75)} + \frac{\sin(75)}{13.43^2}(1+2(13.43)^2)(1) + \frac{\sqrt{3.14}}{13.14} * \sin^2(75) * \sqrt{\frac{3876.9}{300}} \approx 2.40$

Orbital Decay at 400km for one time step:

[5] $a = \frac{1}{2}\rho v^2 \frac{C_d A_{tot}}{m} = \frac{1}{2}(0.961*10^{-9})(7500)^2 * \left(\frac{2.40*(0.01+0.5*\sin(75))}{2.33}\right) = 0.014\,m/s^2$

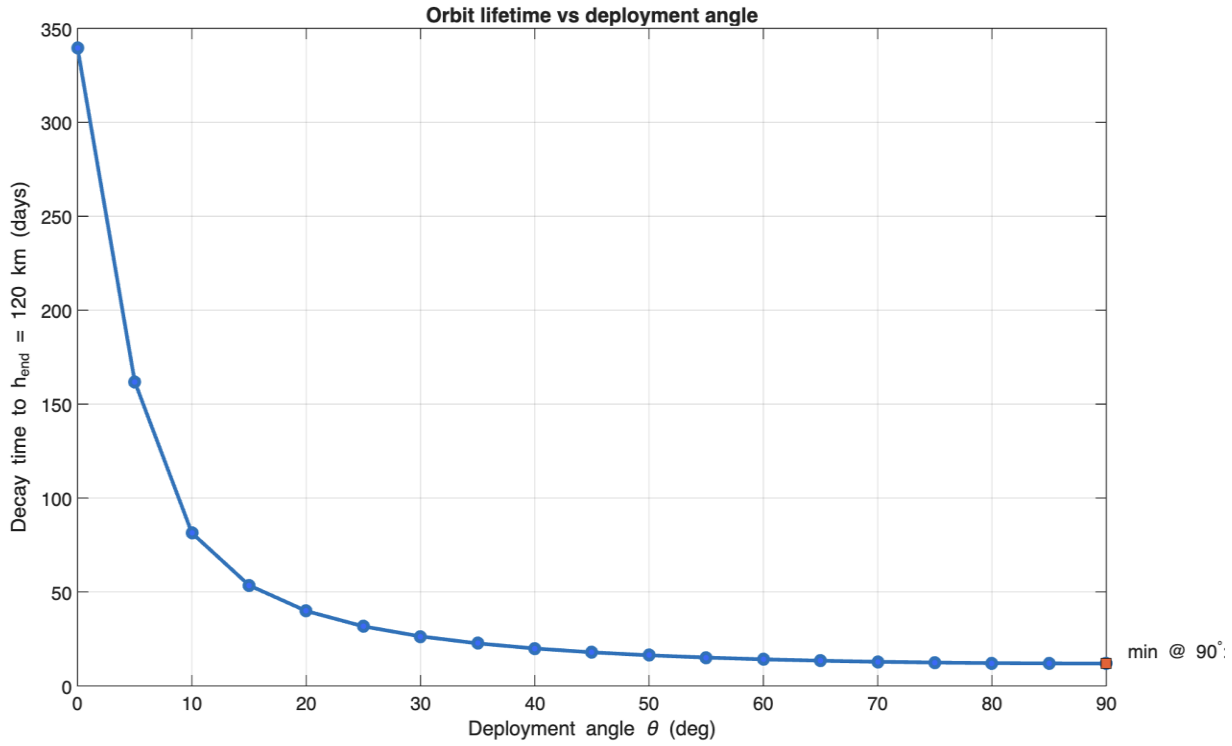
[5] $\dot{a} = -\rho\sqrt{\mu a}\left(\frac{C_d A_{tot}}{m}\right) = -(0.961*10^{-9})\sqrt{(3.98*10^{14})(6778137)}\left(\frac{2.40*(0.01+0.5*\sin(75))}{2.33}\right) = -0.034\,m/s$

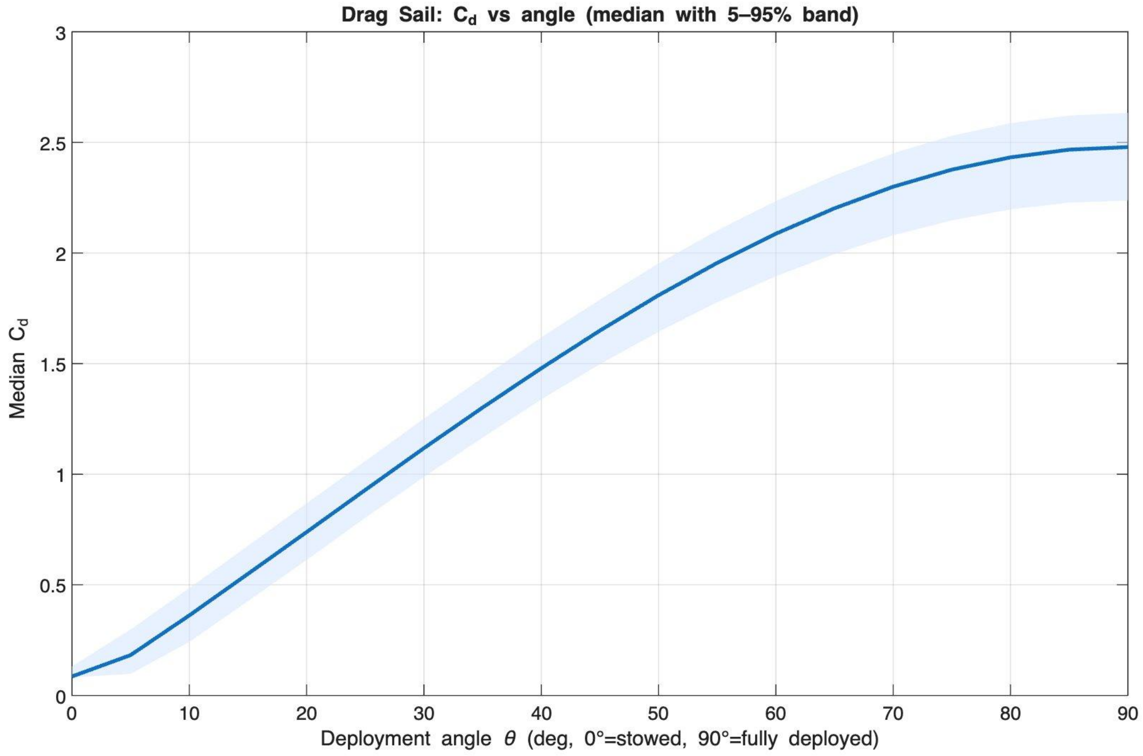
Use Δa of 1km decrease

[5] $\Delta t = \frac{\Delta a}{|\dot{a}|} = \frac{(1000)}{|-0.034|} = 29411.76\ seconds = 8.16\ hours$

Liam Pettit, Project Manager

6.3.3 Monte Carlo Simulation CD + Orbital Decay



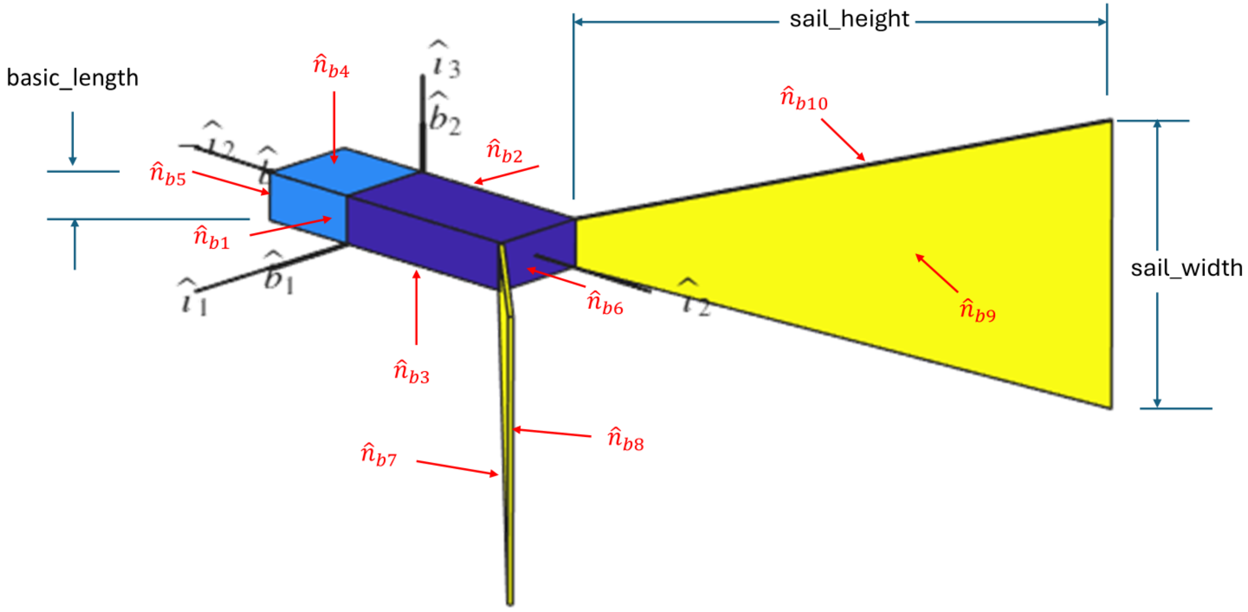


- Simulation results show an effective Cd and orbital decay rate
- At a deployment angle of 35° SV is expected to deorbit within 22.5 days

Liam Pettit, Project Manager

6.3.5 Stability Analysis – Aerotorque Code

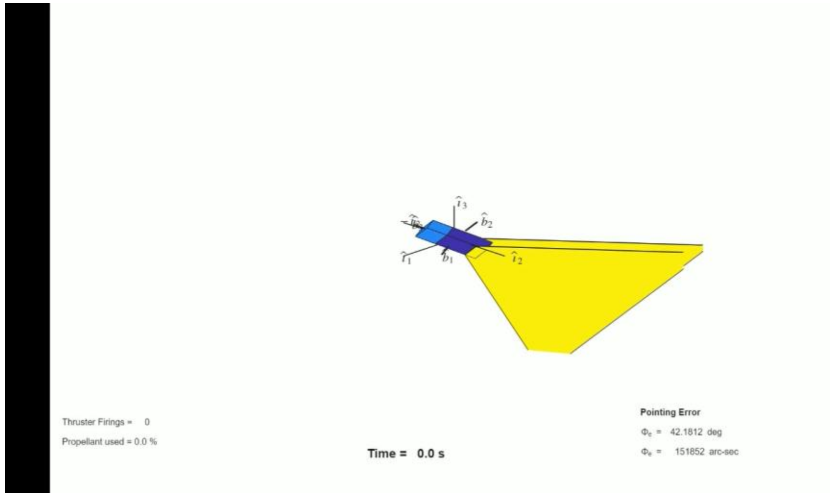
- Using Dr. Swenson's Aerotorque MATLAB script, the team was able to simulate the attitude of the parent CubeSat with the drag device.
- The code computes and simulates the aerodynamic forces on the device
- The code also allows us to determine the Center of pressure relative to the center of mass of the vehicle



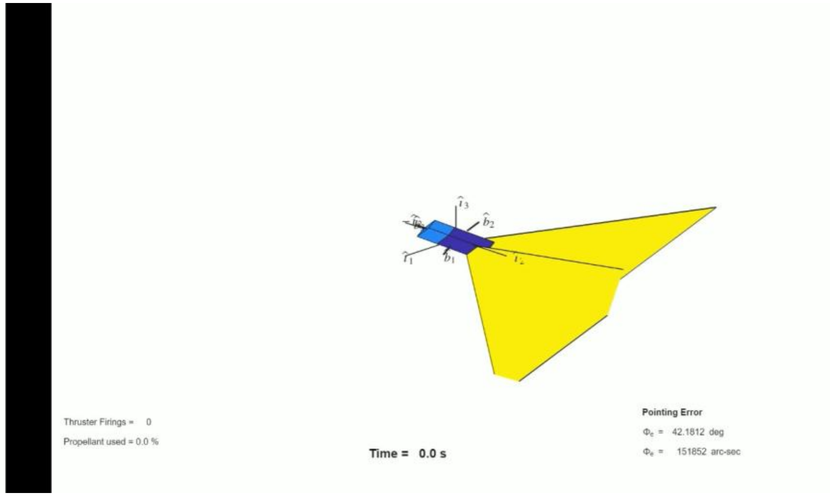
Graphic of the drag device and parent cubesat with the body and inertial frames

6.3.5 Stability Analysis – Aerotorque Code

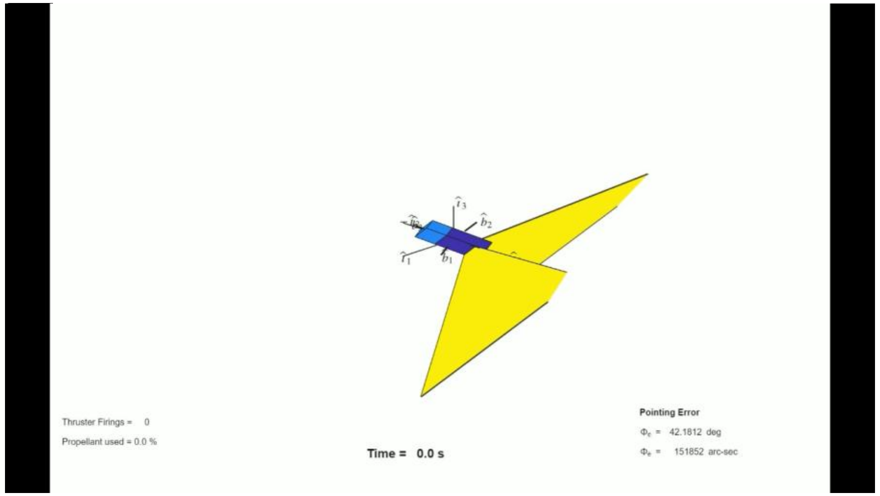
- The code computes the drag force on each face that is subjected to the flow
- The team utilized the same initial conditions for the Aerotorque code as the Monte Carlo Simulation
- The code assumes no damping and no energy loss



Wing angle = 0 degrees



Wing angle = 30 degrees

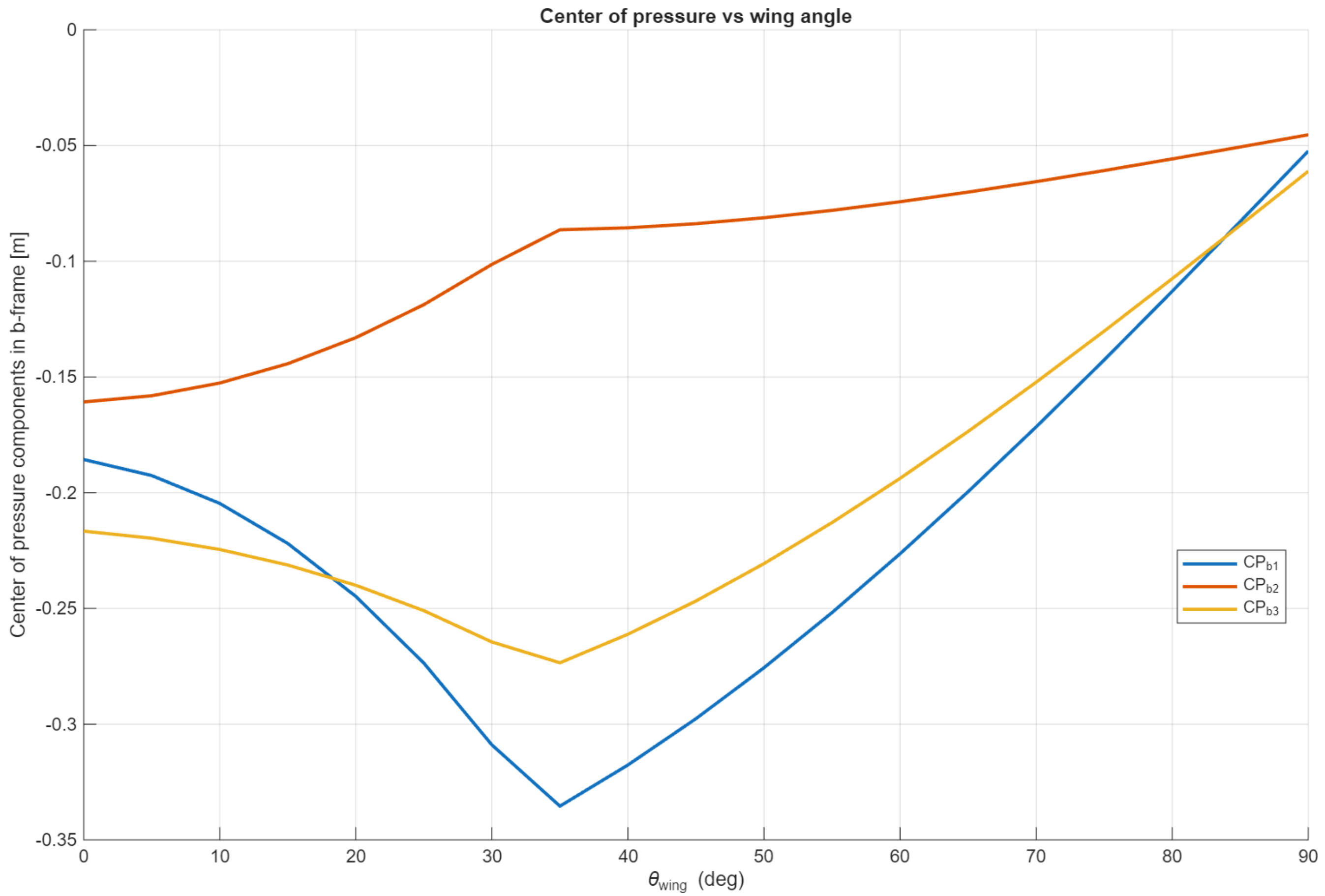


Wing angle = 60 degrees

Nathan Stephens, Controls

6.3.5 Stability Analysis – Center of Pressure vs Wing Angle

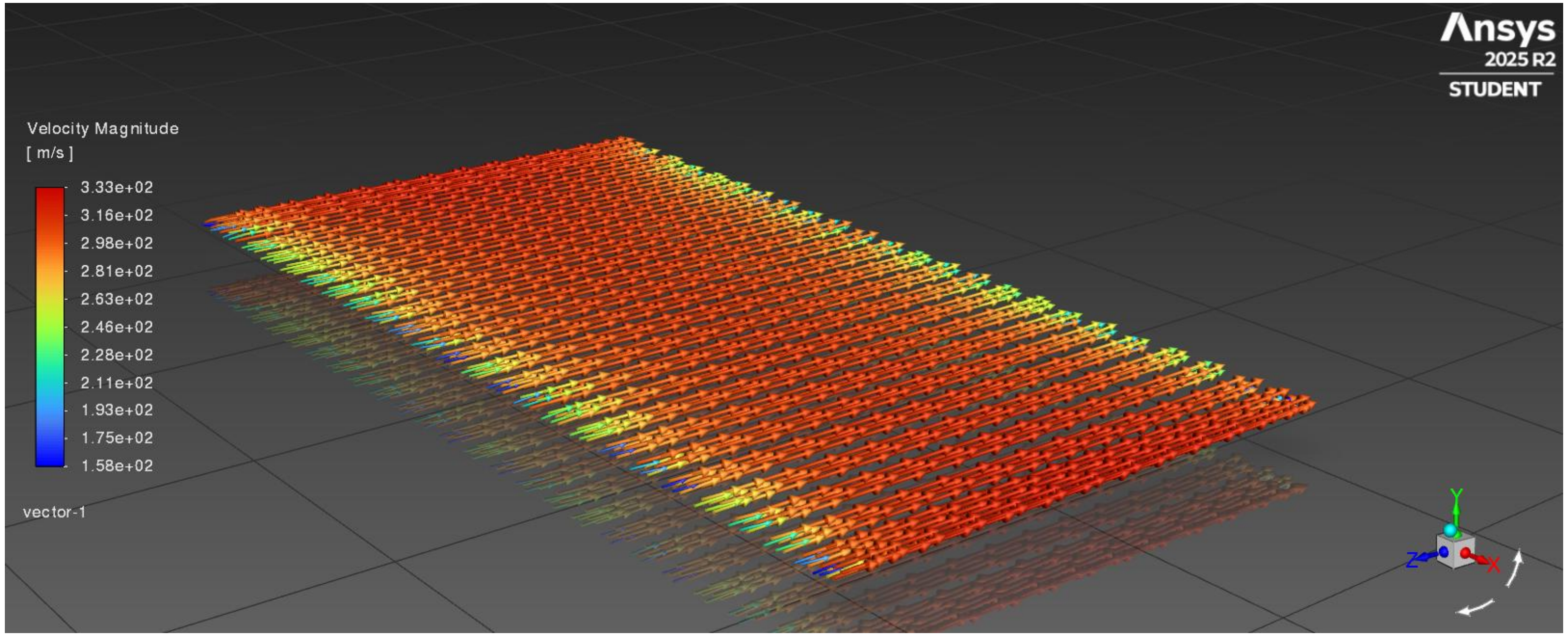
- The team evaluated how the Center of Pressure shifts relative to the spacecraft body as the drag sail's angle is modulated.
- The motion of the CP away from the spacecraft's center of mass increases passive aerodynamic stability and generates restoring moments during attitude disturbances.
- Maximum stability occurs near the wing angle where the CP reaches its most downstream position which is between 30 and 40 degrees.



Graph showing the Center of pressure in each body frame versus the angle of the wing

Nathan Stephens, Controls

6.3.6 Computational Fluid Dynamics



Using the same conditions for the Monte Carlo simulation and the Stability Analysis, a Computational Fluid Dynamics analysis was performed to determine the drag Coefficient and Drag Force of a flat plate.

- The analysis yielded a Drag Force acting on the plate of 0.0028 Newtons and a Drag Coefficient of 555.33.
- Typical Drag Force values are 1e-6 N in magnitude while for a flat plate the Cd should be between 1.8 and 3 [#]
- CFD is not often used for these circumstances as the flow is no longer a continuum and is a free molecular flow.

6.4 Electronics Subsystem Requirements

Requirement #	Requirement Text	Parent Requirement	Requirement Rationale	Verification Method	Verification Strategy
ES.01	The inrush current at connection shall be ≤5 amps.	SYS.08	To avoid tripping host EPS breakers, the initial current must be limited.	Test, inspection	The team shall test the start-up current when turning on the mechanism. Also inspect components for inrush limiting parts.
ES.02	The attachment shall provide overcurrent and short-circuit protection.	SYS.08	To ensure that the electrical system is operational, it must be resistant to common electronic problems.	Test, inspection	The team shall test that the attachment doesn't hav e an overcurrent or short-circuit. Also inspect components for
ES.03	The electronics shall accept the host CubeSat power and tolerate ±20% host power variation.	SYS.08	EPS should be able to be operational even while power levels fluctuate from parent CubeSat	Test	The team shall ensure that shall work with a fluctuating power source with a given amount of variance.

Titus Mills, Electronics

6.4 Electronics Subsystem Requirements

Requirement #	Requirement Text	Parent Requirement	Requirement Rationale	Verification Method	Verification Strategy
ES.04	The electronics shall support a low-power sleep mode with consumption ≤3 watts.	SYS.08	The CubeSat attachment will not be in operation most of the time so a sleep mode will be useful to conserve energy. A sleep mode consuming 15% of max wattage makes the attachment more practical.	Test	The team shall test the power needed from the attachment while in sleep mode.
ES.05	The attachment shall provide real-time communication for voltage, current, and cumulative energy used.	SYS.08	The CubeSat should be able to relay its internal electrical conditions to ensure that it's in operational state.	Test	The team shall check that the electrical system relays its conditions back to an external computer.
ES.06	The attachment shall provide real-time communication for the temperature.	SYS.08	The CubeSat should be able to relay its temperature so the user is aware of its condition and can ensure operationality.	Test	The team shall test that the system can check and output the temperature of specific parts.

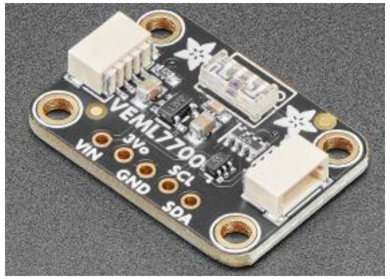
Titus Mills, Electronics

6.4.1 Trade Studies – Electronics Parts List

Voltage/Current Sensor:
Adafruit INA260
- Avg power consumption
- Small
- Large range (V & A)
- No need for resistors
- Used for voltage and current sensing

Temperature Sensor:
SparkFun TMP102
- Avg power consumption
- Small
- Large range (℃)
- Cheap
- Used with probe

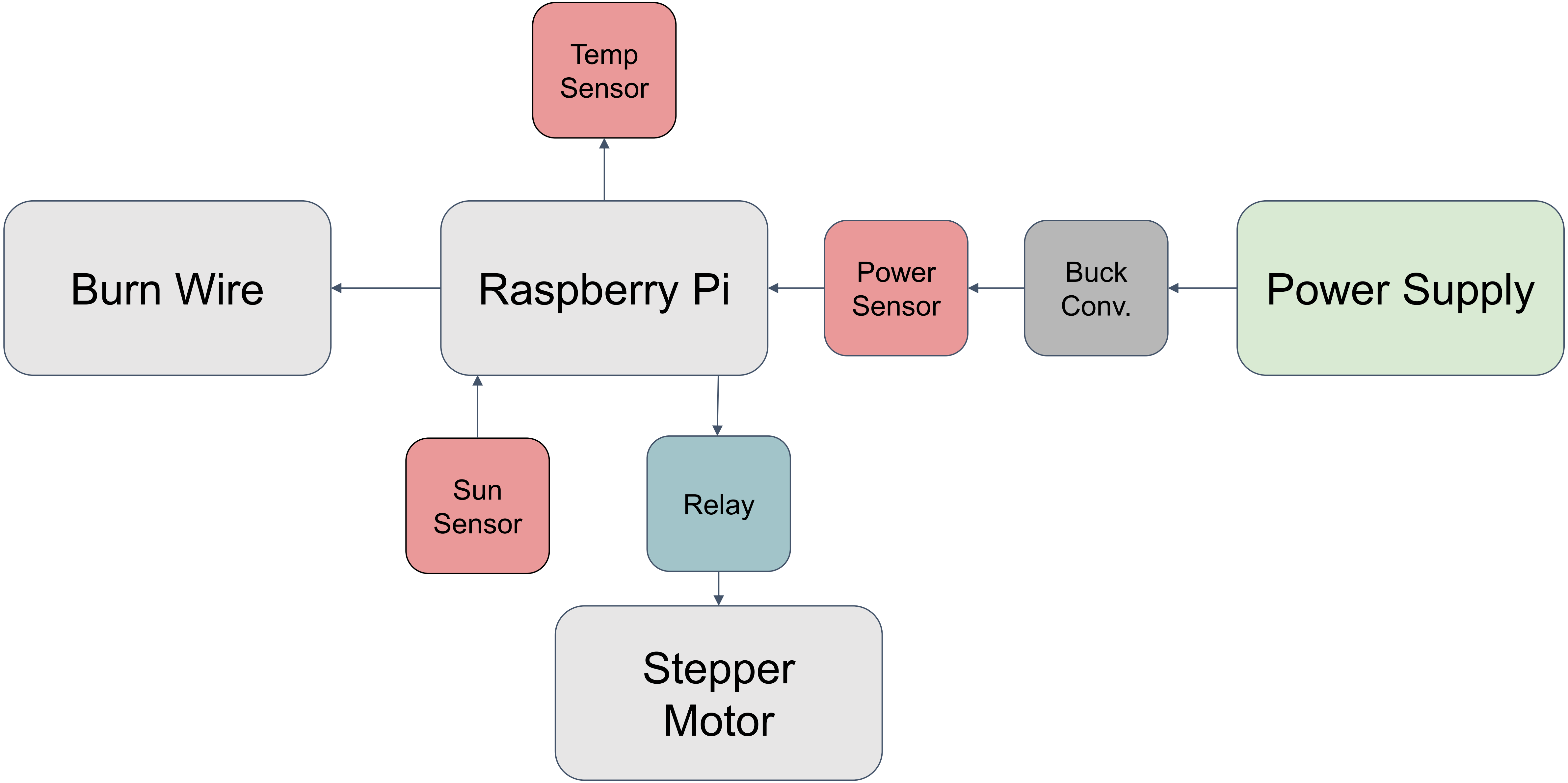
Sun Sensor:
Adafruit VEML7700
- Low power consumption
- Small
- Large range (lux)
- Cheap
- Used for detecting deployment



Buck Convertor:
DFR1015
- Large range of inputs
- Large range of outputs
- Medium/large size consideration
- Used for accepting varieties of power inputs

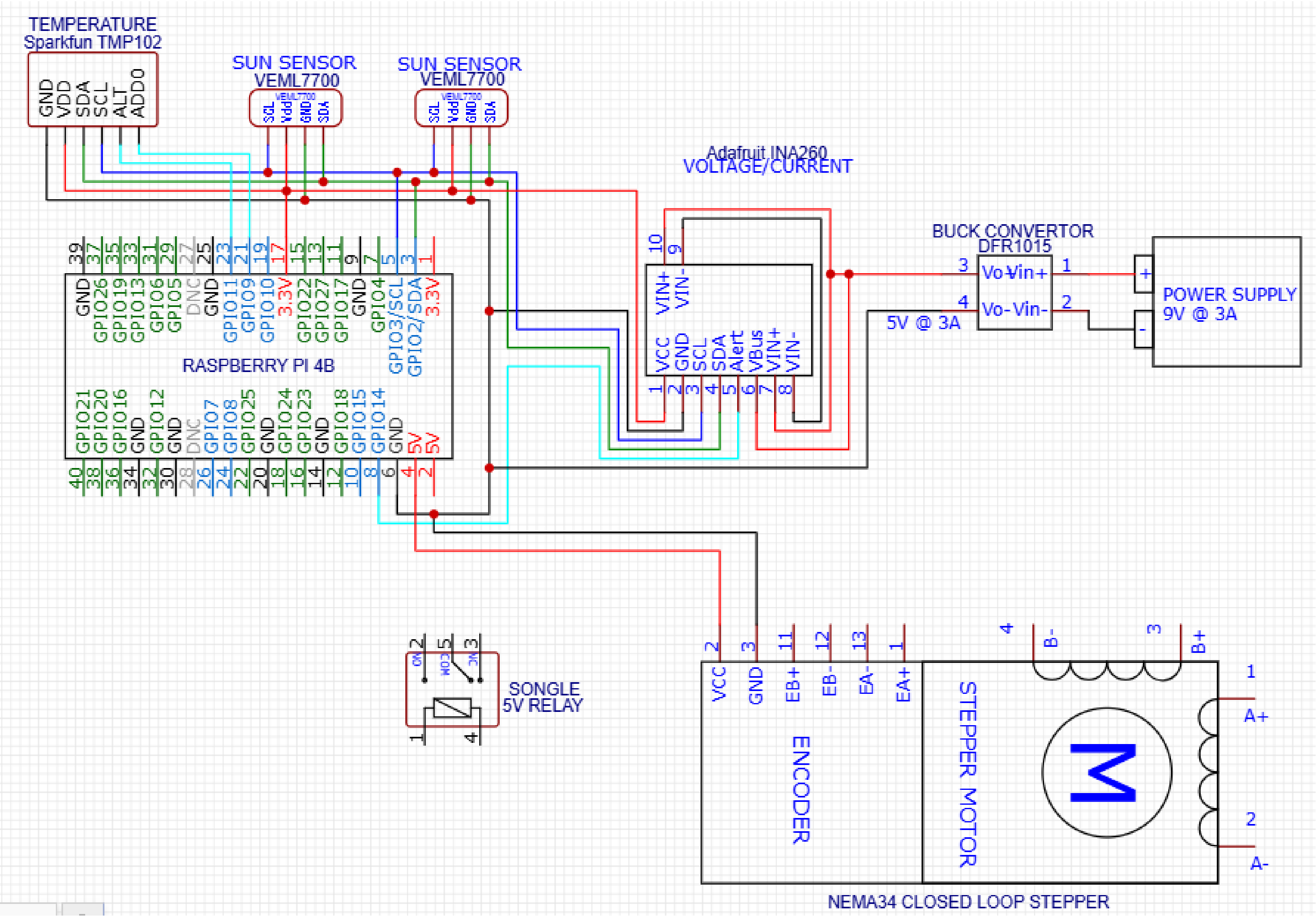
Relay:
Arduino Songle Relay
- Avg power consumption
- Small
- Decent range
- Comes in Arduino kits
- Used for overcurrent protection/activation

6.4.2 Electronics Low Level Schematic



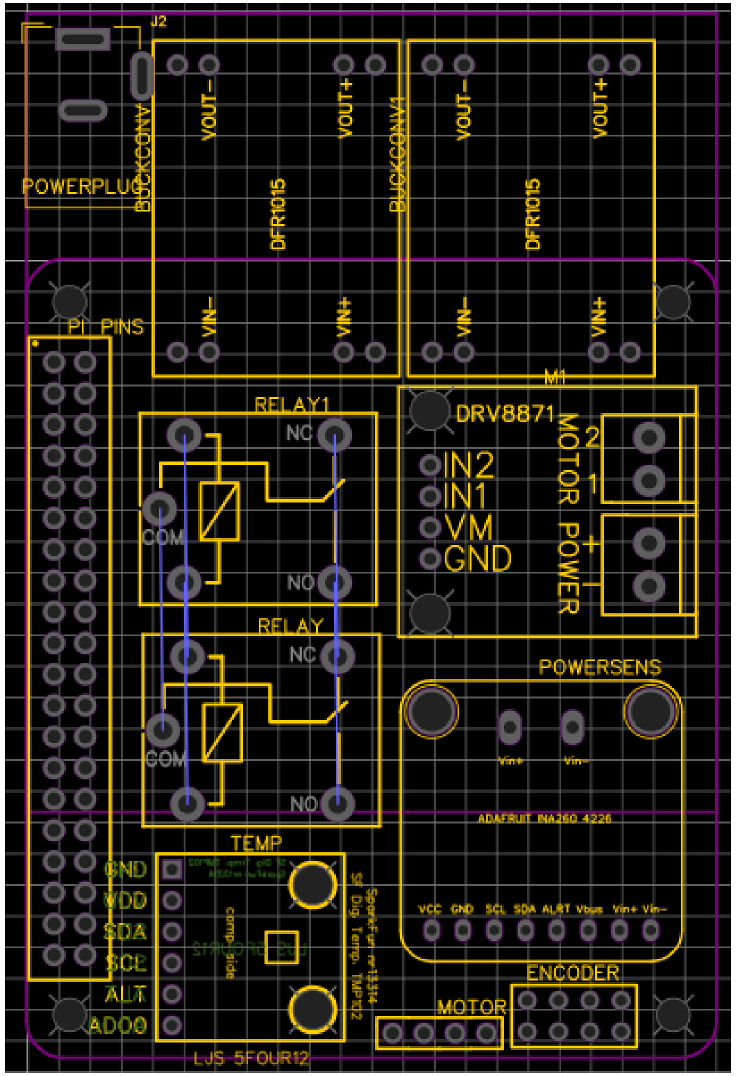
Jimmy Maskill, Electronics Lead

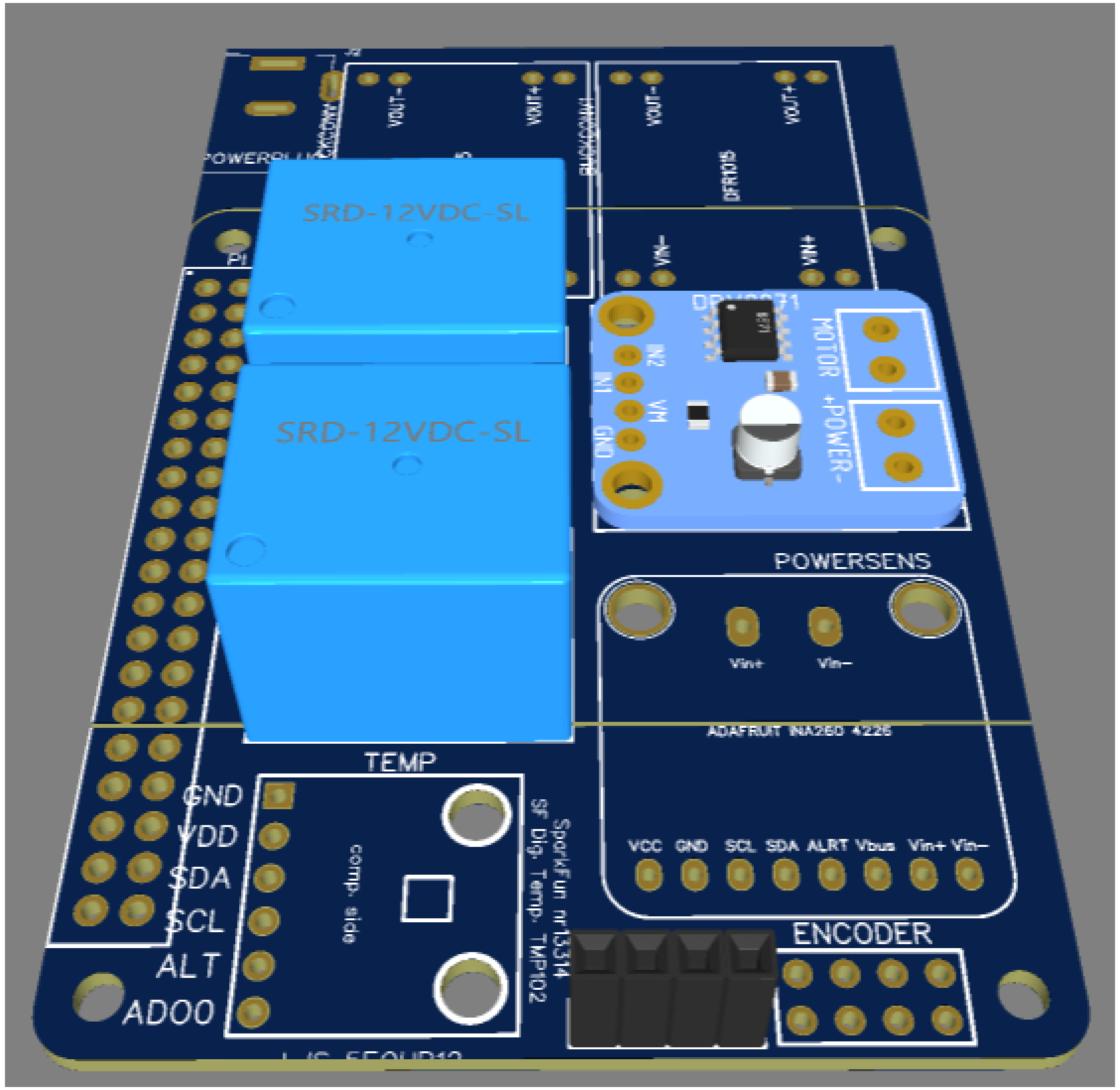
6.4.3 Electronics High Level Schematic



Jimmy Maskill, Electronics Lead

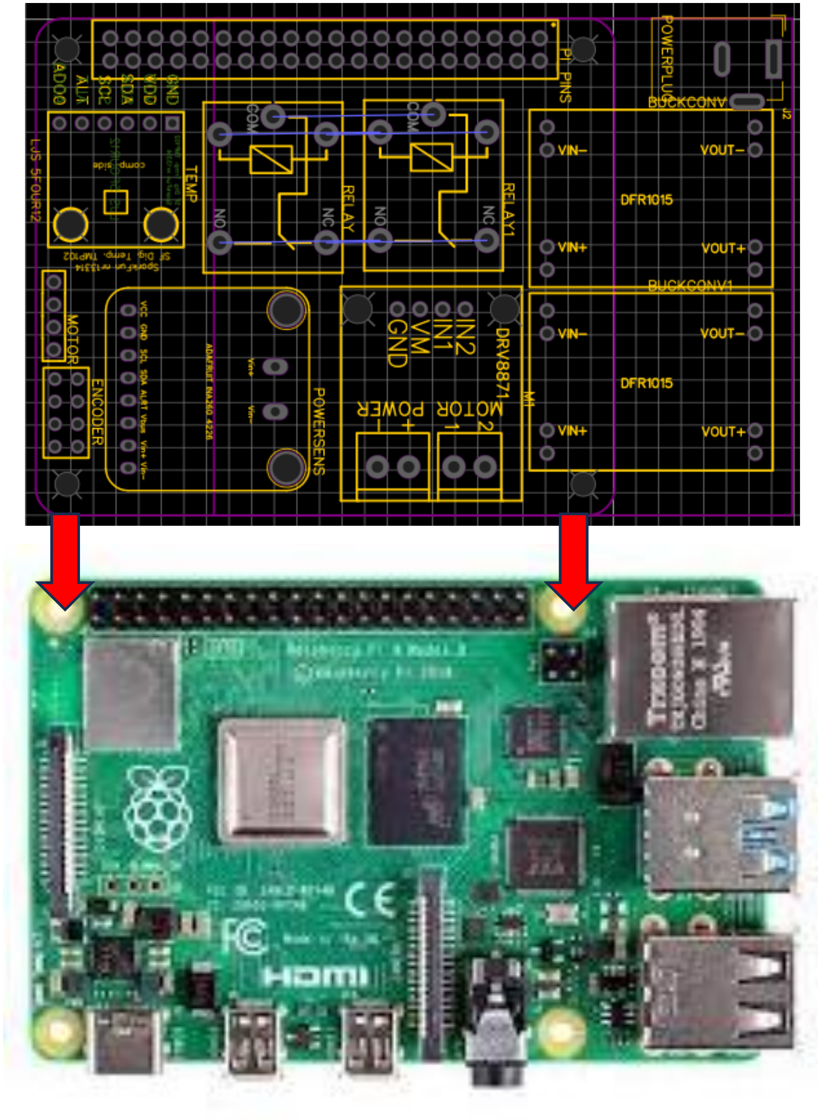
6.4.4 Electronics PCB Design





Jimmy Maskill, Electronics Lead

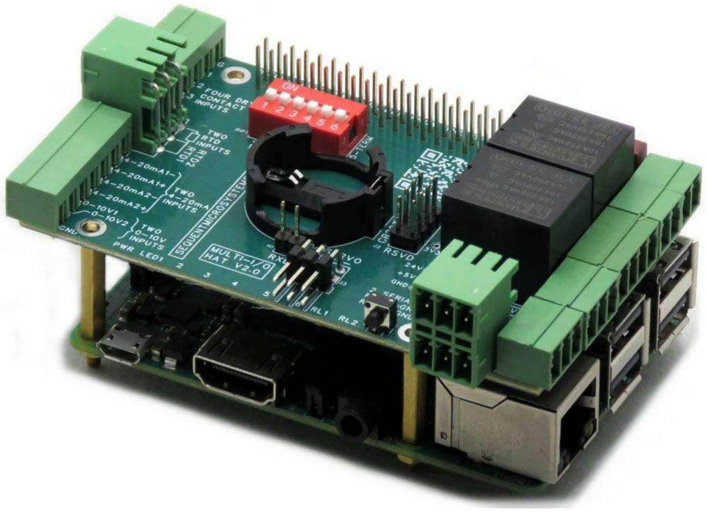
6.4.4 Electronics PCB Design



Custom PCB

Raspberry Pi 4

- Drastically improves organization and ease of use
- Will sit directly on top of the pins of the Pi 4
- Houses sensors and other components required by multiple system and subsystem requirements



****Insert pic of electronics CAD model (PLACEHOLDER)**

Jimmy Maskill, Electronics Lead

7.1 Mass Budget

- Current estimated total project mass of 0.692 kg
- Excluding deployment plates and gear integration
- Gives 1.968 kg to work with before exceeding mass budget requirement of 2.66 kg [SYS.06].

Mass Budget			
Part	Number of Entities	Mass per Entity (kg)	Total Mass (kg)
Aluminum Cubesat Frame	1	0.28	0.28
Stepper Motor	1	0.29	0.29
Adafruit INA260	2	0.002	0.004
Raspberry Pi 4	1	0.05	0.05
Songle 5V Relay	2	0.01	0.02
SparkFun TMP102	1	0.018	0.018
Buck Converter	1	0.022	0.022
Custom PCB	1	0.006	0.006
Adafruit VEML7700	2	0.001	0.002
		Total Mass:	0.692

Morgan Lee, Systems Engineer.

7.1 Electrical Power Budgets

Electrical Power Budget					
Component	**Quantity**	**Voltage (V)**	**Peak Current (A)**	**Peak Power (W)**	**Total Power**
Raspberry Pi 4 Model B	1	5	1.28	6.4	6.4
NEMA 11 Stepper Motor	1	5	1.34	6.7	6.7
NEMA 11 Stepper Motor Encoder	1	5	0.02	0.1	0.1
Adafruit INA260 Power Sensor	1	5	0.0003	0.0015	0.0015
TMP102 Temperature Sensor	1	3.3	0.01	0.033	0.033
Adafruit VEML7700 Sun Sensor	2	3.3	0.045	0.1485	0.297
Songle 5V Relays	2	5	0.0714	0.357	0.714
				System Power	14.2455

Morgan Lee, Systems Engineer.

8.0 Bill of Materials & Financial Budget

Bill of Materials						
Item Description	Vendor	Quantity	Price Per Unit	Total Cost	Subsystem	Order Status
Aluminum Rectangle Tube	McMaster-Carr	1	$30.23	$30.23	Structures	Ordered
Aluminum 90 Degree Angles	McMaster-Carr	1	$8.67	$8.67	Structures	Ordered
Aluminum Rivets 250 Pack	McMaster-Carr	1	$12.73	$12.73	Structures	Ordered
Stepper Motor	Stepper Online	1	$33.89	$33.89	Mechatronics	Not Ordered
Adafruit INA260	Adafruit	2	$9.96	$19.92	Electronics	Not Ordered
Raspberry Pi 4	ARL Lab	1	$0.00	$0.00	Full System	Delivered
Songle 5V Relay	Arduino Kit	2	$0.00	$0.00	Electronics	Delivered
SparkFun TMP102	SparkFun	1	$5.95	$5.95	Electronics	Not Ordered
Buck Converter	Arduino Kit	1	$0.00	$0.00	Electronics	Delivered
Custom PCB	Easy EDA	1	$30.00	$30.00	Electronics	Not Ordered
Adafruit VEML7700	Adafruit	2	$4.96	$9.92	Electronics	Not Ordered

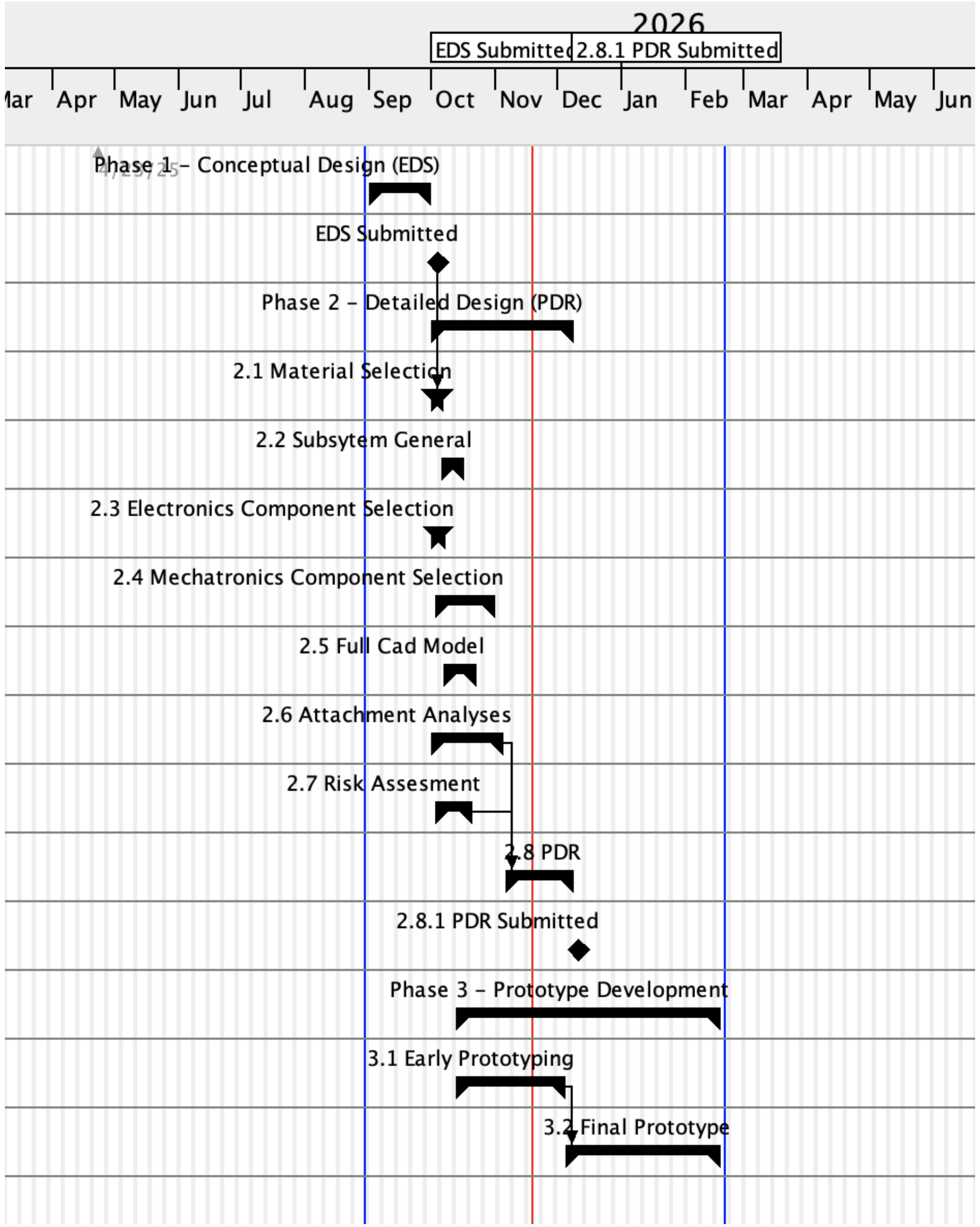
- Currently on track to spend $156.27 of total budget so far
- Estimated shipping costs of $15.63 (10% of total)
- Narrowing down deployment design & materials, estimating another -$200 from budget
- With a contingency of 20%, $1,303.72 of budget remains

Financial Budget	
Component Subtotal	$151.31
Predicted Deployment Mechanism Cost	$200
Contingency (20%)	$70.26
Total Cost	$421.57
Provided Budget	$1,750
Remaining Budget	$1,328.43
Percent of Budget Remaining	75.91%

Morgan Lee, Systems Engineer.

8.2 Schedule – Fall 2025

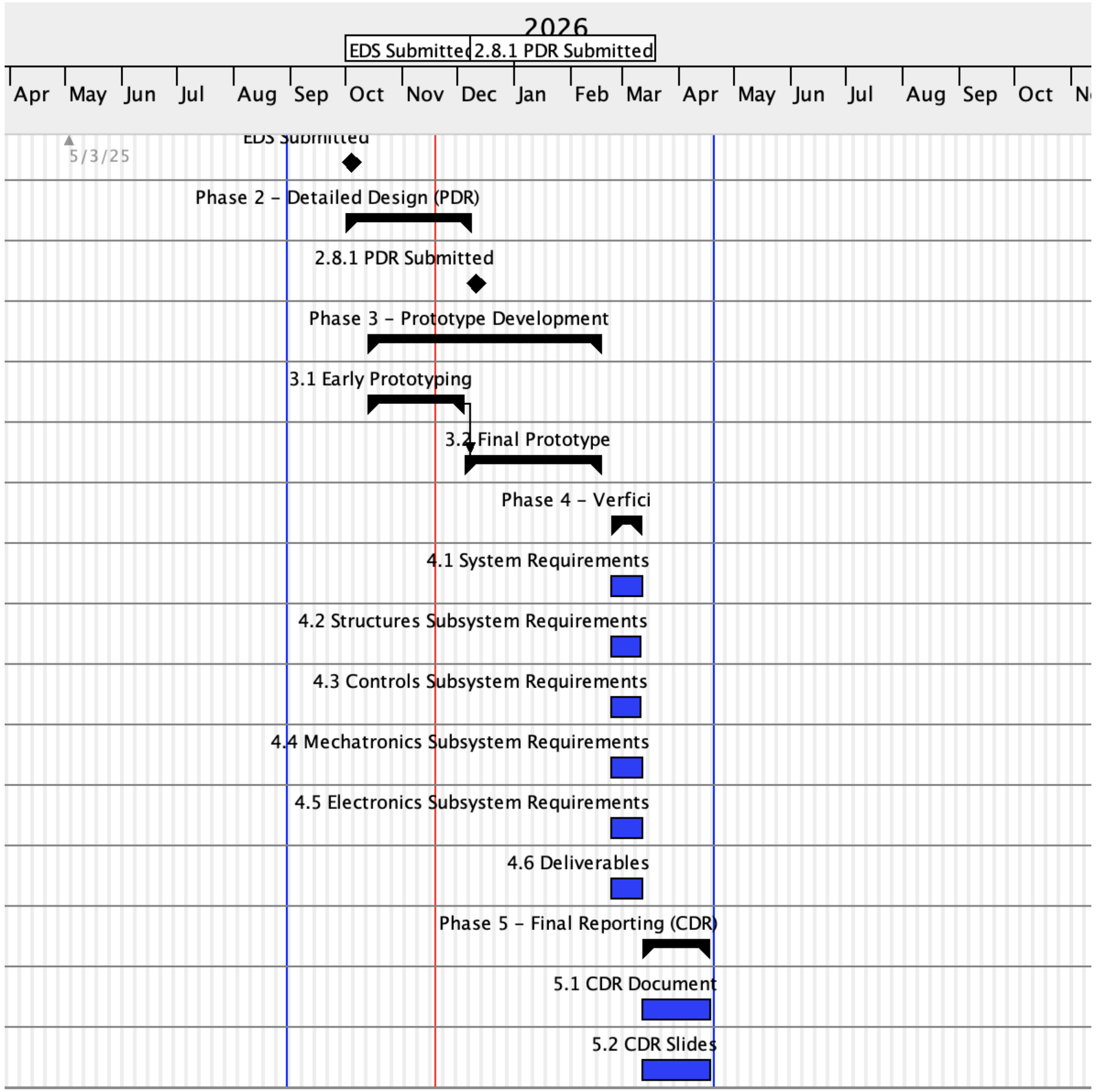
- Project Broken up into 5 Phases
  - Phase 1: Conceptual Design (EDS)
  - Phase 2: Detailed Design (PDR)
  - Phase 3: Prototype Development
  - Phase 4: Testing and Evaluation
  - Phase 5: Final Reporting (CDR)
- High Level Overview of Fall 2025
  - Included Phase 1, 2, and start of 3



Liam Pettit, Project Manager.

8.2 Schedule – Spring 2026

- Primary focus is Phase 3, 4, and 5
- Expected to finish Phase 3 early Spring



Titus Mills, Electronics.

9.0 Fabrication Plan

Frame Construction:

- Measure and mark all required lengths for the 2U frame on the purchased aluminum bar.
- Cut aluminum bar to size using a metal saw.
- Assemble frame using 90° aluminum brackets and fasten joints using rivets.

Electronics Integration:

- Mount custom PCB to Raspberry Pi 4.
- Fasten Pi + PCB assembly to designated interior side bar.
- Install sun sensors on external surfaces of the frame.
- Route sensor wiring into the frame and to the EPS.
- Attach stepper motor to opposite side bar.
- Wire stepper motor to electrical system.

Drag Sail Deployment System

- Integrate purchased gears with the stepper motor
- Install expandable booms and clock spring into each of the two deployment plates
- Fasten drag-sail film to the booms
- Attach custom designed deployment plates to the gear system by axle

Morgan Lee, Systems Engineer.

10.0 Test Planning

Testing Plans				
Test Name	Test Description	Testing Method	Requirement Verified	Timeline
Mechanical Deployment Test	Verify the drag sail deploys from minimum to maximum CSA in <150 seconds.	Orient the attachment horizontally and vertically. Command deployment and measure total actuation time. Repeat on vibration table to verify performance under launch-like conditions.	MECH.05	Feb
Power Variation Tolerance	Verify electronics operate correctly under ±20% host power variation.	Run attachment while adjusting input voltage ±20% from nominal and confirm continuous operation.	ES.03	Jan
Telemetry Communication Test	Confirm real-time data transmission for voltage, current, temperature.	Connect to parent CubeSat computer and verify continuous telemetry during idle and motor operation. Temperature measured on Raspberry Pi or stepper motor.	ES.05 & ES.06	Jan
Deployment Test	Confirm parent CubeSat command triggers deployment and attachment reports deployment status back to host.	Send deployment command to attachment. Verify burn wire activation and mechanical response. After sending deployment command, confirm attachment transmits correct status for both successful and intentionally failed deployment.	CS.02	Feb
Full-System Functional Test	Validate entire integrated system under real operating conditions.	Perform end-to-end test including signal reception, actuation, telemetry reporting, and deployment verification.	SYS.04	Feb

Morgan Lee, Systems Engineer.

11.0 Risk Management

Risk Assessment				
Risk Type	**Failure Mode**	**Mitigation**	**Risk Severity**	**Risk Likelihood**
Safety	**If** mishandling occurs during arming, **then** a sudden energy release may injure personnel or damage equipment.	Use physical safety pins, PPE, two-person rule, and barrier shield during arming.	High	Low
Technical	**If** the mechanism binds or fails to release, **then** the sail fails to deploy, resulting in an invalid test and possible hardware damage.	Conduct repeated dry runs, verify tolerances, add redundant manual release option, inspect latch prior to arming.	Medium	Medium
Technical	**If** there is insufficient torque or a stall under load, **then** modulation capability is lost and the control test fails.	Bench-test motors at full load, monitor current, add thermal cutoff.	Medium	Medium
Safety / Technical	**If** ESD or assembly damage occurs, **then** an electrical short or personnel shock may result.	Use wrist straps and grounded benches, verify insulation.	High	Low
Schedule	**If** critical components or machining are delayed, **then** milestones are missed and available test time is reduced.	Order early, maintain backup vendors, add 2-week float, track lead times weekly.	Medium	Medium
Financial	**If** the project budget is exceeded, **then** components may be missing or testing capability may be reduced.	Maintain cost log, approve purchases through advisor, use inexpensive surrogate materials.	Medium	Medium
Operational / Process	**If** incorrect assembly or alignment occurs, **then** the mechanism may jam or hinge damage may occur.	Use assembly checklists, keyed parts, peer inspection, and photo documentation.	Medium	Low
Technical / Operational	**If** a sensor or logging failure occurs during the test, **then** test data is lost, requiring a repeat test and causing time loss.	Validate DAQ before test, run redundancy (video + telemetry), record timestamps and backups.	Medium	Medium

Morgan Lee, Systems Engineer.

12.0 Conclusions

- The ASTRA Project design is complete.
- The ASTRA team is ready to move forward onto CDR and fabrication
- The risks have been analyzed and deemed manageable
- The ASTRA team believes they will be in compliance with all objectives and requirements by CDR.
- The ASTRA team believes they should pass PDR

Liam Pettit, Project Manager.

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References

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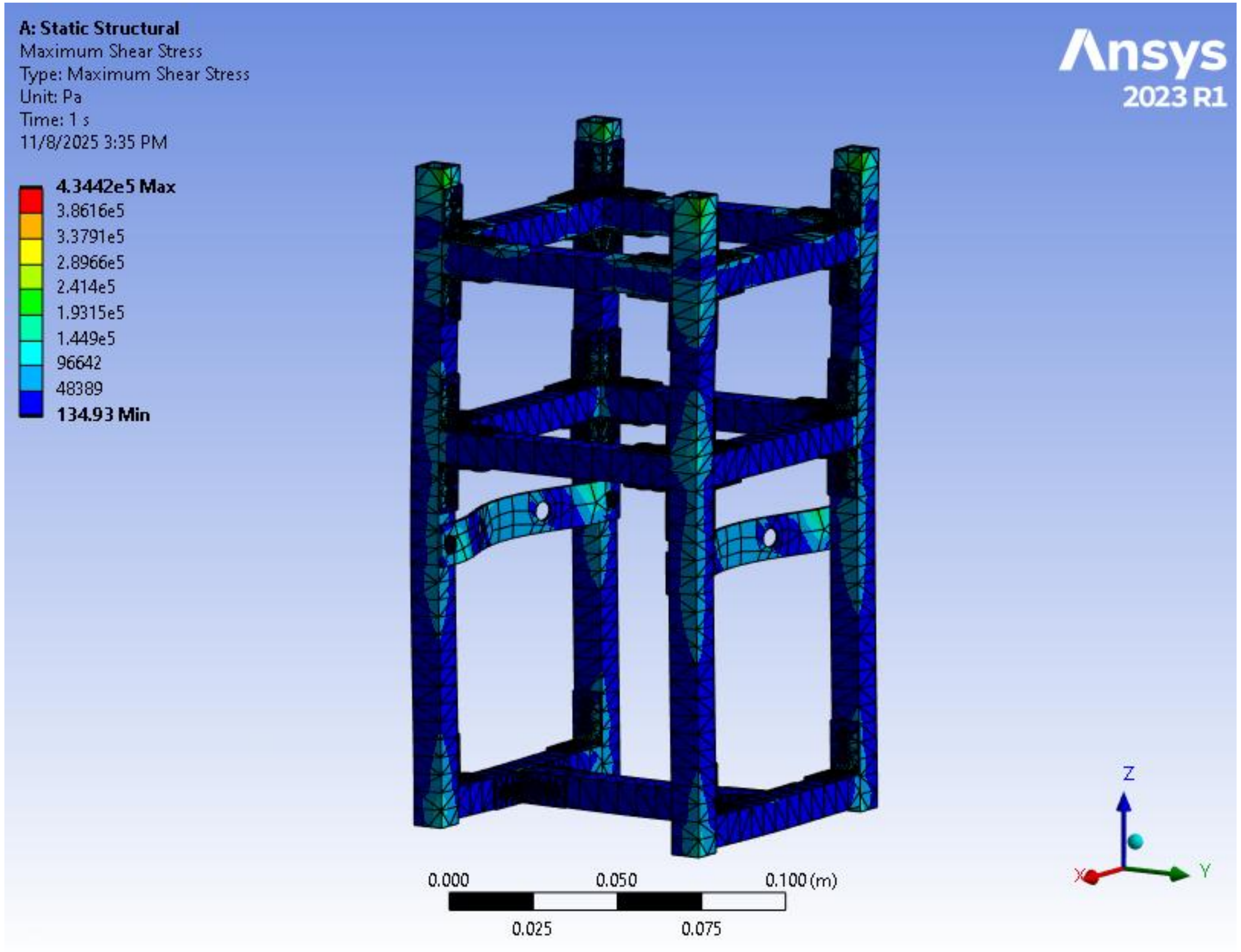
- [13] Shigley, J. E., Budynas, R. G., and Nisbett, J. K., *Mechanical Engineering Design*, 10th ed., McGraw-Hill, New York, 2014.

Questions?

Supplemental Slides

6.1.4.1 Structures Testing: FEA – Frame Static Loading



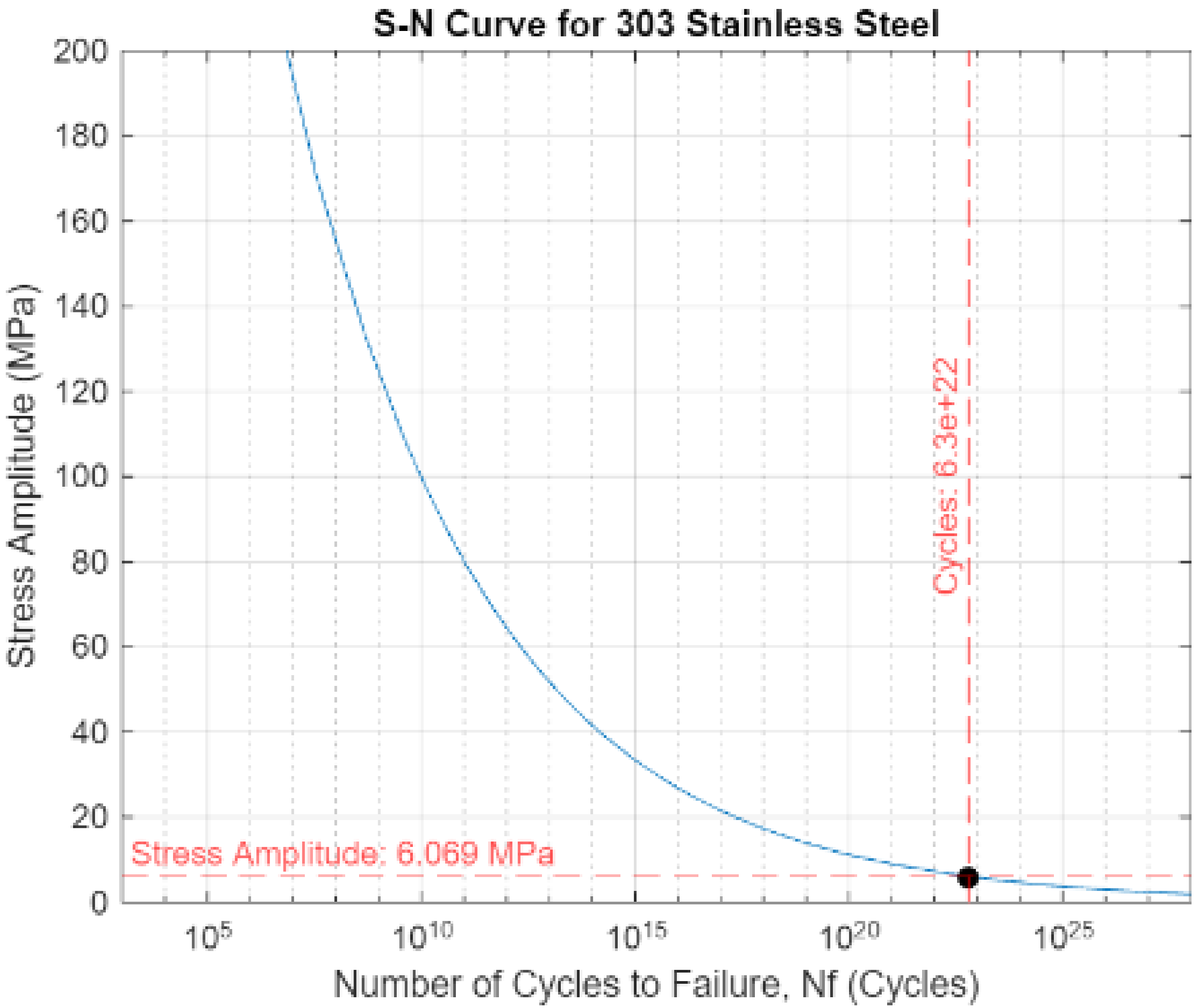
Material:	Aluminum 6061-T6
Yield Stress:	276 MPa
Poisson's ratio:	0.33
Young's Modulus:	68.9 GPa
Max Stress:	434.42 KPa
Max Deformation:	0.0028 mm
Nodes:	135109
Elements:	55986

Factor of Safety: 635.33 (STR.02)

Because the frame must comply with launcher compatibility specifications and enable component mounting, it cannot easily be optimized for a lower factor of safety.

Nathan Mulford, Structures

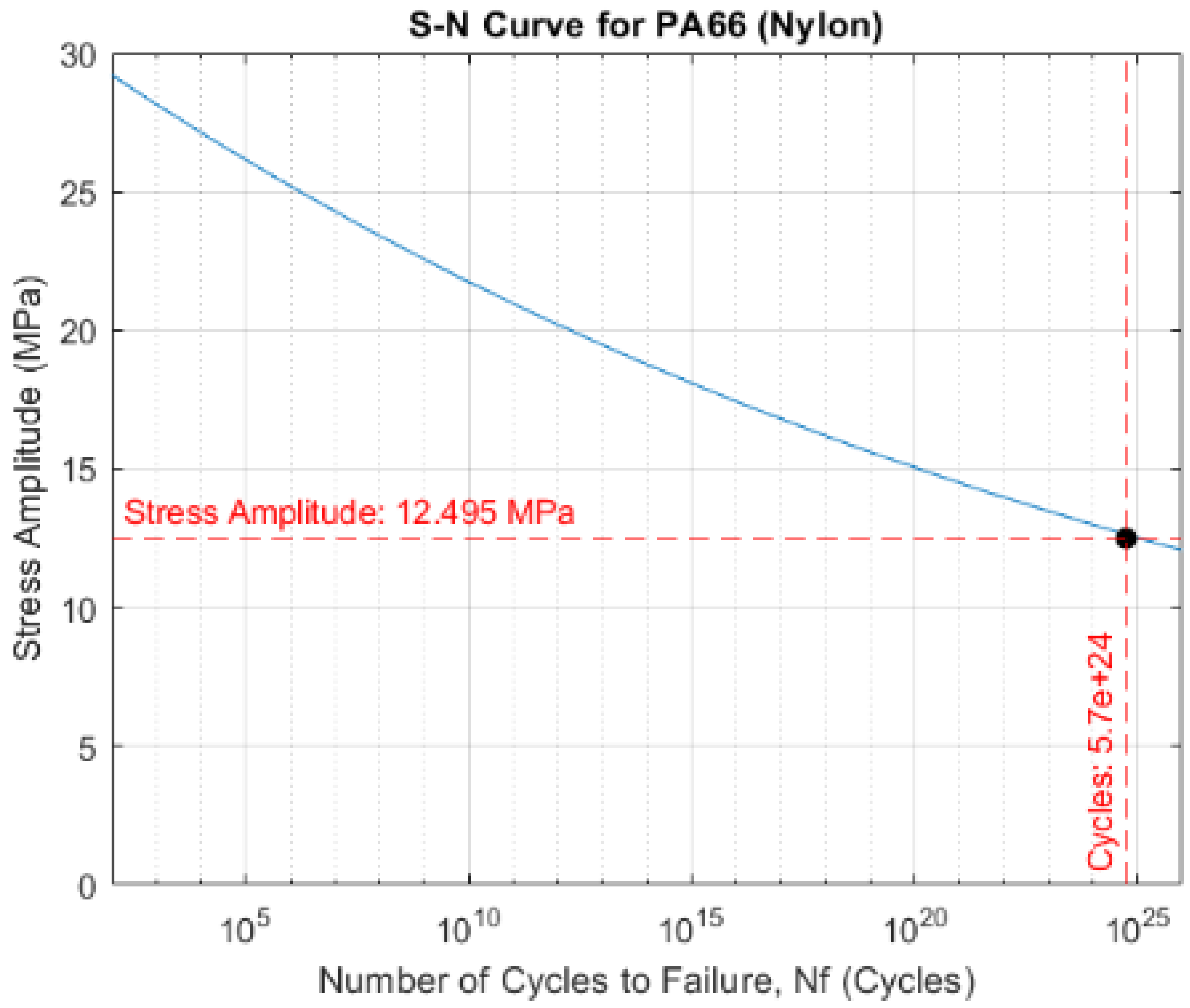
6.1.5.5 Structures testing: FEA – Drag Modulation Cycles



$$N_f = \frac{1}{2}\left(\frac{\sigma_a}{\sigma_f{}'}\right)^{\frac{1}{b}} = \frac{1}{2}\left(\frac{6.0686}{950}\right)^{\frac{1}{-0.095}} = 6.32 * 10^{22}\ cycles$$

$$FOS = \frac{6.32 * 10^{22}}{13500} = 4.86 * 10^{18}$$

6.1.5.5 Structures testing: FEA – Drag Modulation Cycles



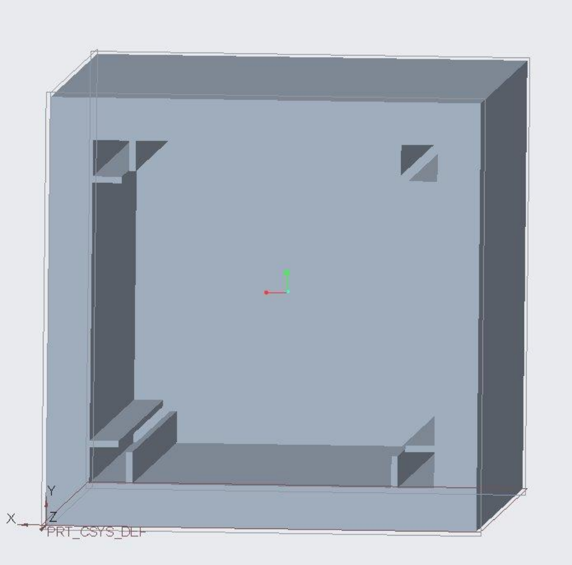
$$N_f = \frac{1}{2}\left(\frac{\sigma_a}{\sigma_f{}'}\right)^{\frac{1}{b}} = \frac{1}{2}\left(\frac{12.49}{31.45}\right)^{\frac{1}{-0.016}} = 5.66 * 10^{24}\ cycles$$

$$FOS = \frac{5.66 * 10^{24}}{13500} = 4.19 * 10^{20}$$

Nathan Mulford, Structures

5.1.2 Structures Initial Considerations

- Frame Material
  - Weight
  - DAS Compatibility
- Frame Design
  - Structural Loading
  - Launcher Compatibility
  - Parent Sat Compatibility
- Component Integration
  - Volume Constraints (2U)



5.1.3 Full System Drawings

- The

6.1.4 Frame Dimensions

- Include picture with basic frame dimensions

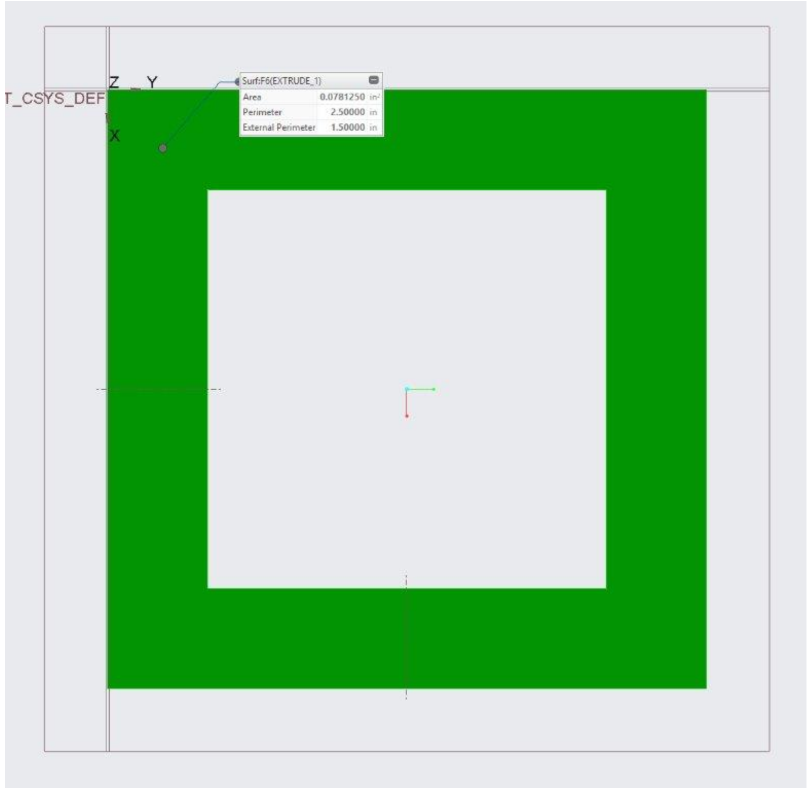
6.1.5.2 Structures testing: FEA – Rail Static Loading

- 1200 N on a single rail
- Used Creo to compute the cross-sectional area

$$\sigma_{avg} = \frac{F}{A} = \frac{1200\ N}{50.4\ mm^2} = 23.81\ MPa$$

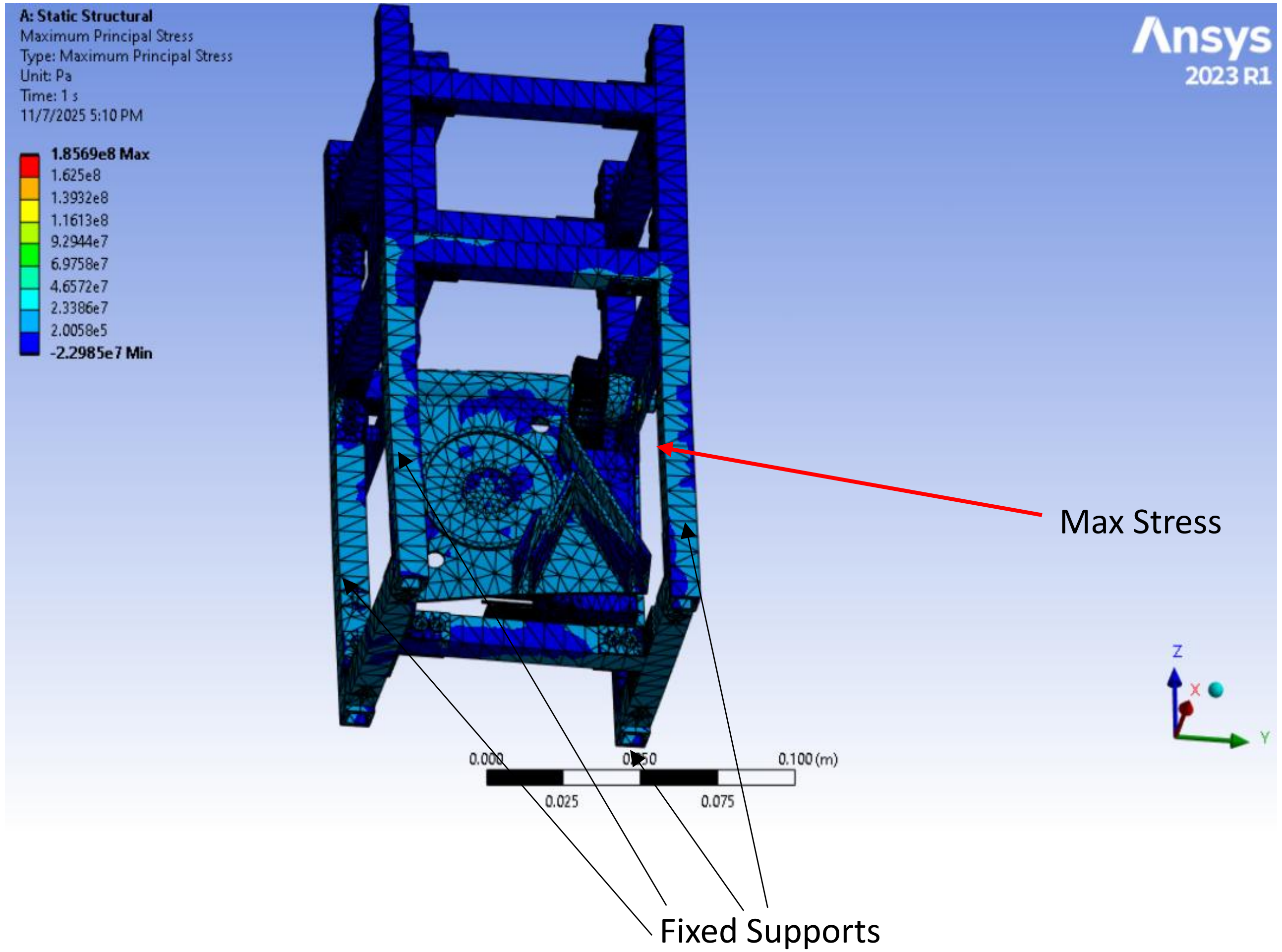
$$\sigma_{yield} = 276\ MPa$$

$$FOS = \frac{\sigma_{yield}}{\sigma_{avg}} = \frac{276\ MPa}{23.81\ MPa} = 11.59$$



$$A = 0.078125\ in^2 = 50.4\ mm^2$$

6.1.5.6 Structures Testing: FEA – Deployment



Material: Aluminum 6061-T6
Yield Stress: 276 MPa
Poisson's ratio: 0.33
Young's Modulus: 68.9 GPa

Simulated Load: 10 N
Max Stress: 1.857 MPa

Nodes: 135109
Elements: 55986

Factor of Safety: 148.63 (STR.02)

Because the frame must comply with launcher compatibility specifications and enable component mounting, it cannot easily be optimized for a lower factor of safety.

Alvaro Cameo, Structures

6.2.1.1 Actuation Method Trade Study

Actuation Method Decision Matrix	Weight	Screw Gear		Worm Gear		Two actuators	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Cost	25%	5	1.25	5	1.25	1	0.25
Weight	10%	4	0.4	5	0.5	1	0.1
Reliability	25%	3	0.75	3	0.75	5	1.25
Complexity	10%	2	0.2	3	0.3	4	0.4
Volume	10%	2	0.2	4	0.4	4	0.4
Power Req	20%	4	0.8	4	0.8	2	0.4
Total Score	100%		3.6		4		2.8

Worm Gear Selected

- Chosen for simplicity due to few parts
- Vertical symmetry
- Volumetrically efficient

6.2.1.2 Gear Material Trade Study

Gear Material Decision Matrix	Weight	Stainless Steel		Nylon		PEEK	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Weight	10%	1	0.25	5	1.25	5	1.25
Cost	20%	4	0.4	5	0.5	1	0.1
Durability	15%	5	1.25	3	0.75	4	1
Strength	10%	5	0.5	3	0.3	4	0.4
Vacuum Reliability	25%	2	0.2	4	0.4	5	0.5
Ease of use	20%	5	1	5	1	3	0.6
Total Score	100%		3.6		4.2		3.85

Nylon Selected

- Chosen primarily for its accessibility in terms of cost and customization of sizes
- Low strength and durability are less important for low loads and short missions
- No risk of cold welding

6.2.1.3 Stepper Motor Trade Study

Actuator Motor Decision Matrix	Weight	11HS20-0674-ME1K		11HS20-0674S		6627T38 NEMA 14	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Cost	10%	3	0.3	5	0.5	1	0.1
Strength	25%	4	1	2	0.5	4	1
Volume	25%	3	0.75	5	1.25	4	1
Weight	20%	3	0.6	4	0.8	5	1
Encoder	20%	5	1	1	0.2	1	0.2
Total Score	100%		3.65		3.25		3.3

11HS2-00674-ME1K Selected

- Chosen for its smaller size, NEMA 11 vs 14
- Higher torque in favor of rotational speed
- Built-in encoder to simplify assembly

6.2.2.2 Deployer Assembly

Deployer assembly drawing

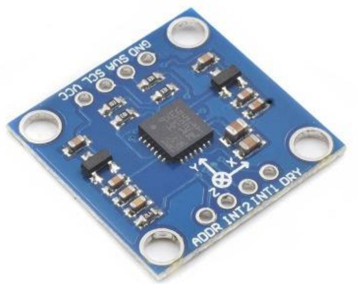
6.2.3 Actuation Assembly

- Drawings of actuation mechanism

6.2.5 Mechatronics - Mass

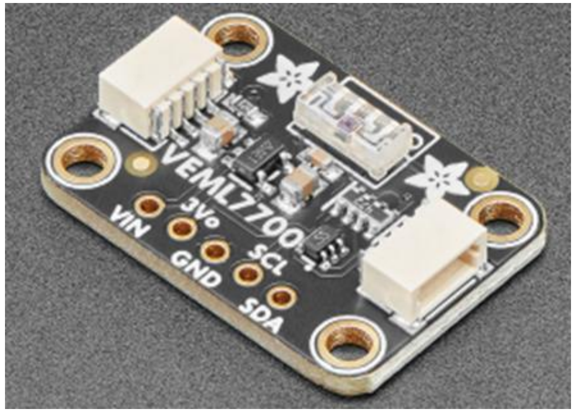
- Mass table

6.3.1 Controls Trade Study – Deployment Verification



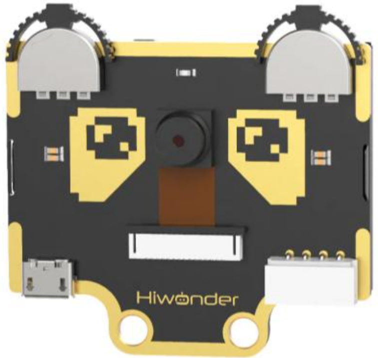
Accelerometer [#]

- Measures changes in acceleration during deployment
- Simple to integrate and low power
- Limited ability to confirm full deployment



Sun Sensor [#]

- Detects panel orientation using solar incidence
- High accuracy in confirming deployed state
- Low power and low cost



Camera [#]

- Visually confirms deployment
- High information content
- Higher power, cost, and sensitivity to lighting

Nathan Stephens, Controls

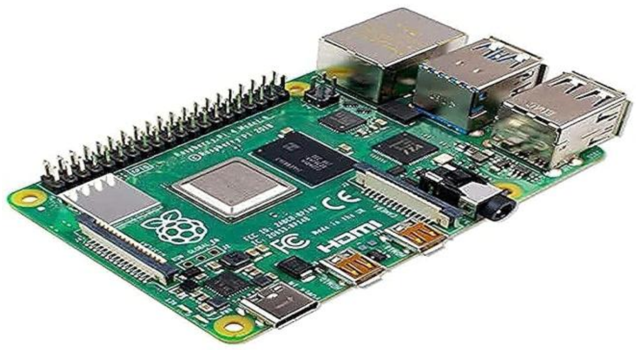
6.3.1 Deployment Verification Decision Matrix

Deployment Verification Method	Weight	Accelerometer		Sun Sensors		Camera	
		Score	Weighted	Score	Weighted	Score	Weighted
Speed of Measurement	10%	5	0.5	5	0.5	3	0.3
Cost	20%	4	0.8	5	1	1	0.2
Accuracy/Viability in Meas.	30%	3	0.9	3	0.9	5	1.5
Power Consumption	20%	5	1	5	1	1	0.2
Certainty of Full Deployment	20%	1	0.2	4	0.8	5	1
Total Score	100%		**3.4**		**4.2**		**3.2**

- Evaluated Accelerometer, Sun Sensors, and Camera using weighted criteria
- Highest priorities: Accuracy/Viability, Power, Cost, and Certainty of Full Deployment
- Sun Sensors had the highest total score (4.2). Chosen due to high accuracy, low power, and reliable deployment confirmation

Nathan Stephens, Controls

6.3.1 Controls Trade Study Mockup CubeSat Flight Computer



Raspberry Pi 4 [#]
- Low cost, easy to program
- Strong I2C/UART support
- Good performance per watt

Jetson Nano [#]
- Designed for AI/vision applications
- Higher processing power
- Higher power draw, less ideal for basic mockup

Tinker Board 2S [#]
- Compact SBC with good I/O
- Moderate performance
- Struggles in power efficiency and ease of use

Nathan Stephens, Controls

6.3.1 Mockup CubeSat Flight Computer Decision Matrix

MockUp Cube Sat Flight Computer	Weight	Raspberry Pi 4		Jetson Nano		Tinker Board 2S	
		Score	Weighted	Score	Weighted	Score	Weighted
Cost	30%	4	1.2	2	0.6	2	0.6
Compatability with I2C and UART	20%	5	1	5	1	5	1
Size	10%	3	0.3	4	0.4	3	0.3
Power Consumption	30%	5	1.5	4	1.2	1	0.3
Ease of Use	10%	5	0.5	5	0.5	3	0.3
Total Score	100%		**4.5**		**3.7**		**2.5**

- Compared Raspberry Pi 4, Jetson Nano, Tinker Board based on cost, compatibility, power, ease of use
- Highest weights: Cost, I2C/UART compatibility, and Power Consumption
- Raspberry Pi 4 scored highest (4.5). Chosen for best compatibility, low cost, and low power usage

Nathan Stephens, Controls

6.3.2 Controls Functionality Overview

The attachments control systems capabilities will consist of triggering physical actions such as deployment and modulation of the sails, in addition to triggering a power reducing sleep-mode and data feedback to the operator (successful deployment and modulation of sails).

- Deployment: On-board computer will receive command for deployment at a specific time, for which the corresponding scripts will be ran to send current through burn-wire at specific time and trigger deployment of sails.
- Modulation: On-board computer will receive commands for modulation of sail angle, for which corresponding scripts will be ran to trigger stepper motor and change sail orientation.
- Sleep-mode: On-board computer will receive command to activate sleep-mode, for which corresponding scripts will trigger relays to cut power from unnecessary components and reduce power consumption of Raspberry PI 4.
- Data feedback: On-board computer communicate with sun-sensors to verify and feedback data to ensure successful deployment of sails and corresponding orientation angle of the sail.

Cole Schumacher, Controls

6.3.5 Controls Stability Analysis

- As the sail opens, the projected aerodynamic area increases and the Center of Pressure (CP) moves farther behind the spacecraft’s center of mass. Past a certain angle the CP moves back toward the CG.
  - A larger CP–CG separation produces a stronger restoring aerodynamic moment.
  - Small attitude deviations create a restoring torque that drives the CubeSat back toward the velocity vector.
  - Maximum stability occurs near the wing angle where the CP reaches its most downstream position which is between 30 and 40 degrees.

Cole Schumacher, Controls

6.3.3 Monte Carlo Simulation CD + Orbital Decay Results

Deployment Angle	Cd	Accel (μG)	Days in Orbit
0	0.086	1.18E-06	339.40
5	0.182	2.31E-06	161.89
10	0.362	4.58E-06	81.39
15	0.550	7.03E-06	53.55
20	0.739	9.55E-06	39.88
25	0.929	1.20E-05	31.69
30	1.118	1.44E-05	26.35
35	1.301	1.68E-05	22.63
40	1.479	1.91E-05	19.91
45	1.649	2.12E-05	17.86
50	1.809	2.34E-05	16.29
55	1.955	2.52E-05	15.08
60	2.087	2.68E-05	14.14
65	2.202	2.83E-05	13.39
70	2.300	2.96E-05	12.83
75	2.377	3.05E-05	12.41
80	2.432	3.12E-05	12.13
85	2.467	3.16E-05	11.97
90	2.479	3.18E-05	11.91

Liam Pettit, Project Manager

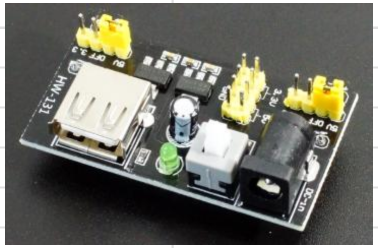
6.4.1 Trade Studies – Mock Parent CubeSat Battery

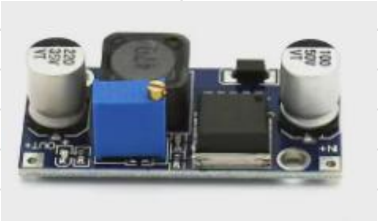
- Placed on mock parent CubeSat
- 9V power supply sent to Raspberry Pi 4B and stepper motor

Buck Convertor	Weight	Elegoo Power MB V2		DFR1015		LM2596	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Operating Voltage	15%	5	0.75	5	0.75	5	0.75
Output Voltage	20%	4	0.8	5	1	5	1
Current Range	15%	5	0.75	3	0.45	3	0.45
Cost	15%	5	0.75	5	0.75	4	0.6
Size	35%	3	1.05	5	1.75	3	1.05
Total Score	100%		4.1		4.7		3.85

Scoring System	
5	Ideal
4	Great
3	Good
2	Acceptable
1	Poor

Elegoo Power MB V2	DFR1015	LM2596
Supply Voltage: 6.5V - 9V	Supply Voltage: 7.5V - 30V	Supply Voltage: 3V - 40V
Output Voltage: 3.3V/5V	Output Voltage: 3.3V/5V/9V/12V	Output Voltage: 1.25V - 35V
Max Current Draw: 400mA	Max Current Draw: 5A	Max Current Draw: 5A
Cost: $2	Cost: $6	Cost: $8 for 10
Size: 55 x 33 x 25mm	Size: 28 x 20 x 10mm	Size: 43 x 21 x 14mm





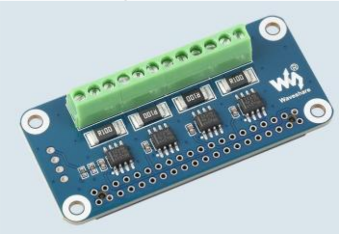
6.4.1 Trade Studies – Voltage/Current Sensors

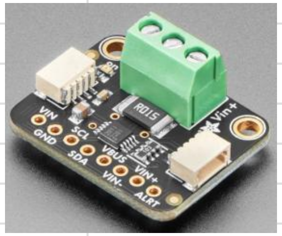
- Provides voltage AND current readings
- No need to add resistors and calculate V=IR
- Avg power consumption
- Small
- Great range

Voltage/Current Sensors	Weight	Waveshare 4-ch		Adafruit INA260		Adafruit INA228	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Operating Voltage	20%	5	1	5	1	5	1
Voltage Range	20%	4	0.8	5	1	5	1
Current Range	30%	2	0.6	5	1.5	5	1.5
Cost	15%	4	0.6	5	0.75	4	0.6
Size	15%	2	0.3	4	0.6	3	0.45
Total Score	100%		3.3		4.85		4.55

Scoring System	
5	Ideal
4	Great
3	Good
2	Acceptable
1	Poor

Waveshare 4-ch	Adafruit INA260	Adafruit INA228
Operating Voltage: 3.3V / 5V	Operating Voltage: 3V / 5V	Operating Voltage: 3V / 5V
Voltage Range: 0 - 26V	Voltage Range: 0 - 36V	Voltage Range: 0 - 85V
Current Range: +/- 3.2A	Current Range: 0 - 15A	Current Range: 0 - 10A
Cost: $20	Cost: $10	Cost: $15
Size: 65 x 30 x 3mm	Size: 22.9 x 22.8 x 3mm	Size: 25.8 x 20.2 x 10.1 mm





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6.4.1 Trade Studies – Temperature Sensors

- Utilizes temperature probe
- Read temps to ensure no overheating
- Cheap
- Small
- Great range

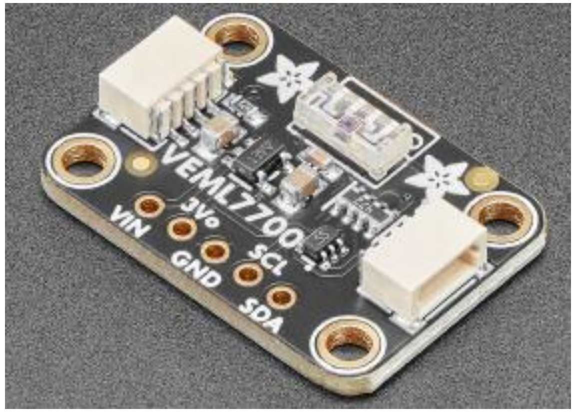
Temperature Sensors	Weight	SparkFun TMP102		Adafruit MLX90632		SparkFun STTS22H	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Voltage	20%	5	1	4	0.8	5	1
Current	20%	5	1	3	0.6	4	0.8
Temp Range	30%	5	1.5	3	0.9	5	1.5
Cost	15%	5	0.75	3	0.45	5	0.75
Size	15%	5	0.75	4	0.6	5	0.75
Total Score	100%		5		3.35		4.8

Scoring System	
5	Ideal
4	Great
3	Good
2	Acceptable
1	Poor

SparkFun TMP102	Adafruit MLX90632	SparkFun STTS22H
Voltage: 1.4-3.6 V	Voltage: 3.3 V	Voltage: 1.5 - 3.6 V
Current: 1-10 uA	Current: 1mA max	Current: 0.5-180 uA
Range: -40C - 125C	Range: -25C - 85C	Range: -40C - 125C
Cost: $8-$10	Cost: $17-$20	Cost: $8-$10
Size: 1.6 x 1.6 mm	Size: 3 x 3 mm	Size: 2 x 2 mm

6.4.1 Trade Studies – Sun Sensors

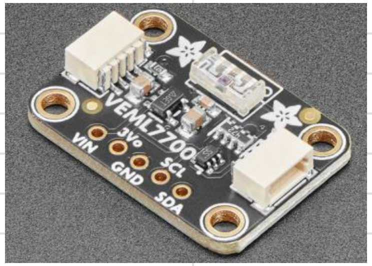
- Used for detecting deployment as sun is then visible
- Small
- Cheap
- Very low draw
- Great range

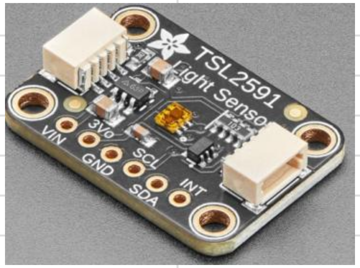


Sun Sensor	Weight	Grove SI1151		Adafruit VEML7700		Adafruit TSL2591	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Supply Voltage	20%	5	1	5	1	5	1
Lux Range	20%	5	1	5	1	5	1
Current Range	30%	3	0.9	5	1.5	4	1.2
Cost	15%	4	0.6	5	0.75	5	0.75
Size	15%	4	0.6	5	0.75	5	0.75
Total Score	100%		4.1		5		4.7

Scoring System	
5	Ideal
4	Great
3	Good
2	Acceptable
1	Poor

Grove SI1151	Adafruit VEML7700	Adafruit TSL2591
Supply Voltage: 3.3V - 5V	Supply Voltage: 2.5V - 5V	Supply Voltage: 3.3V - 5V
Lux Range: 0-1200 lux	Lux Range: 0-1200 lux	Lux Range: 0-88000 lux
Current Draw: 5.6 - 360mA	Current Draw: 0.5 - 45 uA	Current Draw: 0.1 - 4mA
Cost: $13	Cost: $5	Cost: $7
Size: 20 x 20 x 5mm	Size: 17 x 17 x 4mm	Size: 19 x 16 x 4mm





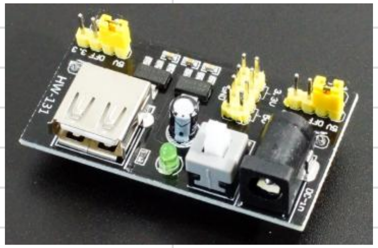
6.4.1 Trade Studies – Buck Convertor

- Used to accept variety of power inputs
- Originally Elegoo Power MB V2 because of Arduino kits
- Large size consideration
- Cheap
- Great range

Buck Convertor	Weight	Elegoo Power MB V2		DFR1015		LM2596	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Operating Voltage	15%	5	0.75	5	0.75	5	0.75
Output Voltage	20%	4	0.8	5	1	5	1
Current Range	15%	5	0.75	3	0.45	3	0.45
Cost	15%	5	0.75	5	0.75	4	0.6
Size	35%	3	1.05	5	1.75	3	1.05
Total Score	100%		4.1		4.7		3.85

Scoring System	
5	Ideal
4	Great
3	Good
2	Acceptable
1	Poor

Elegoo Power MB V2	DFR1015	LM2596
Supply Voltage: 6.5V - 9V	Supply Voltage: 7.5V - 30V	Supply Voltage: 3V - 40V
Output Voltage: 3.3V/5V	Output Voltage: 3.3V/5V/9V/12V	Output Voltage: 1.25V - 35V
Max Current Draw: 400mA	Max Current Draw: 5A	Max Current Draw: 5A
Cost: $2	Cost: $6	Cost: $8 for 10
Size: 55 x 33 x 25mm	Size: 28 x 20 x 10mm	Size: 43 x 21 x 14mm

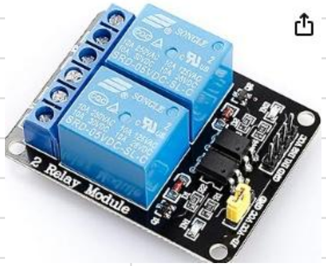


6.4.1 Trade Studies – Relay

- Needed for overcurrent protection/activating systems
- Comes in Arduino kits
- Avg power consumption
- Small
- Cheap
- Great range

Relay	Weight	SunFounder 2 Channel		Grove - Relay		Arduino Songle Relay	
		Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Size	25%	1	0.25	3	0.75	5	1.25
Cost	25%	2	0.5	3	0.75	5	1.25
Voltage Range	10%	5	0.5	5	0.5	2	0.2
Current Range	20%	5	1	5	1	5	1
Operating Voltage	20%	5	1	5	1	5	1
Total Score	100%		3.25		4		4.7

Scoring System	
5	Ideal
4	Great
3	Good
2	Acceptable
1	Poor

SunFounder 2 Channel	Grove - Relay	Arduino Songle Relay
Size: 6.86 × 6.35 × 2.03 cm	Size: 6.85x3.33x2.01 cm	Size: ToBeMeasured
Cost: $10	Cost: $3	Cost: $9 (Free)
Voltage Range: 0 - 5V	Voltage Range: 0 - 36V	Voltage Range: 0 - 5V
Current Range: 0-3.2A	Current Range: 0 - 15A	Current Range: 0 - 10A
Operating Voltage: 3.3V / 5V	Operating Voltage: 3V / 5V	Operating Voltage: 3V / 5V
		

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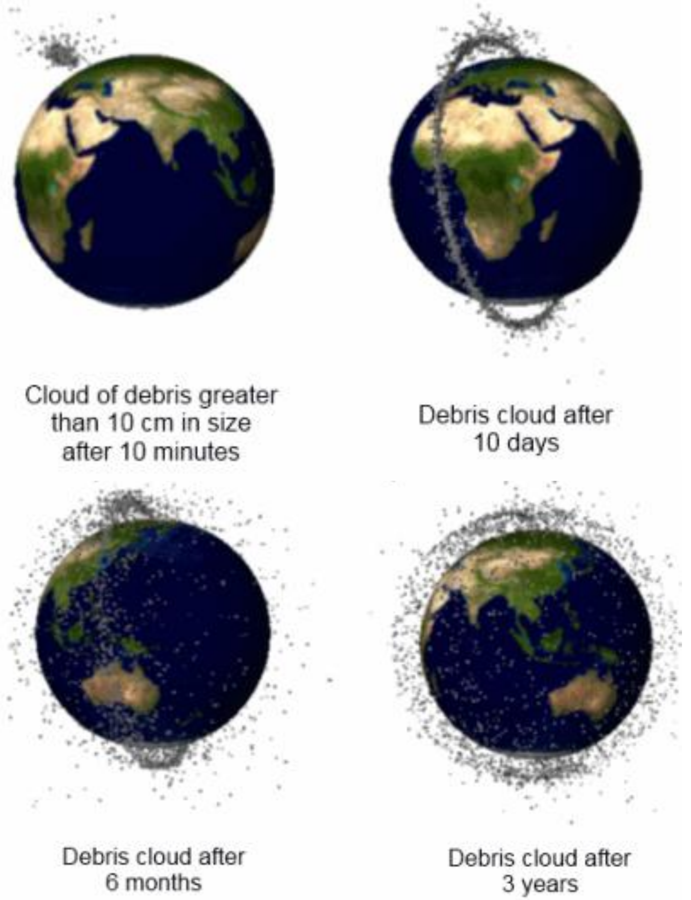
2.4 Broader Impact

- On January 11, 2007, China launched a direct ascent ASAT missile from Xichang, destroying its own FY-1C weather satellite at 863 km altitude, which resulted in significant contribution to the amount of space debris in orbit.

- Incidents such as the Chinese FengYun-1C engagement resulted in a 25% increase in the amount of trackable space debris [8].

- The possibility of CubeSat collision with both space debris and other satellites continues to increase.



Evolution of the debris cloud from a kinetic kill ASAT attack. [9]

[8] European Space Agency, "Space Environment Statistics".
[9] Secure World Foundation, "2007 Chinese Anti-Satellite Test Fact Sheet".

Jimmy Maskill, Electronics Lead