ASEN 4028 Senior Projects

May 4, 2020

CUBE^3

CU Boulder Engineers Creating Universal Boom Extensions for CUBEsats

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Team CUBE^3 has worked to develop a collapsible boom structure for CubeSat missions to separate a sensitive payload from the spacecraft bus. This boom structure is constructed of carbon fiber structural elements, PEEK connectors, and superelastic Nitinol hinges. The assembly collapses to stow within a 7x10x10 cubic centimeter volume and deploys up to 80 centimeters in length. The structure is built to support a 500 gram payload with data and power cable provisions. By design, the boom has a first resonant frequency above 2.5 Hertz because frequencies lower than this may be problematic for CubeSat control systems. The structure weighs just under a kilogram (including the payload) and has been designed to survive in a low earth orbit space environment for one year. Extensive thermal modeling and thermal chamber testing have shown that the system is operable within the temperature regime expected on orbit, with a nominal deployment temperature of 10°C. The design integrates a sensor that monitors boom deployment and relays progress to the flight computer. Due to the COVID-19 pandemic, the team was unable to conduct a launch environment test to verify the structure can survive a 10-G launch environment, though preliminary analysis shows promising results. Apart from this setback, the team was ahead of schedule in manufacture and test. Initial tests demonstrated a clear path to verifying all requirements and suggested that the boom design is viable.

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Nomenclature

ATK	Alliant Techsystems
Batten	X & Y-axis element of structure (normal to Longerons)
C2	Command and Control
CAM	Computer Aided Manufacturing
CDR	Critical Design Review
CNC	Computer Numerical Control
COTS	Commercial Off The Shelf
Covid-19	COronaVIrus Disease 2019
CubeSat	A small satellite conforming to standardized physical dimensions
IR	Infrared
ISS	International Space Station
LEO	Low Earth Orbit
LiDAR	Light Detection and Ranging
Longeron	Z-axis element of deployed structure (pointing between CubeSat and Instrument)
NASA	National Aeronautics and Space Administration
Nitinol	Nickel-titanium Alloy
PDR	Preliminary Design Review
PEEK	Polyether ether ketone - A robust plastic with a high degree of space-ratedness and low electrical conductivity
PLA	Polylactic Acid
UV	Ultraviolet
U	Unit, a measure of CubeSat volume equivalent to a cube with 10 cm sides

1. Project Purpose

Rowan Gonder, Roger Heller

THE purpose of this project is to solve the problem of a sturdy extendable boom small and light enough to work effectively on a CubeSat. To date, over 1000 CubeSats have been launched into Earth's orbit [1], and over 3000 more forecast to be launched within the next six years. With this explosive growth in the market, interest is certain to grow in the field of deployable structures for a variety of applications. For example, the CANVAS mission proposes deployment of a magnetic field sensor on a carbon fiber ribbon that curls into a tubular boom in order to distance the sensitive instrument from the electromagnetic interference (EMI) of the spacecraft electronics and power distribution subsystems. With a little imagination, one can easily envision other applications: cameras separated by greater distance to take advantage of parallax in measuring distance to other orbital objects, a charged particle detector set at a distance from the shadow of the bus, or a communications antenna able to take advantage of wavelengths not available in the constrained physical dimensions of a standard CubeSat configuration. However, any technical solution to this particular challenge also faces the constraints imposed by the CubeSat architecture and operating environment, specifically in the areas of physical dimensions, mass budget, vibration response, attitude control, and survival in the space environment.

With this in mind, this project proposes the development of a novel deployable structure for use on CubeSats which is capable of accommodating a notional scientific instrument. Specifically, this system will be able to deploy on command from either ground support equipment (GSE) or the spacecraft flight computer (FC). The structure will place a notional instrument payload with a mass of 500g and physical dimensions delimited by an 8x8x8cm cube at a distance no less than 60cm from the spacecraft structure, measured from the point of closest approach between the instrument and the spacecraft. In addition, the structure will provide routing for electrical power and signal cabling to the instrument from the spacecraft bus. Because the attitude determination and control subsystem (ADCS) operates at 5.0 Hz, it cannot control resonant modes slower than 2.5 Hz. Therefore, the structure shall have a first resonant mode greater than or equal to 2.5 Hz and the ability to survive a simulated space launch vibration profile while in the stowed configuration. While stowed, the deployable structure with the instrument attached will occupy a space no larger than 1.5 U. Finally, the system will provide positive confirmation via telemetry reported via the flight computer when deployment is complete.

As noted previously, solutions to this particular challenge do exist on the market. However, this project aims to offer attractive alternatives in three key areas. The first being that the resonant frequency will be higher than that of existing solutions. Secondly, rather than providing for cable routing after the fact, this project will incorporate both power and signal wiring into the design. Finally, the cost of this project is predicted to be much lower than other solutions on the market and potentially applicable to a wider range of mission applications.

2. Project Objectives and Functional Requirements

A. Objectives

Ben Pearson

Table 1 defines the levels of success for each Critical Project Element (CPE) for the CUBE^3 project. Level 1 describes the minimum criteria for meeting project requirements. Level 2 is a slight step up and describes an expected attainable goal above the minimum standard. Levels 3 describes a level of success that is difficult to complete but is expected to be doable within the time and budgetary limits of the project. Not all CPEs have all three levels as they were not defined by the customer or the team.

Table 1 Levels of Success

Project Element	Level 1	Level 2	Level 3	Justification
Deployable Boom Structure (DBS): Deployment Length *Validation Method: System test*	The boom can be extended 60 cm past the exit of the spacecraft body.		The boom can be extended 1 m past the exit of the spacecraft body.	The customer's absolute minimum requirement is 60 cm boom deployment, but the full 1 m is indicated to be the objective distance.
Deployable Boom Structure (DBS): Resonant Frequency *Validation Method: System test*	The boom demonstrates a first frequency mode over 2.5 Hz when analytically modelled.		The boom demonstrates a first frequency mode over 2.5 Hz in a vibe table test environment.	A first frequency mode of 2.5 Hz is a customer requirement. The team will first perform a modelling analysis on the proposed boom before constructing and testing it.
Deployable Boom Structure (DBS): Total Mass and Size *Validation Method: System test*	The deployable boom system and the 1.5 U containment structure have a mass of less than 1.5 kg.			Customer has asked that the entire assembly *including* the instrument be less than 2 kg. The instrument weighs 500 g. Customer needs also include a 1.5 U maximum volume. The instrument alone is 8x8x8 cm.
Deployable Boom Structure (DBS): Deployment Time *Validation Method: System test*	The boom fully deploys in less than 2 minutes.			This is a simple customer requirement.
Deployable Boom Structure (DBS): Damping Time *Validation Method: System test*	Mathematical models indicate the termination of any significant oscillation less than 2 min after deployment.		Testing environment indicates the termination of any significant oscillation less than 2 min after deployment.	As with rigidity, testing will follow analytics. The customer has heavily indicated a preference for passive (material driven), rather than active, damping.
Environmental Resilience (ER) *Validation Method: Thermal-Vacuum Tests*	Analysis indicates probable 1 year lifespan on orbit.	Vacuum testing indicates probable 1 year lifespan on orbit.	TVac testing indicates probable 1 year lifespan on orbit.	This structure must be designed to survive LEO for over one year. Factors to consider include temperature, vacuum, UV, and radiation.
Software Interface (SI) *Validation Method: System test*	The external C2 computer is able to send commands to the boom electronics.	The external C2 computer is able to send commands to boom electronics and receive telemetry from the deployment sensor.	The boom successfully deploys when commanded. C2 computer receives telemetry from deployment sensor and test instrumentation.	If attached to a real satellite, this boom would interface directly with the CubeSat's computer. For testing, the team will use its own microcontroller.
Payload Connectivity (PC) *Validation Method: Inspection*	The system is able to deploy power and data cables to the sensor payload at the end of the boom.			One major drawback to the current commercial boom in use by the customer's team is an inability to carry wires to the payload at the end. The customer would like a boom for which this is not an issue.

B. Concept of Operations

Adam Hu, Michael Burke

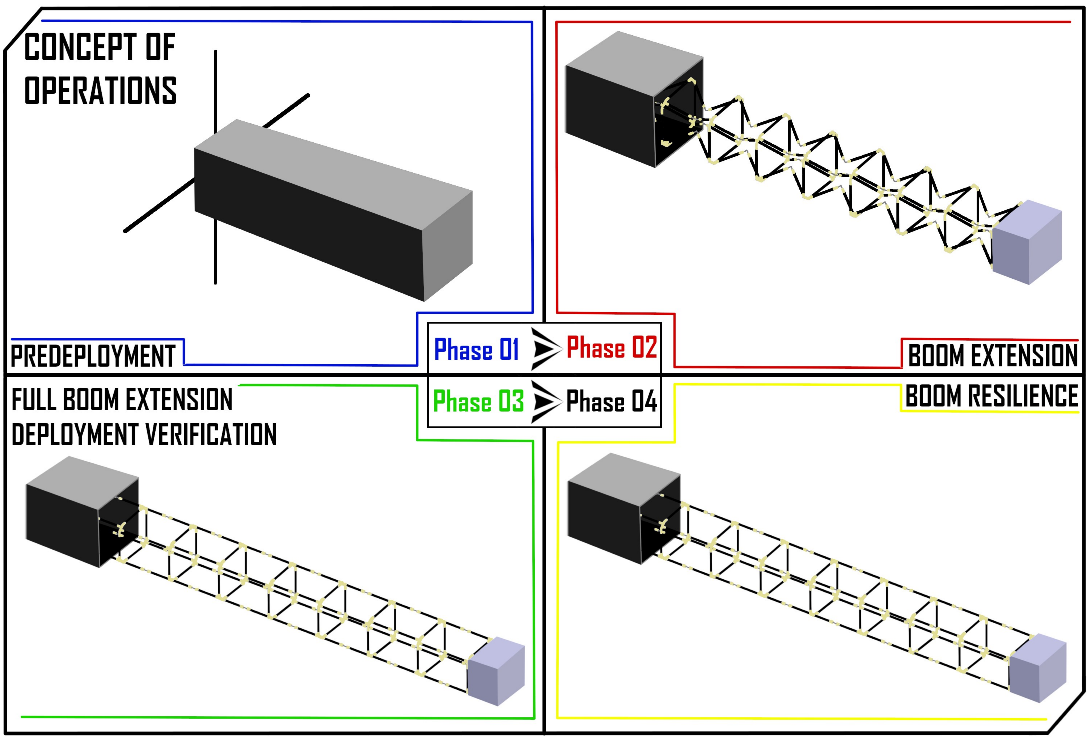


Fig. 1 CONOPS

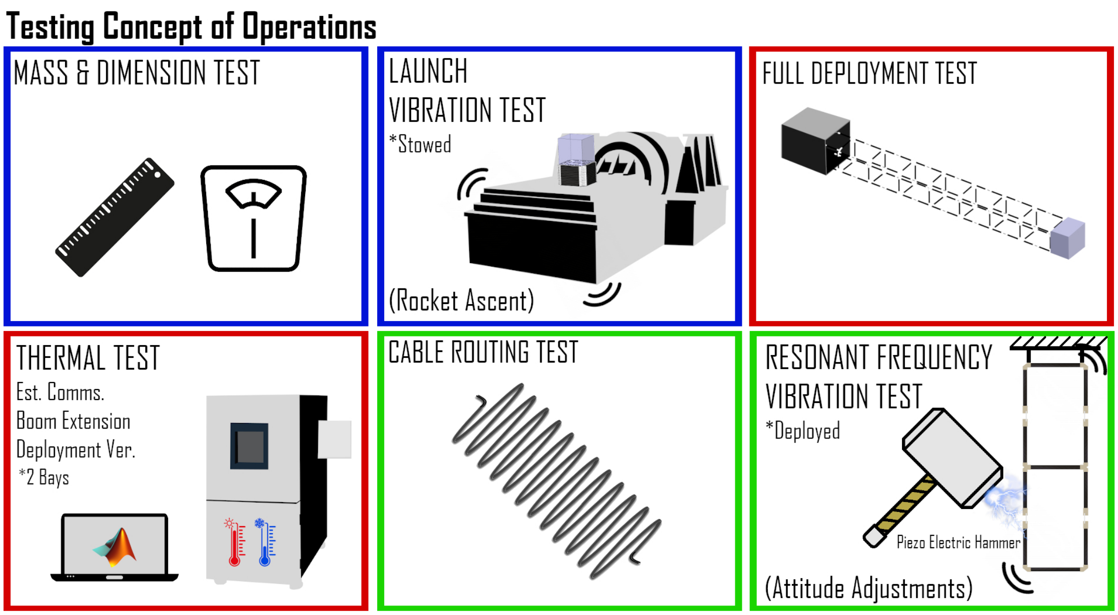


Fig. 2 Testing CONOPS

Given in the above two images are the CONOPS and testing CONOPS respectively. Note the color coordination between the two. These colors help to indicate and map each requirement validation test back to a specific phase of the CONOPS showcasing the relationship between each. If we begin at phase one of the CONOPS, enclosed in blue, we see that this validates the pre-deployment phase. This was verified through the mass dimension test along with the launch vibration test in the stowed configuration. The mass was measured to ensure the team met the mass requirements and the dimensions were also measured to verify that the boom would fit within a 1.5 U CubeSat. Phase two is the boom extension verification and the team validated this through a full deployment test on a table and a thermal test with only two bays in a thermal chamber. Details of these tests will be provided in the testing section. Phase three is confirmation that the boom has deployed successfully and this was seen through the cable routing test and resonant frequency test. Note how there is no yellow within the testing CONOPS because the validation for this phase was conducted through strictly analysis.

C. Project Deliverables

Michael Burke

1. Course Deliverables

Given here is a list of the course deliverables that were required by the team.

- Project Definition Document (PDD)
  - Primary statement of work and team project understanding.
- Conceptual Design Document (CDD)
  - Presentation of baseline designs, architectures, and critical components for project execution.
- Preliminary Design Review (PDR)
  - Down-selection of traded projects elements and preliminary analyses to gauge viability.
- Critical Design Review (CDR)
  - Thorough presentation of analyses and detailed design elements for project components and trajectory.
- Fall Final Report (FFR)
  - Complete team analysis and expectations to a high degree of fidelity. Encompasses master plan for physical development, verification, and validation.
- Manufacturing Status Review (MSR)
  - Presented assessment of manufacturing preparedness and outline of manufacturing plan.
- Test Readiness Review (TRR)
  - Presented assessment of test preparedness and outline of testing plan.
- AIAA Paper
  - Overview of project motivations, processes, analyses, and findings.
- Executive Summary
  - Very high level assessment of project progress and status.
- Final Oral Report (FOR)
  - Project close-out presentation describing project process arc, results, verification, and validation.
- Project Final Report (PFR)
  - Complete findings of all project elements, processes, and engineering methodologies.

2. Customer Deliverables

Given here is a list of the customer deliverables that were required by the team.

- Physical Boom Structure
  - Primary project element and deliverable.
- Resonant Frequency Test Results and Analysis
  - Analytical and tested assessment of primary boom structure resonant frequency.

- Thermal Chamber Results for Deployment Restraints
  - Space environment restrictions and capabilities for boom structure and deployment mechanisms.
- Mass/Dimension Test Results
  - Final size and volume, within customer requirements, of developed system.
- Data Rate From Cables
  - Data and power routing expectations between customer CubeSat and instrument supported by primary boom structure.
- Launch Environment Results
  - Expectations of survivability from the initial rocket launch environment.

D. Functional Block Diagram

Rowan Gonder

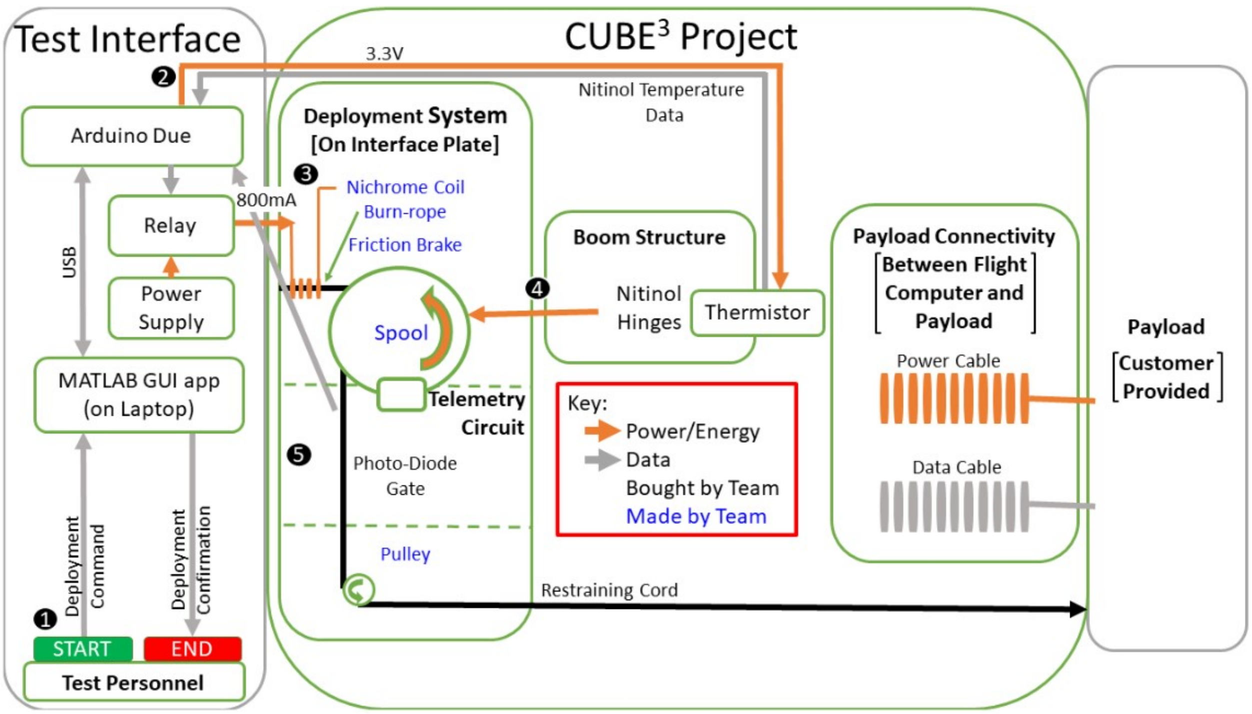


Fig. 3 Functional Block Diagram

As shown in the Functional Block Diagram above, the boom assembly will be used to isolate a payload .8 meters from a CubeSat. Once the command to deploy is sent to the CubeSat, the temperature on the structure's Nitinol hinges will be checked to ensure it is above the thermal chamber tested 10°C minimum full deployment temperature. If this is true, a relay will be closed allowing power to be sent through the nichrome wire wrapped around the burn-rope. Once the burn-rope melts, the spool and restraining cord will be released allowing deployment to begin. Deployment is fully powered by stored energy in the Nitinol hinges and is slowed by a friction brake on the spool. Also on board will be a telemetry circuit comprised of a photo-diode gate which will count the number of turns the spool completes by reading voltages on the receiver which change when the painted half of the spool comes into view. This data will be sent back to the computer and processed to display on the user interface as the deployment progress. It has been determined through analysis that the spool should complete 22 rotations in a single deployment. Once the boom is fully extended it will require no power to remain in the fully deployed configuration. The boom assembly will also act to transfer power and data to the payload for the entire CubeSat mission duration via routed cables through the structure.

E. Functional Requirements

Michael Burke

Given below is a numbered list of all nine functional requirements we had for this project. An explanation of the source and rationale for each can be found in section 3A, *Requirements Flow-Down*, of this report.

1) The boom structure shall be capable of deploying an instrument of up to 500 grams with the dimensions 8x8x8 centimeters.
2) The deployable boom structure shall provide routing for power and signal cabling up to a total of 12 wires at a minimum size of 30 American Wire Gauge (3 separate differential signals and a 3-wire power setup).
3) The boom assembly, in the undeployed state with the instrument attached, shall have dimensions within 1.5U and fit within the confines of the NanoRacks CubeSat Deployer (NRCSD).
4) The boom assembly shall be capable of receiving commands from and sending deployment status confirmation to the CubeSat flight computer.
5) The boom assembly shall be capable of re-stowing the fully deployed boom structure into an undeployed state through a manual assist.
6) When fully deployed the first resonant frequency of the boom structure shall be greater than or equal to 2.5 Hertz.
7) The boom assembly shall survive up to 10 g vibration in the undeployed configuration.
8) The deployable boom shall survive the space environment in both the stowed and deployed configurations for an operational lifespan of 1 year.
9) When fully assembled, with the 500 gram instrument attached, the whole boom assembly shall have a mass less than or equal to 2 kilograms.

3. Design Process and Outcome

A. Requirements Flow-Down

Michael Burke

FR 1: The boom structure shall be capable of deploying an instrument of up to 500 grams with the dimensions 8x8x8 centimeters.

Motivation: This is the main goal of the project. The mass and dimensions coming directly from the customer.
Verification Method: Demonstration / Test
Verification Success Criteria: The boom assembly can successfully deploy the instrument without failure.

DR 1.1: The boom structure shall have the capability to attach an instrument of 500 grams or less, with the dimensions 8x8x8 centimeters.

Motivation: In order to deploy the instrument there must be a place on the boom structure which allows for the attachment of the instrument to occur.
Verification Method: Demonstration
Verification Success Criteria: An instrument can be attached to the boom structure.

DR 1.2: The boom structure, when fully deployed, shall extend a minimum distance of 60 centimeters from the attachment point of the instrument to the outer edge of the CubeSat.

Motivation: This is a requirement directly from the customer who specified that this is the minimum distance in which the instrument in question must be from the CubeSat.
Verification Method: Demonstration
Verification Success Criteria: The fully extended boom structure spans a distance of 60 cm or greater.

DR 1.3: The deployment mechanism used to extend the boom structure shall be capable of using 30 Watts of power or less in order to fully extend the boom structure.

Motivation: This power requirement, along with the value, came directly from the customer following the question of what the power available would be.
Verification Method: Test
Verification Success Criteria: The deployment mechanism uses less than 30 W of power during deployment.

DR 1.4: During the deployment process the boom structure shall reach full extension in under 2 minutes.

Motivation: This deployment time requirement, along with the value, came directly from the customer following the question of what deploy speed should be designed.
Verification Method: Demonstration
Verification Success Criteria: The deployment process takes less than 2 minutes.

SR 1.4.1: During the deployment of the boom structure the acceleration experienced by the attached instrument shall be a maximum of 10 g's.

Motivation: This is a customer specific requirement aimed at aiding in the protection of the attached instrument. Any loading above this value will result in the instrument breaking.
Verification Method: Test
Verification Success Criteria: The instrument's acceleration does not exceed 10 g's during deployment.

DR 1.5: Any oscillation which occurs in the spacecraft due to the deployment process shall be damped out in under 2 minutes.

Motivation: This requirement comes directly from the customer as it is believed that any oscillations that occur must be damped out in this time in order to avoid any repercussions from the oscillations.
Verification Method: Test
Verification Success Criteria: Any oscillation that occurs can be damped out in under 2 minutes.

FR 2: The deployable boom structure shall provide routing for power and signal cabling up to a total of 12 wires at a minimum size of 30 American Wire Gauge (3 separate differential signals and a 3-wire power setup).

Motivation: This is a specific requirement from the customer, as one of the main goals of this project is to improve on the wire capability of other boom assemblies on the market.
Verification Method: Demonstration
Verification Success Criteria: 12 wires can successfully be stowed within the boom assembly while deployed and undeployed.

DR 2.1: The boom assembly shall have the capability of routing 3 separate differential signals, each of which will have wires of 30 American Wire Gauge (AWG) or larger.

Motivation: This stems from the parent requirement as 9 of the 12 wires must be used for differential signals. The minimum wire gauge came directly from the customer.
Verification Method: Demonstration
Verification Success Criteria: The 9 wires used to accommodate 3x differential signals can successfully be stowed within the boom assembly while deployed and undeployed.

DR 2.2: The boom assembly shall have the capability of routing a three-wire power setup capable of transporting 15 Volts at 0.5 Amps.

Motivation: This stems from the parent requirement as 3 of the 12 wires must be used for power supply. The voltage and amp numbers came directly from the customer.
Verification Method: Demonstration
Verification Success Criteria: The 3 wires used to accommodate the power setup can be successfully stowed within the boom assembly while deployed and undeployed.

FR 3: The boom assembly, in the undeployed state with the instrument attached, shall have dimensions within 1.5U and fit within the confines of the NanoRacks CubeSat Deployer (NRCSD).

Motivation: This size requirement came directly from the customer as the boom assembly must take up only one half of a full 3U CubeSat.
Verification Method: Demonstration
Verification Success Criteria: The full boom assembly can fit within a 1.5U space.

DR 3.1: The boom assembly, in the undeployed state with the instrument attached, shall have a stow length less than or equal to 15 centimeters.

Motivation: This requirement stems from the parent requirement as the length of a 1.5U space is 15 cm.
Verification Method: Demonstration
Verification Success Criteria: The full boom assembly has a length less than or equal to 15 cm.

DR 3.2: The boom assembly, in the undeployed state with the instrument attached, shall have a stow height less than or equal to 10 centimeters.

Motivation: This requirement stems from the parent requirement as the height of a 1.5U space is 10 cm.
Verification Method: Demonstration
Verification Success Criteria: The full boom assembly has a height less than or equal to 10 cm.

DR 3.3: The boom assembly, in the undeployed state with the instrument attached, shall have a stow width less than or equal to 10 centimeters.

Motivation: This requirement stems from the parent requirement as the width of a 1.5U space is 10 cm.
Verification Method: Demonstration
Verification Success Criteria: The full boom assembly has a width less than or equal to 10 cm.

DR 3.4: The boom assembly, in the undeployed state with the instrument attached, shall conform to the NanoRacks IDD mechanical specifications by accommodating 6 millimeters by 6 millimeters rails at the corners of the 10 centimeters by 10 centimeters cross section.

Motivation: This is a customer specific requirement aimed at having the boom assembly be compatible with the NanoRacks launching system.
Verification Method: Demonstration
Verification Success Criteria: The full boom assembly fits within the NanoRacks Deployment volume.

FR 4: The boom assembly shall be capable of receiving commands from and sending deployment status confirmation to the CubeSat flight computer.

Motivation: The boom assembly must be able to communicate with the flight computer in order to receive the deployment command and send the fully deployed verification signal.
Verification Method: Test
Verification Success Criteria: The boom assembly can successfully communicate with the flight computer.

DR 4.1: The deployment mechanism shall be capable of starting the deployment process on command when provided by Ground Support Equipment (GSE) or the spacecraft computer.

Motivation: This is the requirement that stems from the parent requirement actually stating that the boom assembly must be able to deploy on command.
Verification Method: Test
Verification Success Criteria: The boom deploys successfully on command.

DR 4.2: The boom assembly shall be capable of sending confirmation to the flight computer about deployment status.

Motivation: This is the requirement that stems from the parent requirement actually stating that the boom assembly must be capable of sending a deployment verification signal of the deployment status.
Verification Method: Test
Verification Success Criteria: The boom successfully signals its deployment status.

SR 4.2.1: The boom assembly shall be capable of identifying the deployment status of the boom arm.

Motivation: This requirement stems from the above requirement in which the boom assembly must have some way of verifying the success of the deployment.
Verification Method: Test
Verification Success Criteria: A successful verification of deployment status can occur.

DR 4.3: Following deployment (successful or unsuccessful), power to the deployment mechanism shall be shut off.

Motivation: This requirement comes from the customer who stated that the boom assembly must not draw power once deployment has completed.
Verification Method: Test
Verification Success Criteria: Power to the deployment mechanism can successfully be turned off following deployment.

FR 5: The boom assembly shall be capable of re-stowing the fully deployed boom structure into an undeployed state through a manual assist.

Motivation: This is a specific requirement from the customer, as part of this project requires being able to test multiple deploys while in the lab, so the boom assembly must be able to re-stow for re-test.
Verification Method: Demonstration / Test
Verification Success Criteria: Boom assembly successfully re-stows.

DR 5.1: The boom assembly shall be capable of multiple re-stows and re-deploys of the boom structure.

Motivation: This requirement stems from the parent requirement as the boom assembly must be tested for multiple deploys in order to prove resilience of the system.
Verification Method: Test
Verification Success Criteria: Boom assembly successfully re-stows and redeploys multiple times.

FR 6: When fully deployed the first resonant frequency of the boom structure shall be greater than or equal to 2.5 Hertz.

Motivation: This is a specific requirement from the customer, as one of the main goals of this project is to improve on the resonant frequency of other boom assemblies on the market.
Verification Method: Test
Verification Success Criteria: When tested, the first resonant frequency is measured to be greater than or equal to 2.5 Hz.

DR 6.1: The boom structure, when fully deployed, shall be compatible with the XACT-15 ADCS system used by the spacecraft.

Motivation: When the boom structure is fully deployed the ADCS system on board the CubeSat must still be able to function. This means the frequency response for boom structure is within the controllable range of the XACT-15 ADCS system.
Verification Method: Analysis
Verification Success Criteria: Successful use of the XACT-15 system occurs while fully deployed.

FR 7: The boom assembly shall survive up to 10 g vibration in the undeployed configuration.

Motivation: The 10 g vibration number came from the customer along with a document on how to perform the "Random Vibe", "Sinusoidal Vibe", and "Shock" testing needed to prove the system will survive launch.
Verification Method: Analysis / Test
Verification Success Criteria: The boom assembly remains intact and undamaged after enduring 10 g vibrations.

DR 7.1: The boom assembly shall survive environmental conditions of launch in the undeployed configuration. The launch environment will be simulated by a compressed vibe test of up to 10 g's.

Motivation: Vibe testing is purely to ensure that the system doesn't break during launch, so we will vibe test for launch conditions.
Verification Method: Test
Verification Success Criteria: The boom assembly remains intact and undamaged after enduring 10 g vibrations in a test environment.

FR 8: The deployable boom shall survive the space environment in both the stowed and deployed configurations for an operational lifespan of 1 year.

Motivation: The 1 year lifespan came directly from the customer as the time in which the boom assembly should remain functional. The customer also specified three key aspects of the space environment in which research should be done. These are broken down into the following three children requirements.
Verification Method: Analysis / Test
Verification Success Criteria: Boom assembly components do not break, decay, or reduce in functionality as a result of time spent in the space environment.

DR 8.1: The boom assembly shall survive the thermal fluctuations of the space environment in both the deployed and undeployed configuration. The thermal fluctuations will be simulated through thermal chamber testing and TVAC testing.

Motivation: This requirement focuses on one specific aspect of the space environment in which the boom assembly must be capable of surviving.
Verification Method: Test/Analysis
Verification Success Criteria: Boom assembly components do not break, decay, or reduce in functionality as a result of thermal fluctuations.

DR 8.2: The boom assembly shall survive the radiation of the space environment in both the deployed and undeployed configuration.

Motivation: This requirement focuses on one specific aspect of the space environment in which the boom assembly must be capable of surviving.
Verification Method: Analysis
Verification Success Criteria: Boom assembly components do not break, decay, or reduce in functionality as a result of radiation in space.

SR 8.2.1: The boom assembly shall survive UV radiation within the space environment in both the deployed and undeployed configuration.

Motivation: This requirement focuses on one specific aspect of the space environment in which the boom assembly must be capable of surviving with an emphasis on the solar spectrum in Low Earth Orbit (LEO).
Verification Method: Analysis
Verification Success Criteria: Boom assembly components do not break, decay, or reduce in functionality as a result of UV radiation.

FR 9: When fully assembled, with the 500 gram instrument attached, the whole boom assembly shall have a mass less than or equal to 2 kilograms.

Motivation: This is a specific requirement from the customer, as the mass of the boom assembly must not exceed the typical mass of half a 3U CubeSat. The value, given to us by the customer, leaves some room for margin if extra mass is needed else where within the CubeSat.
Verification Method: Demonstration
Verification Success Criteria: A 2 kg or less weight measurement is achieved when the full boom assembly is weighed.

B. Boom Structure

Ben Pearson

The design process for the primary boom structure focused on similar heritage systems for inspiration and baseline concepts. The notion of a boom in a space system is not necessarily new, but the reduced dimensions and relatively high resonant frequency due to the CubeSat restrictions served as the primary design concerns. Existing architectures which especially gained traction in the preliminary research and seemed primed to suit the team's needs included a small coilable truss from ATK and a much larger boom system in use on the International Space Station (ISS) [2]. These designs offered the team some pivotal guidelines on material expectations and generalizable capabilities in the aerospace environment.

From an early stage in the project both of these concepts, scaled to requisite size, were analyzed for their viability and suitability in meeting the 2.5Hz resonant frequency requirement. Their most simple iterations were fed through SolidWorks resonance tests, which were in turn validated with simple hand calculations (as demonstrated in Table 2 using the equations shown to the right). Finding both designs to be structurally sound from this very basic level, the team performed a trade study between them (and others) to best assess the most workable option and a path forward. The trade focused on facets such as machinability, design complexity, and team preparedness.

Preliminary Bending Frequency Approximation [3]:

$$f = \sqrt{\frac{EI}{M}}, \text{ where } EI = \frac{n}{2} E A_l R^2$$

Preliminary Torsion Frequency Approximation [3]:

$$f = 2\pi\sqrt{\frac{GJ}{I+\frac{1}{3}I_b}}, \text{ where } GJ = \alpha n E A_d R^2 \cos^2\theta \sin\theta \cos^2(\frac{\pi}{n})$$

Table 2 Preliminary Hand Calculation Results

	ISS-like	Coilable
Bending Frequency	14.96 Hz	12.9 Hz
Torsion Frequency	NA	6.42 Hz

Table 3 Trade Study Grades for Conceptual Prototypes

Criteria	Weight	ISS-like	Stackable	Inch-worm	Coilable Truss	Screw
Mass	10%	5	5	5	5	4
Manufacturability	20%	4	4	4	4	4
Mechanical Complexity	20%	4	4	3	4	3
Heritage	15%	5	3	3	5	4
Rigidity	15%	5	5	5	5	4
Team Knowledge	20%	5	5	4	4	4
Weight Total	**100%**	**4.6**	**4.3**	**3.9**	**4.4**	**3.8**

The *ISS-like* design was shown as the most practical option moving forward, so the team down-selected and focused its energies on maximizing its capabilities. The frequency calculation equations of a cantilever beam (and, less clearly, the more complex equations above) demonstrated that frequency resonance would be proportional to the square root of strut area, and inversely proportional to the mass of the system. As such, the team recognized that the components, especially the longerons, should be as wide and lightweight as possible - mathematical proofs of ideas which aligned with engineering judgement.

Fundamental Frequency Equations:

$$f = \sqrt{\frac{EI}{4mL^4}}$$

where

$$EI = \frac{n}{2} E A_l R^2$$

To these ends, and to additionally support a customer request that the system should minimize use of metal components, the team opted to utilize carbon fiber and polyether ether ketone (PEEK) plastic as the chief structural elements. In addition to good strength properties and low densities these materials benefited from reasonably strong heritage and resilience in the space environment. Additionally, both of these materials had high electric resisitivity, reducing the potential for the inducement of an interfering electric field, in accordance with a request from the customer.

These materials were also selected for their coefficients of thermal expansion, which were both low and, importantly, similar. Every iteration of this design required interlocking pieces of some description, so it was of great importance that they expand and contract at a similar rate to avoid cracking in extreme thermal environments or under the stress of repeated thermal cycling in low Earth orbit.

The keystone material choice, however, was that of the superelastic Nitinol hinges, which the team intended to utilize as both a deployment driver and a structural element. Nitinol is a nickle-titanium alloy processed, in this case, to have an unusually high degree of elasticity and a considerable resistance to deformation. This was actually a material borrowed from the aforementioned Coilable Truss concept explored by ATK and, although typically used in the medical industry, Nitinol has a small degree of heritage in space as a Mars Rover tire, and is being explored by NASA for utilization in bearings and gears [4]. Used in the team's intended way, the Nitinol hinges acted as springs between the layers - providing deployment force while compressed, but providing both rigidity and damping to the deployed architecture.

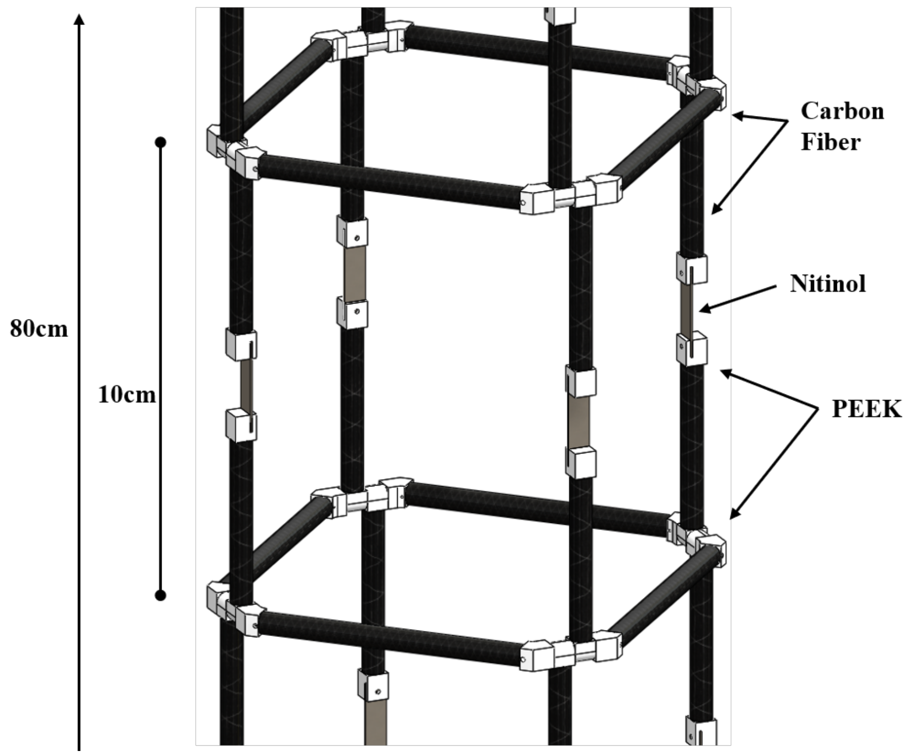


Fig. 4 Preliminary Boom Design

Before beginning construction, the team ran a series of simulations, supported by mathematical models, to demonstrate that the proposed structure would meet resonant frequency requirements. As a student project, the team found itself somewhat limited for software options. Ideally it would have utilized an advanced modeling software like Ansys or Abaqus, but encountered substantial issues with both licensing and availability - limiting the feasibility of these options. Instead, the team took further advantage of the SolidWorks frequency calculation capabilities, with careful verification of the software's reliability using hand calculations.

Table 4 Analytic Results Compared with SolidWorks Software

Simplified Model	Analytic Result	SoldWorks Result	Error
Single Rod, 110mm, No Payload	452.2Hz	452.6Hz	0.1%
Four Rods, 1250mm, No Payload	53.9Hz	61.1Hz	13.4%
12 Bay Truss, 1250mm, No Payload	71.6Hz	31.1Hz	56.6%
4 Rods, 1250mm, Torsion Analysis	24.5Hz	21.3Hz	13.1%

First, using the aforementioned fundamental equations, the structural analysis subteam compared the resonances of a single, 110m carbon fiber rod, and found a difference between SolidWorks and hand calculations of less than 0.1%. The subteam then followed the same procedure with four rods, and found a variation of about 13.4%. Addition of mechanically basic bays to the model then resulted in a difference of almost 57%. There is, of course, a non-trivial divergence here - but the team recognized that neither the hand calculations (this time utilizing the Discrete Stiffness Method) nor the software were capable of capturing the full picture [5]. This margin was considered to be acceptable, and suitably established the legitimacy of the SolidWorks software for these purposes.

Having substantiated its frequency modeling capabilities, the SolidWorks design was equipped with a 500 g instrument, per the requirements, and the simulation was run once again. The resultant resonant frequency presented as 8.8 Hz for 12 bays, and the team felt confident moving forward with the proposed design. Afforded the opportunity to take a deeper dive into the structural design and components, tweaks were made to the boom architecture, and a more realistic structure was simulated further. This had been a challenge until the software had been validated since it struggled to run a test with a mesh fine enough to properly cope with the number of parts attributed to the real model. The results of these further simulations are tabulated below.

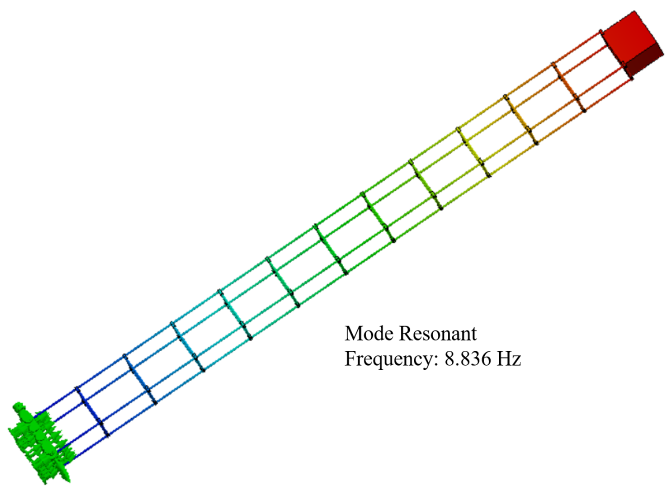


Fig. 5 SolidWorks Analysis with 500g Instrument

Table 5 Updated SolidWorks Frequency Model Results

Number of Bays	No Instrument [Hz]	500 gram Instrument [Hz]	No Instrument Error [Hz]	500 gram Instrument Error [Hz]
1	236	34.97	±2.25	±0.25
2	111	19.75	±4.59	±0.51
3	76	14.72	±6.75	±0.76
4	57	12.10	±9.00	±1.02
5	46	10.34	±11. 25	±1.28
6	38	9.05	±13.50	±1.52
7	32	8.05	±15.75	±1.79
8	28	7.24	±18.00	±2.04

Once the team reached a comfortable point in the modeling, a few weeks were spent creating a high-fidelity prototype, using cheaper Delrin rather than PEEK, to perfect and smooth both the manufacturing and frequency testing processes. The team tested epoxy strength between connections, elastic temperature ranges and bending radii of Nitinol, then deployment force of a two bay structure. These informed minor manufacturing and design decisions before finalizing the PEEK manufacturing plan. Finally, the team performed preliminary resonant frequency tests on the prototype - not with the expectation of generating usable results, but with the goals of identifying any areas in which the design may need a serious re-evaluation, and familiarizing the team with test equipment.

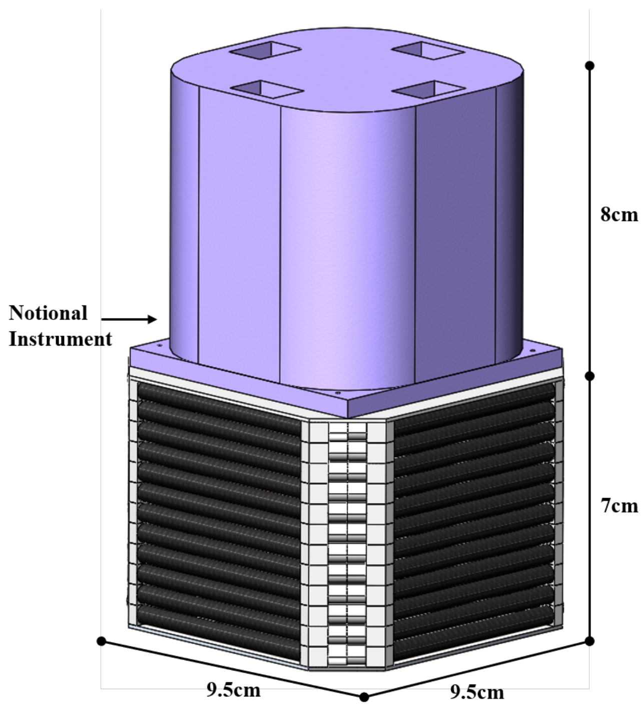


Fig. 6 Collapsed Boom Final Design (11-bay Model)

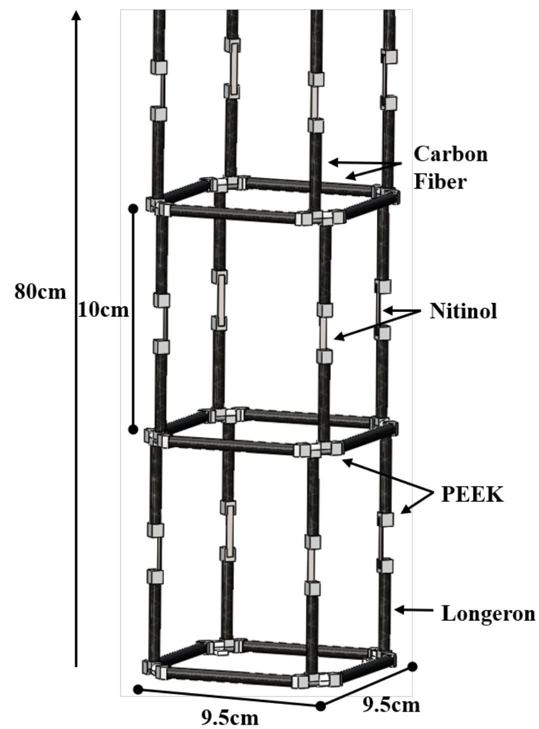
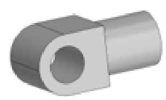
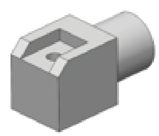
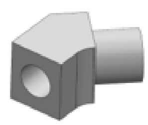
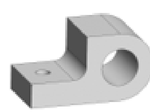


Fig. 7 Extended Boom Final Design (3 of 8 bays)

The final boom system closely resembled the system created after just the first month's worth of design work. However, it was not without incremental tweaks based on testing results, and in a system this compact, small tweaks can have big impacts. Early changes included a shift from aluminum connectors to PEEK connectors. This accommodated the recognition that PEEK is less dense (and therefore less massive), to satisfy the customer's aversion to metal, and to ease the machining process for the many many small parts required. The carbon fiber also changed in both length and wall thickness to strike a balance between rod area and mass, in alignment with expectations imparted by iterative analytical results and models.

The most substantial changes, though, were made in the lead-up to prototype manufacturing. Having experimented with the bending radius of the Nitinol hinges, for example, the team recognized that the part to which the hinges should attach would need alteration and expansion. This was compounded by a recognition that supply of the Nitinol itself could be challenging, and that the team was therefore restricted more than it had expected to be for its dimensional specifications. As such, the connecting part was designed to be a little bit bigger, and held the Nitinol in a manner that would be more conducive to the manufacturing process. Similar alterations were made to the other PEEK connectors shortly before the manufacturing process. Without compromising the structural needs of the design, decisions were made to have the Carbon Fiber rods wrap around the PEEK, rather than vice versa, and some of their edging was simplified. Table 6 below complies the final iterations of structure parts, their composition, and their abundance in an 80cm boom.

Table 6   Final Boom (80 cm) Structure Part List

Part Name	Part Count	Material	Picture	Dimensions [mm]
Battens	36	Carbon Fiber		L = 60 (± 0.1) Ø$_{Outer}$ = 5 Ø$_{Inner}$ = 4.5
Longerons	64	Carbon Fiber		L = 35 (± 0.1) Ø$_{Outer}$ = 5 Ø$_{Inner}$ = 4.5
Corner Rods	36	Carbon Fiber		L = 18 (– 0.5) Ø$_{Outer}$ = 3
Hinge Pieces	56	PEEK		See Part Drawing Below
Middle Connectors	64	PEEK		See Part Drawing Below
Corner Pieces	72	PEEK		See Part Drawing Below
Nitinol	32	Nitinol		L = 23 W = 3 H = 0.51
Interface Connectors	8	PEEK		See Part Drawing Below

Most of the detailed alterations seem trivial when listed as such and, structurally, most were. But they were absolutely crucial to the manufacturing process and the ability of the team to complete manufacturing in a reasonable time. Without having started early, and without building the prototype, the needs could have remained uncovered until too late in the design process.

This recognition lead to the design, risk, and manufacturing subteams working close together throughout the duration of this project. Doing so meant that both responsiveness to issues in manufacturing and ability to actually rectify the issues themselves was a streamlined and timely.

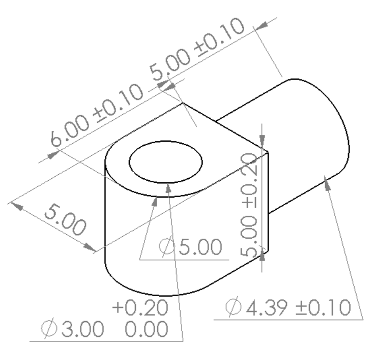


Fig. 8   Hinge Pieces [mm]

For these reasons, when design issues appeared, as they did, there was a plan already in place from a risk management perspective, and a coordinated effort to enact the solution. Further elaboration on this concept is given in both the Manufacturing and the Risk Mitigation sections of this document.

The re-evaluation of the hinge connector as discussed above was a direct beneficiary of the focus on interconnection and communication, but no part received more attention than the Nitinol hinges themselves. Almost every material aspect about the hinges increased their risk factor. They were challenging to work with because of their titanium content, prone to crimping when drilled too fast, and so small that design contingencies would be severely restricted. The material's expense and limited availability also magnified the impacts of any error, and restricted the team's ability to test manufacturing processes.

These recognized concerns lead to extra attention being paid to part design and contingencies. Thus, when it became evident that the team would be unable to procure Nitinol of 5mm width, there was a new hole pattern available to work for a 3mm wide piece instead. When conventional drill bits became blunt or snapped, the team knew exactly which carbide tipped drill bit to purchase, and how to get one within two days. When planning for the worst case scenario, the team had backup spring-based designs in case Nitinol proved to be inadequate or too problematic. This contingency never had to be enacted, but could if future project iterations require it.

With the redesigns and manufacturing plans in place using these methods, the team was able to fully complete two booms - one prototype with Delrin connectors, and one with PEEK. In total, the team manufactured in excess of 1500 parts, with material enough for almost three 1.2 m long booms, not including the 88 nuts and 88 screws required to build each structure as designed. It is challenging to emphasize quite how much the iterative process of making the Delrin boom, and addressing concerns both cooperatively and preemptively, expedited the process of executing the fully realized PEEK design.

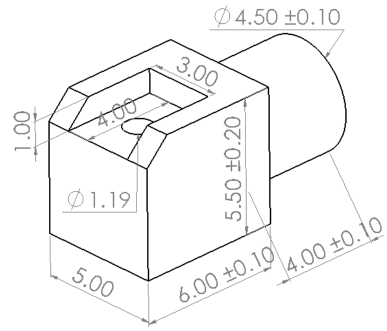


Fig. 9 Middle Connectors [mm]

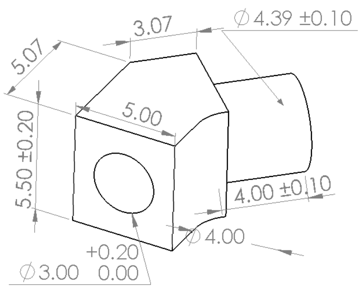


Fig. 10 Corner Pieces [mm]

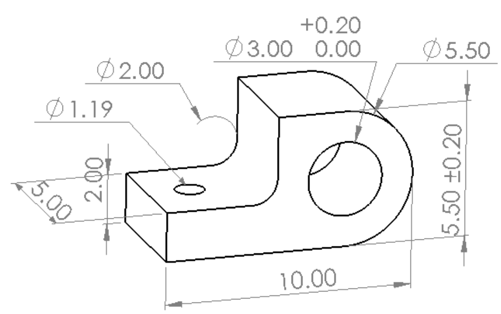


Fig. 11 Interface Connectors [mm]

C. Data and Power

Evan Johnson

A primary motivator for the conceptualization of this boom project was the ability to transfer data and power to and from the payload. A handful of the CubeSat boom architectures studied did not readily have this capability built in. The team started design of this boom with a data and power requirement in mind. In order to satisfy DR 2.1 and DR 2.2 four separate shielded twisted pairs of wires are used. These wires accommodate three differential signals along with a three wire power setup at 15 V and 0.5 A. The third wire in the three wire power setup is provided through the shielding of the power cable and is used for a ground reference. Outgassing constraints imposed by the team early on in the design process also required the insulation of the cables to have low outgassing properties. This design constraint was built into many design components to allow for potential thermal vacuum testing during the validation portion of the project. After considering 10 different options from various manufactures, 28 AWG Kapton insulated shielded twisted pair cable was chosen, made by Accu-Glass. Key considerations in choosing this cable included minimum bend radius constraints, price, and sample availability.

The specific design of the cable routing system was heavily dependant on the conceptual design chosen from table 3. Various cable routing systems were conceptualized based on the 5 designs outlined in the table. The data coil design was designed specifically for the *ISS-like* design and will therefore be discussed. The primary boom structure has 4 open cavities, of which 3 are occupied. 1 cavity holds the deployment system discussed in the following section. The other 2 spaces, on opposite sides of each other, contain 2 data coil assemblies, shown in figure 12. Each data coil contains 2 shielded twisted pair cables. The data coils were designed to have a radius of 10.8 mm, roughly 2.5 times larger than the recommended minimum bend radius of the twisted pair cables, 3.81 mm. The two twisted pair cables are held in a coil configuration with heat shrink sections. Sections of heat shrink are used instead of fully encasing the twisted wire cables to maximize the use of containment tube space and decrease the force required to pull the coils out of their containment tubes.

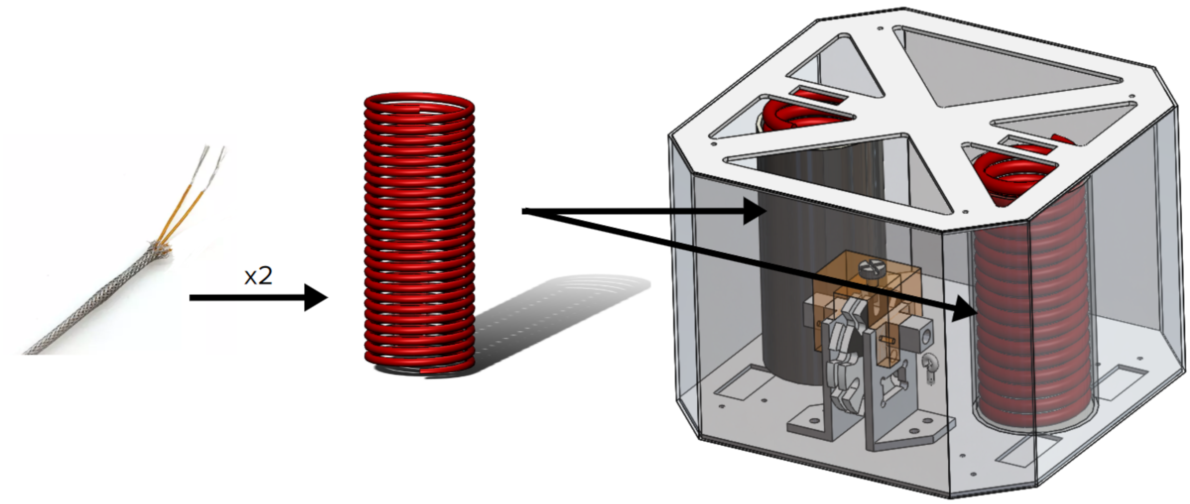


Fig. 12 Data and Power Assembly

D. Deployment System

Ben Pearson, Evan Johnson

The boom's deployment system was the subsystem which allowed the boom to extend from its compact, 9.5x9.5x7cm volume to its full 80cm length. Its strong reliance on the configuration of the primary boom architecture meant that its finer details were developed quite some time after the fleshing out of the other physical subsystems, but its base parameters and requirements were known from the start. The system needed to demonstrate quite a litany of capabilities for something that would, by necessity, be so small. In addition to restraining the boom from full deployment in a challenging environment, the subsystem needed to receive commands from software to execute its release, determine terminal deployment length, and survive the vibration profile of a rocket launch. These requirements were compounded by a need for an electrically passive system while collapsed, and the (often overlooked) capability to be set up within a nearly sealed container.

The first facet of this system that the software subteam explored was the deployment verification mechanism, which would inform the software of a successful boom extension. Considered options included a camera, a LiDAR Module, a simple electric switch, and a break-wire - and each demonstrated different benefits for integration. To suit fundamental dimension constraints (as outlined by requirements and boom architecture), the team considered both mass and volume in the trade study. Options which exceeded these constraints were not considered, but the need to drive ever smaller and lighter persisted in this cramped CubeSat environment. The team also considered the ability of the components to gauge the deployment of the boom accurately, affording higher scores to mechanisms with tight bounds, but also to mechanisms which could measure deployment incrementally - allowing for recognition of partial or flawed extensions. More subjective trade categories consisted of risk and team knowledge, which assessed probability of success and contingencies while best leveraging existing team experience and technical know-how. Of these metrics, accuracy was afforded the most weight. Full weight distribution and scores are listed below in Table 7.

Table 7 Deployment Telemetry Trade Study

Criteria	Weight	LiDAR Module	Electric Switch	Camera	Break-wire
Mass	10%	5	5	1	4
Volume	15%	5	5	2	5
Team Knowledge	20%	4	5	4	5
Risk	20%	2	4	5	5
Accuracy	35%	5	5	2	4
Weighted Score	100%	**84%**	**96%**	**56%**	**91%**

Conclusively, the electric switch concept, in which a rotating spool could periodically trigger a switch as the structure extended, was selected as the best path forward. It demonstrated strength in all categories, and lost points only in *Risk* as there was an assumption that its periodic nature would allow more room for mechanical errors. By default, the team first proceeded with a physical snap-switch, going as far as to purchase one and fully incorporate it into the electrical system with software. It was pointed out in a review, however, that there may be better ways forward by incorporating similar fundamentals but with a different way of sensing a spool rotation.

With this in mind, the team performed a follow-on trade study for the switch mechanism by adding non-tactile methods to the existing physical option. As demonstrated by the full trade table below, with considerations for complexity, size, and redundancy opportunities, both the IR sensor and the optical encoder soundly surpassed the in-place snap switch. The team thus selected the highest scoring component, the IR sensor, and designed the specifics of the remaining deployment system around it. An IR sensor functions by returning emitted reflectivity data. As will be explained shortly, this meant that the switch could be triggered by a simple change in the reflectivity of the material in front of it.

Fig. 13 IR Sensor

Table 8 Deployment Telemetry Switch Trade Study

Criteria	Weight	Snap Switch	IR Sensor	Optical Encoder
Mechanical Complexity (0-5)	30%	2	5	3
Redundancy Opportunity (0-1)	10%	0	1	1
Software Complexity (0-5)	10%	5	5	3
Power Draw (0-5)	10%	5	3	4
Size (0-5)	40%	1	5	4
Weighted Score	100%	**40%**	**96%**	**74%**

Following this new sensor concept, the subsystem design revolved around a notched spool with light and dark-colored halves. The fundamental notion was that a spool of strong (90 N) polyethylene cord could restrain the boom from deploying, and then a pin could pull from the spool's notches to trigger extension. The strength of the cord, 90 N, was far greater than the restraining force required to hold down the Nitinol in the boom, measured to be 10.8 N. This strength was chosen in anticipation of additional loading from the payload encountered during a launch environment. As the spool rotated, its light and dark faces would alternate over the sensor's photo-diode and the software connected could generate a deployment length resolution within half a spool rotation. The entirety of this subsystem is outlined and detailed in Figure 14 below.

Most challenging aspects to this design process were the spool itself and the pin-pull mechanism though for slightly different reasons. The entire spool system was only able to squeeze to a height within 7 cm meaning that the spool itself was very small which presented many manufacturing challenges of which the design members needed to be wary. The team required a few efforts to achieve a notch size in the spool that suited both manufacturing capabilities and system requirements. Also the fine degree of tolerancing or the inability of the manufacturing process to provide an adequate degree of tolerancing mandated a last-minute addition of wheel bearings to the axle.

The pin-pull mechanism was less challenging from a manufacturing standpoint, but needed to be designed with usability in mind more than any other part to mitigate setup difficulties. The baseline idea was that an un-sprung pin could be held in place by material of the same type holding the boom in the stowed configuration, a polyethylene cord. The deployment software could then send a signal to a relay triggering current to flow through a 34 AWG nichrome wire wrapped around the polyethylene. The small wire gauge and relatively large current, 800 mA, pushed through the nichrome wire causes it to heat up past the melting point of the polyethylene cord thus melting it and releasing the pin and subsequently the spool. Pressed for time, this particular mechanism probably received the least thorough design analysis of all parts, and suffered for it. The decision was made to route the polyethylene directly over a cross-hatch in the pin itself, resulting in a direct interface between the two. This added difficulty in setup, and presented more opportunity for friction to saw through the polyethylene before the nichrome was even triggered to pass current. With the benefit of hindsight, the team would choose to completely redesign the 'burn-box'.

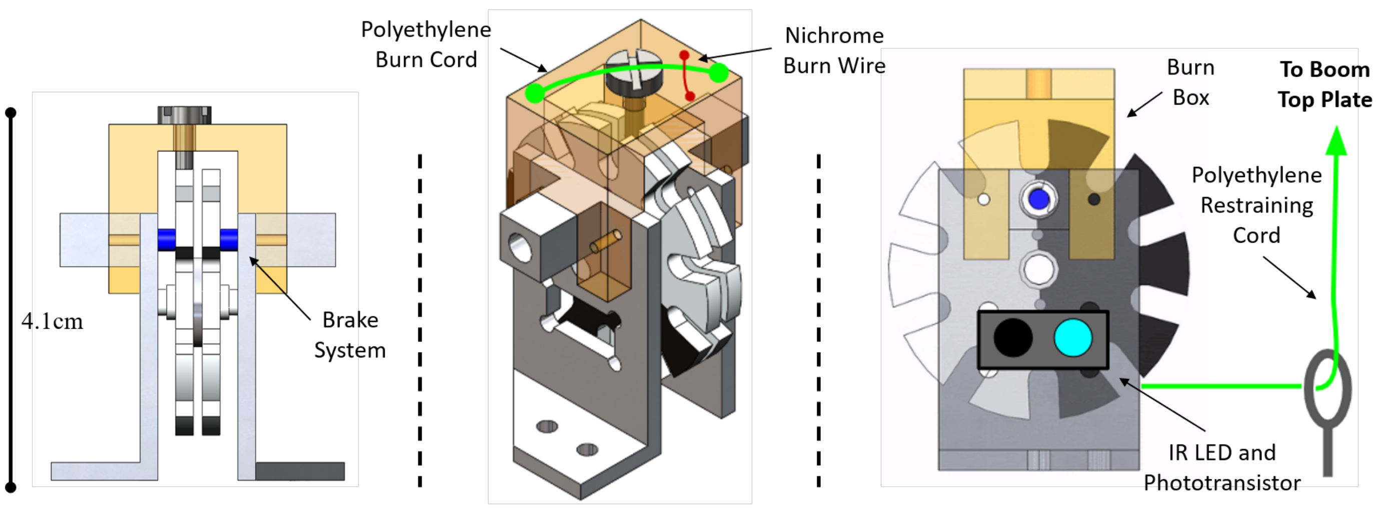


Fig. 14 Deployment System from Varied Perspectives

The remaining aspect of this subsystem was its brakes, intended to limit the rate of deployment. This limitation fulfilled a customer requirement of holding acceleration to within 10 g's, and ensured the satisfaction of a design-driven requirement regarding the strength of the carbon fiber-epoxy interfaces which held the boom together. The brake pads themselves were designed to be the ends of tiny aluminum rods, shown in dark blue in Figure 14. Aluminum was selected as a material to maximize the coefficient of friction against the spool surface, though during testing concerns over cold-welding were brought up by other team members and so a quick addition of foam to these brakes was made. The protrusions into which the brakes were inserted also hosted tiny springs and were tapped for set-screws, which could be adjusted to alter the applied brake force. The tiny springs were chosen to have a maximum spring force of 14.95 N. This was based on a moment balance performed at the spool axle with an approximated extension force, F_{Boom}, of 10.8 N, shown in figure 15. The moment balance was set to the static case of the brakes preventing any rotation of the spool. While this amount of brake force would never be necessary, it presents the highest loading case for the brakes from which they could be adjusted to a lesser force.

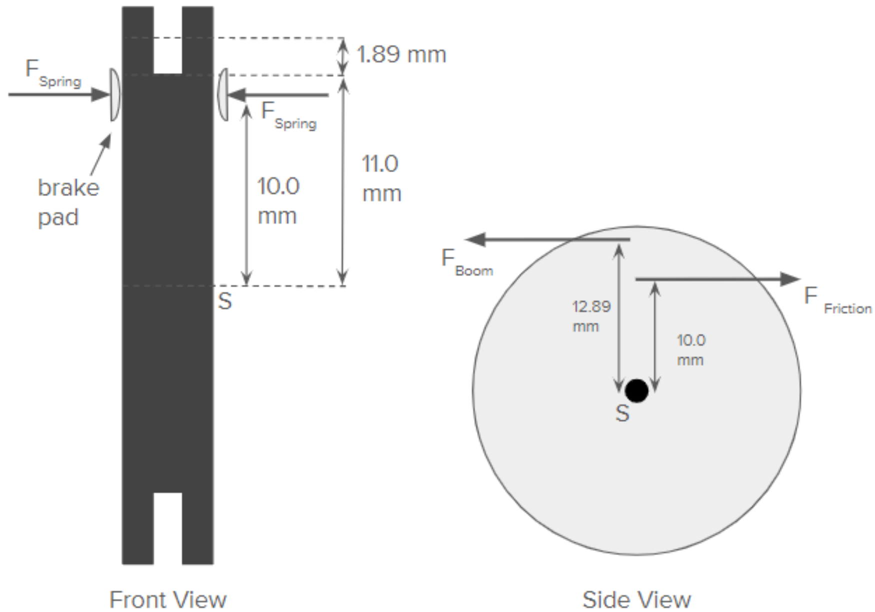


Fig. 15 Moment Forces Acting on Spool During Deployment

The moment balance performed is shown below:

$$\Sigma M_S = F_{Boom} \cdot 12.89mm - 2 \cdot F_{friction} \cdot 10mm = F_{Boom} \cdot 12.89mm - 2 \cdot \mu F_{Spring} \cdot 10mm = 0 \quad (1)$$

$F_{Friction}$ is multiplied by 2 to account for a brake on each side of the spool. A conservative value of μ of 0.47 was used, less than the coefficient of aluminum on aluminum to account for potential PEEK brake pads. F_{Boom} is set equal to 10.8 N which was the estimated restraining force required to constrain the Nitinol. Solving for F_{Spring} gives:

$$F_{Spring} = \frac{F_{Boom} \cdot 12.89mm}{2 \cdot \mu \cdot 10mm} = \frac{10.8N \cdot 12.89mm}{2 \cdot 0.47 \cdot 10mm} = 14.95N \quad (2)$$

Because testing was cut short, it is hard to gauge exactly how valuable this brake system actually was — or if it was needed at all. Design of the system was based on preliminary deployment force testing and conservation of energy models, neither of which suggested a likelihood of exceeding 2 g's during deployment. However, modeling the 'snap' acceleration at the completion of the boom extension proved troublesome, compounded by the non-linearity of the Nitinol and its unusual material properties. As such, the team made the decision to use the brakes for the preliminary testing and utilize that data to assess a need for brakes moving forward. Unfortunately, the team only made partial progress on assessing that need. Based on preliminary results detailed in the Verification and Validation section, it is suspected that they might be extraneous and that their complexity might outweigh their direct benefits. Future iterations of this design may omit them completely.

E. Software

Roger Heller

From the outset, the software and hardware microcontroller for this project were intended to emulate the command and telemetry functions of the CubeSat flight computer. Strictly speaking, the software was never meant for delivery to the customer or use outside of the CUBE^3 test environment. The software design process followed a trade study methodology that evaluated candidate software languages in terms of their utility and usability. Specifically, the trade study completed for the Critical Design Document evaluated C2 software availability, documentation, microcontroller compatibility, flexibility, team knowledge, and transferability. The availability criteria considered whether a given software was easily obtainable without excessive cost or license maneuvering. Documentation addressed the extent of the online knowledge base, to include example code and an active community that could answer any potential questions.

Microcontroller compatibility characterized the ease of working with readily available microcontrollers to create the interface between the software and hardware. Flexibility sought to describe how easily a given codebase could be modified to address novel use cases. Team knowledge surveyed the familiarity of all team members with each language. Finally, the transferability metric considered how widespread a given software language or package is in the aerospace industry. These criteria were assessed to adequately characterize the applicability of each candidate software to the project.

The original software trade study evaluated OASIS CC, Python, COSMOS, and C/C++. The results of that trade study indicated that custom Python code running on a Raspberry Pi microcontroller was the best option for the project. After these results were presented in the Critical Design Review (CDR), members of the Project Advisory Board (PAB) recommended the Arduino Due microcontroller in place of the Raspberry Pi. The first benefit in this swap was that instead of purchasing a Raspberry Pi, the team could check out a Due from the Aerospace Electronics Lab at zero cost. Secondly, MATLAB, a high-level programming language used extensively throughout the Aerospace Engineering Sciences academic program, features a hardware support package for Arduino that creates an easy, reliable interface between a computer running MATLAB and Arduino microcontroller hardware. The MATLAB/Arduino option was evaluated in the same trade matrix as was used previously and emerged as a clear winner, which the team elected to carry forward into development.

4. Manufacturing

The realization of this project was driven by a tremendous effort on all parts. Manufacturing was no exception, this subteam created, in addition to two low-fidelity prototypes, a complete high fidelity prototype boom and parts enough for two full booms of 1.2 m each, though the final design and subsequent booms did not require the full length or all parts. Each of these three complete boom architectures required the manufacture of almost 500 pieces. Tolerancing for these parts was generally within 0.1 mm and each needed connecting and assembling so as to be tight, straight, and untwisted. This is to say nothing of the interfaces between the architecture and its surroundings, or of the deployment system. The enormity of this task was recognized very early in the project planning process and the manufacturing team made every effort to work at an accelerated pace to meet the need, and to mitigate the possibility of major schedule slips.

A. Primary Boom Structure

Ben Pearson, Collin Doster, Adam Hu

The boom structure, or rather, boom structures, were the primary sources of design focus and physical manufacturing time by two orders of magnitude. This is because, fundamentally, the most crucial and the most challenging to meet requirements were based on its performance. These concerns were massively compounded by the sheer quantity of parts required to complete even one such structure, and the incredibly high degree of consistency and quality that was required for them to perform as designed. Remarks were made by numerous advisory board members, and engineers with whom the team collaborated that this may have been the first known instance of a production-line project in the CU aerospace curriculum.

Planning allowed for the team to recognize that parts originally designed (ahead of schedule) for PDR were functionally acceptable, but practically impossible to produce on the necessary scale. As such, the emphasis on planning and design enabled the team to revise the parts considerably and for the better. Planning also dictated that half the team become certified to a high level in the machine shop within a month of class offerings, and that more than a third of team members were fully certified to use CNC machines in before Thanksgiving break. Planning encouraged the purchase of better, digital calipers than initially offered, and allowed the members overseeing part quality to define acceptable size bounds before parts were made. The resulting quality assurance practices were therefore proactive, rather than reactive. It became possible to assess products for measurable quality and adjust practices early, rather than taking (or wasting) a large number of parts and trying to find the best of them when already too late.

The most crucial aspect of this manufacturing planning process was the decision to create a very high-fidelity prototype very early in the project timeline. The team committed 45 hours a week during winter break between the entire subteam, while the shop was nearly empty. Aside from the clear benefits of building familiarity with the machines and methods, this hastened effort provided a platform upon which the team could perform preliminary tests, and ironed out any remaining construction kinks. In all the prototype took around 120 hours to produce but the amount of time it saved the team in the semester could possibly have been triple that. To cut down on costs, the team used Delrin instead of PEEK for prototype connector parts. They are very analogous materials, but Delrin lacks the UV durability for an exposed space environment and so were only used for testing purposes.

It should be recognized that even with the quality control methods and prototyping, part loss ranged between 15 and 20%. There were practice parts to consider, procedural kinks to work out, feeds and speeds to be dialed in. The team definitely improved on these issues with practice and awareness of pitfalls.

Immediately following subsections of this report describe the steps taken to manufacture the parts from a high-level perspective. Future teams are advised to choose the tools best available to them, but to heavily invest in carbide coatings where possible. Even without breakage however, $CUBE^3$'s manufacturing subteam suggests limited repeated use of end mills. After 1500 parts, even in plastic, they wear down - and will cause otherwise perfect cuts to experience miss-sizing. Requisite part counts and nomenclature can be found in Table 6 above.

1. PEEK Parts

The PEEK (or Delrin in the case of the prototype) parts in the boom structure were the chief time-sinks and sources of difficulty in the manufacturing process. Fundamentally though, they all experience the same basic first steps. As demonstrated by Figures 16 and 17 below, they each start out as one of many elements on a 6 inch bar of 3/8 x 3/8 inches. Cost saving may be achieved by cutting these bars out of a plate. These bars are then placed into a CNC machine, which cuts up to a dozen parts into each bar. CAM files are provided in accompanying documentation where possible but, unfortunately, access to the computers upon which they were stored became limited by the Covid-19 pandemic.

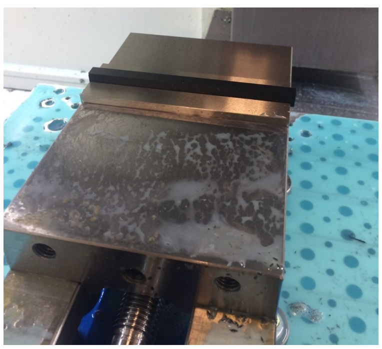


Fig. 16 Raw Delrin Bars in CNC

Fig. 17 Raw Delrin Bars Converted to Part Blanks

These parts, still attached to their parent bars, were then ready for a process referred to as 'Tophatting'. This is a semi-technical way of saying 'turning the part over and facing off the excess'. At face value this is a relatively simple process, but one which is complicated somewhat by the irregular shape of the corner pieces, and further by recognizing that an imperfect part's size on the clamping faces could cause slippage and ruined parts. The solution to this issue was the development of 'softjaws', specially developed vice jaws, to hold the parts in place. The team built these jaws out of aluminum, and made them fully reversible, so they could be used with the corner pieces on one side, and the others on the reverse. Figure 18 below shows the simple CAD of these softjaws in a vice, and Figure 19 beside it demonstrates their usage. Theoretically, if slippage is a non-issue, the sides with the square slots could be replaced by properly sized parallels in a regular vice, but it is important to recognize how slim the height margin is if this is the chosen path. The manufacturing subteam cautions against clamping too tightly - it is a good way to squeeze soft, plastic parts out of usability.

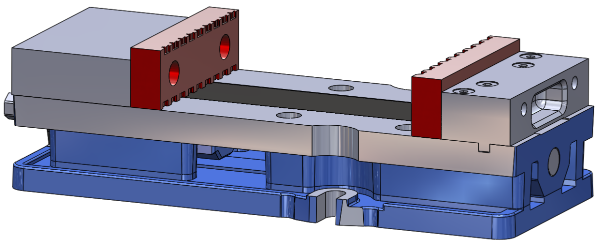


Fig. 18 Softjaws (Red) in a Kurt-DX6 Vice

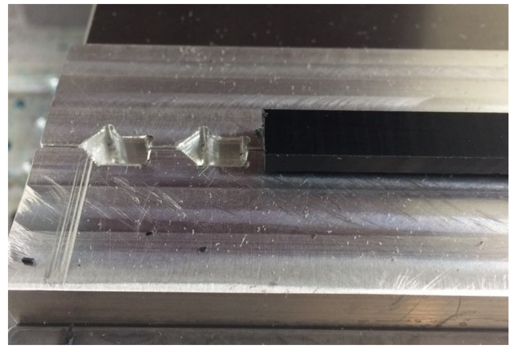


Fig. 19 Softjaws in Use on Corner Pieces

The parts at this point are separated from their original bars, and all but the interface connectors must be spun in the lathe so they may fit within the Longerons and Battens to which they attach. For the middle connectors and hinge pieces this is a simple matter of fitting them within a size-appropriate 5C square lathe collet and cutting to specifications. This is time consuming, as they are done one-by-one, but relatively straightforward. The irregular shape of the corner pieces presented another challenge, however, for this step. To overcome it, the team created another jig, this time to fit an individual corner piece into a 1/2 inch square lathe collet (as shown in Figure 20 below). The team opted to produce about 15 of these from 3D printed PLA, but probably it is the case that a single aluminum jig would have been better. The PLA jigs were easily crushed or lost grip if the team was not careful, which is why 15 were necessary. Generally it is not recommended that asymmetric parts are put into a lathe like this, and is was only possible because the parts were so lightweight. An aluminum jig might have helped this too. To the PLA jig's favor though, each took about five minutes to print. They were actually the more time efficient option. Figure 21 shows one in action.

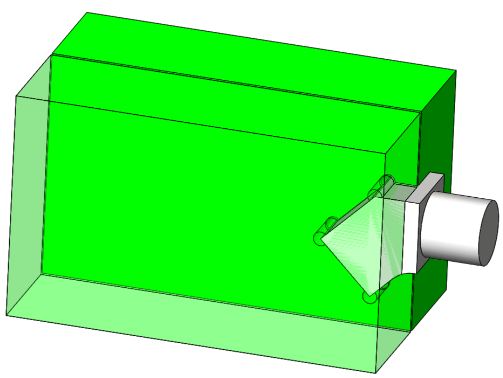


Fig. 20 Square Lathe Collet Jig for Corner Piece

Fig. 21 Corner Piece in Lathe

The final steps for these PEEK parts are simple hole drilling exercises with the mill. The corner piece requires another simple jig. The middle connectors and interface connectors just need to be pushed up against a machine stop for the nut pockets and the interface screws (0-80 again) respectively. It is important to recognize that both these holes need to be tapped with an 0-80 tap at the end (though, it may be the case that future teams tap the middle connectors in the CNC as CUBE^3 did for the final boom).

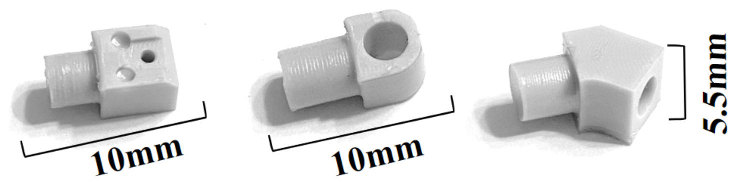


Fig. 22   Actual Manufactured PEEK Parts (Interface Connector Omitted)

There are general considerations that should be made when manufacturing the PEEK plastic. PEEK is a rather expensive polymer, and therefore extra precaution should be taken when milling it. PEEK is prone to building internal material stresses near surfaces that have been milled or cut. While the team deemed it to be beyond the scope of project requirements, the proper way to machine PEEK is to first anneal it in an oven. The annealing process serves to mitigate the build up of surface stresses when machining. This is a time consuming and potentially expensive endeavour but would likely be worth doing should this project be used on a space fairing mission. There are potential benefits to the tolerance of the components as well as their strength, particularly in components with thin walls.

In an effort to slow tool wear and ensure proper tolerances are achieved the use of tool coolant is highly suggested when working with PEEK. The team ran coolant when performing all CNC milling operations (see Figure 16) as well as when parting out blanks on the horizontal band saw. It should be noted that PEEK can be damaged by some coolants so checking for compliance prior to manufacturing is suggested.

2. Carbon Fiber Tubes

Longerons and battens, which made up the main skeleton of the boom structure were no less crucial to the architecture, but were considerably easier to create. The team simple made a purchase of high-quality, thin wall, carbon fiber tubes and spun them in the lathe to cut them to the appropriate length. This was not a trivial process, using the lathe in this manner with a fibrous material is a bit tricky, but after the first 100 such cuts the remaining 300 go by pretty quickly. Use of the smallest, sharpest THINBIT to cut the carbon fiber tubes along with the correct feed rate yielded the best results although there were always some frayed carbon fibers. It is recommended by anyone undertaking this process that it be made a two-person job. A quality control individual and a machinist building muscle memory.

The corner rods were a slightly overlooked element of the design process, and it took the prototyping process and multiple false starts to evaluate best methods. Initial hopes were to use PEEK rods here to minimize friction, but the plastic was too soft for the lathe to really work the smallest available rods to the correct dimensions. The rotation of the lathe produced too much heat which deformed the tubes as it got closer to the desired diameter. The team then switched to carbon fiber tubes of the correct diameter, but the only available COTS option was ‘pultruded’ carbon fiber - rather than the higher quality ‘wrapped’ carbon fiber used in the battens and longerons. Subsequently, the small rods almost always shattered and frayed in the lathe. The best option, it turned out, was simple use of a Dremel blade with the omni-directional attachment. This part was of least importance from a tolerancing perspective. The only crucial restriction was that it be *below* 18 mm, since larger would give the hinge pieces too much freedom. Innovative use of a vice was needed to produce the parts quickly with the omni-directional attachment in the jaws. There was a first pass to cut the tubes to 18.5 mm and a second pass to bring them just under 18 mm. Only about 150 of these needed to be made.

3. Nitinol Hinges

Final manufactured elements of import for the primary boom structure were the Nitinol hinges, which connected bays together and provided the entirety of the boom’s deployment force. Though these pieces were not quite as plentiful as some others, their titanium-alloy and a continued need for precision contributed to the difficulty of their manufacture.

For each boom, the first step to their creation was to covert a meter of coiled Nitinol into about 50 strips. As tolerancing and accuracy of cuts were paramount, this mandated the generation of another PLA jig - depicted in Figure 23 (upside down) below. This jig allowed team members to press strips into the slots and then utilize the shear (a big metal cutter in the shop) to slice the parts to size. Quality Control assessed every single piece for size and cleanliness of cut, allowing for a deviation from nominal of no more than 0.1mm.

Second and third steps respectively focused on drilling and opening up the holes in these tiny strips to allow passage of 0-80 screws and fixture to the PEEK middle connectors. The team was lucky enough to have access to a clamping jig welded together by Matt Rhode, and originally attempted to use tools available in the shop. Figure 24 shows the jig before the addition of the weld. However, it became immediately evident that conventional drill bits were not capable of working a titanium alloy with the requisite degree of consistency before blunting and breaking. This was not unexpected, so the team expended funds to purchase a half-dozen carbide drill bits which were much more durable, but still required occasional refreshment. Two holes were drilled into precisely measured points on each strip, located at either end. The final step was a countersinking of these small holes - effectively creating a angled chamfer around their circumference. The driving factor behind this was a need to have the flat-head screws sit flush in the Nitinol such that they did not extend past the bounds of the middle connectors. This operation was performed with a simple countersink tool, but there were limited opportunities for realistic quality control from a quantitative perspective. As such, the final operation here was imperfect, but repetition and practice afforded a degree of uniformity.

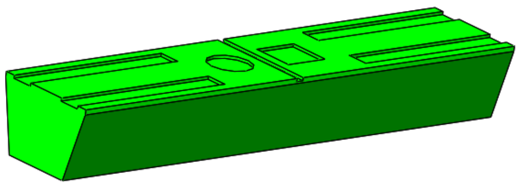


Fig. 23 Nitinol Shear Jig

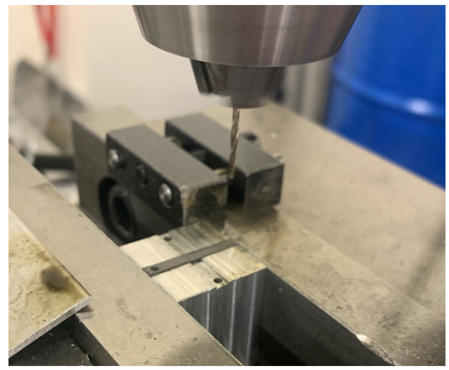


Fig. 24 Nitinol Hole Jig

4. Main Boom Structure Assembly

Putting the boom architecture together was its own considerable manufacturing challenge. Each of the almost 400 individual parts needed to be either epoxied or screwed into one coherent structure to be functional, and misaligned pieces would have severely impacted the system's quality.

The task began by completing the longeron pieces, a fundamentally simple process of epoxying a corner hinge and a middle connector into separate ends of a longeron carbon fiber rod. The Armstrong A-12 epoxy mix used was the 3/2 (A/B) a blend verified by NASA as having demonstrated low outgassing properties [6]. Epoxy was applied directly to the inside of the carbon fiber tubes with toothpicks, and the PEEK components were slotted inside. To ensure that the parts stayed as straight as was necessary the team produced a set of PLA plates with fitted pockets to hold them as they dried. Alongside the longeron production effort was a similar process with the battens, which needed two corner pieces of PEEK at their ends and a different pocketed plate.

After the epoxy in these components were given at least two days to dry, a single corner rod was epoxied into each of the augmented battens, taking precautions to clean any excess epoxy from the rods. These were allowed another few days to dry in a configuration that ensured no slippage or drooping while hardening. While awaiting the drying of the battens, the team pressed the nuts into the augmented longeron pieces. This was a step with an unfortunately high failure rate since nuts were prone to angled entry. For future efforts, the team would perhaps recommend drilling larger holes for the nuts so they were not press-fitted, and holding off on this step until the Nitinol is added later.

Dry epoxy meant that each of the modular 'flat-pack' batten-bays could be constructed. The parts were first laid out side-by-side to ensure their order was correct. To be clear about what this means each batten-bay (the groups of four battens and eight longerons) was configured in one of two ways, alternating longeron direction as they connected to each other. The need for this is very evident once the physical parts are ready to be connected, but slightly less so when considering them on a theoretical basis. Either way, laying them out facilitates organization and clarity in this regard, as demonstrated by Figure 25 directly below.

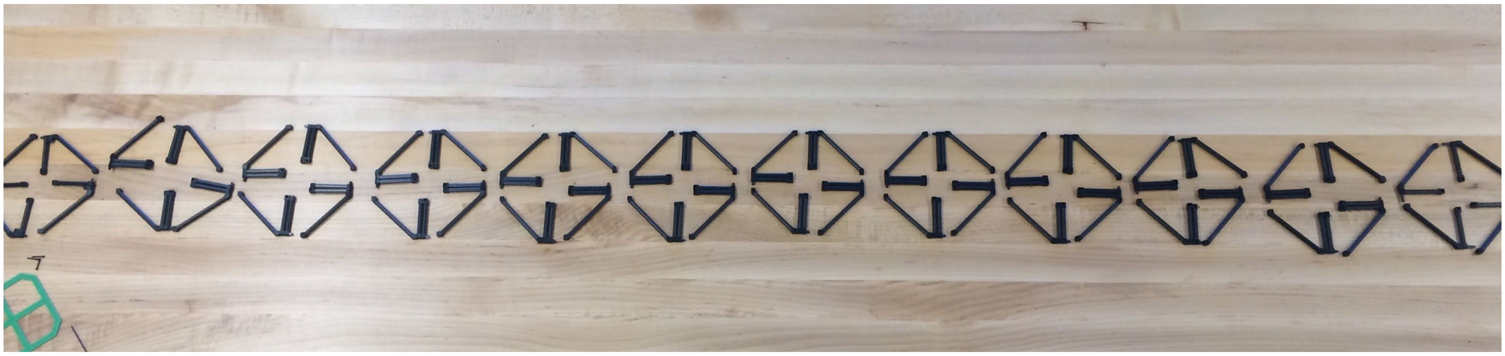


Fig. 25 Delrin Bays Laid Out for 11-bay Boom.

As arranged, it was a relatively simple matter to epoxy the batten-bays together using the same strategy as executed when initially mounting the corner rods. There was, however, the added challenge created by an inability to remove excess epoxy. This is best resolved with practice, and rationing of the epoxy itself. Utterly crucial to this step is pushing the corners together well. Manufactured correctly, the corner rods were just a little shorter than the space between the two corner piece ends - which meant that properly pressed corners applied a force to the otherwise loose hinges. This pressure was not so severe as to prevent deployment, but benefited structural rigidity significantly. To ensure this pressure endured throughout the hardening process and to maintain shape epoxied batten-bays were wedged between heavy steel pieces for almost a week as shown by Figure 26.

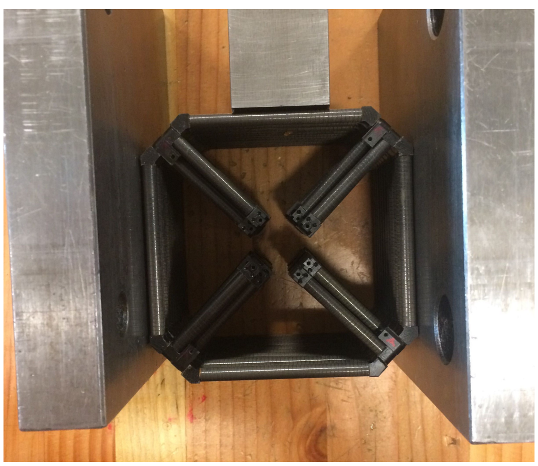


Fig. 26 Collected Batten-Bays in Compression.

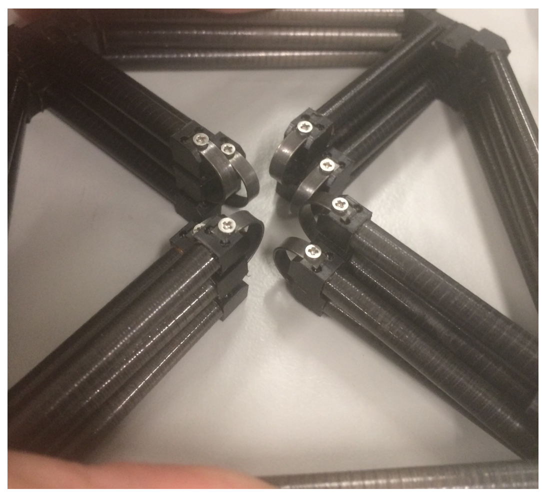


Fig. 27 Two Complete Bays of the Delrin Boom.

The final step for boom structure assembly was the addition of Nitinol used to connect the flat-pack batten-bays. This step required only that screws be threaded through the holes in the Nitinol and into each of the middle connectors, adding bays in a modular manner. Fundamentally, the only tool needed for this aspect of the project was a small screwdriver. Caution needed to be applied to prevent the stripping of screws in some instances, but this was generally only the case in the event that a nut was placed at an angle. Figure 27 above shows a fully screwed-together version of a two-bay Delrin boom. This figure also serves as a cautionary tale, demonstrating that screws will not sit far enough down if the holes in the Nitinol are not large enough, or if 82° screw-heads are used rather than low-profile, 100° screw-heads (shopping list in Table 6 below).

B. CubeSat Interface

Ben Pearson

The CubeSat interface was a reprieve from the repetitive nature of the previous section. Its parts were larger, and significantly fewer in number. Broadly speaking, these were the parts crucial to the connection of the boom architecture and its supported wiring, to the instrument and the main body of the CubeSat.

The notional instrument dummy shown in Figure 28 in blue should also be considered one of these parts. It was also the most fundamentally simple to manufacture, as a solid, 3D printed 8x8x8 cm cube of PLA is quite close to the desired 500 g load. A basic rounding of the edges was all that was required to manufacture this dummy-instrument to the correct specifications, and the team hollowed out some spaces above the tubes holding the cable so the instrument could host any desired 'connectors'. For the sake of the Resonant Frequency tests, it was important that the center of gravity remained central.

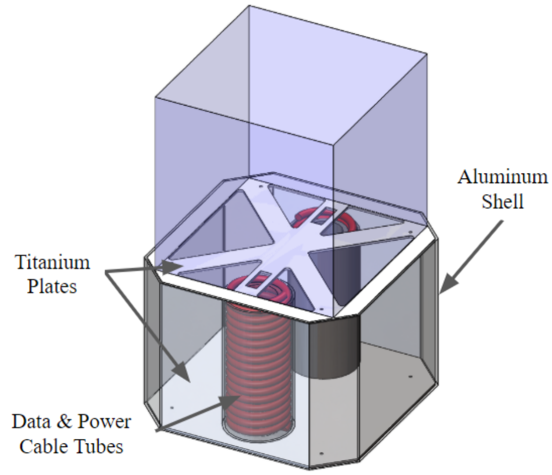


Fig. 28 Collected Elements of CubeSat Interface

This instrument stand-in sat atop a titanium plate, as thin and lightweight as possible so as not to negatively impact the resonant frequency of the structure. The plate provided extra surface area to which the instrument could connect, had wire connector support capabilities, and maintained the solid, geometric profile of the boom's far end. Titanium is renowned for its difficulty to manufacture, and this thin piece was not an exception. Because the holes in the plate required both end mills and drills, the manufacturing team could not realistically have simply pinned it to the CNC base plate and started cutting without risking damage to the machine. Instead, the team sandwiched the uncut titanium plate between two clear acrylic sheets and cut through the top-sheet into the titanium. Doing so meant that the titanium had more direct points of contact to hold it down and prevent slippage, and meant that there was no risk of cutting into the CNC base plate. Cutting titanium is also eased by increasing the spin rate, and reducing the feed rate of the tools - which should be carbide coated at least. The base plate was cut in the same manner but with a different bolt pattern and a more robust inner-face. Both configurations are shown in the Figures directly below. The team clamped the pieces by their corners, and then used a shear to take the corners off for the sake of ease and as tolerance for that final cut was not so crucial.

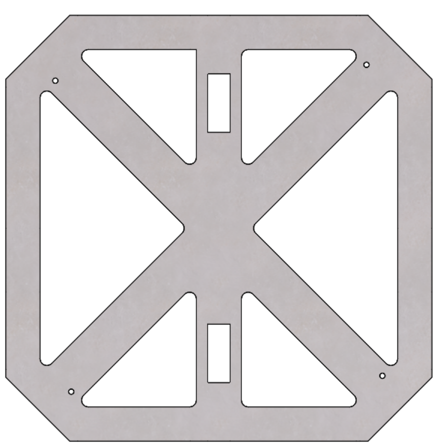


Fig. 29 Top Plate

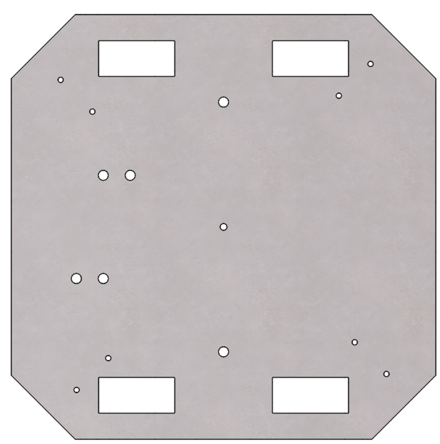


Fig. 30 Base Plate

Remaining constituents of the interface were the tubes into which the power and data cables could coil, and the aluminum shell/encasement. The tubes were simple Delrin rods with an inch-thick hole drilled most of the way through them using a lathe. Crucial to this step was the slow spin rate of the drill to avoid risk of melting the plastic with such a large bit. To mitigate this risk the team used drill bits of increasing sizes and progressively took out more and more material. The wall thickness was then reduced via conventional lathing methods to fit the tubes within the allotted space (to about 28 mm diameter). This diameter ensured that the data coils would be stored at a radius larger than their minimum bend radius, 3.81mm. The aluminum shell was a much more elaborate manufacturing challenge, and the benefits it provides are so limited that the team recommends its omission from future iterations of this design unless it is explicitly requested by a customer. It required the use of a break (a sheet metal working machine) to bend the <1 mm thick aluminum into two perfect halves, and then the halves need to be bound together. It was determined that the break will not create hard angles, and even the best brakes will have inconsistencies in bend positioning. The team eventually developed a passable solution through trial and error. This boom structure could be easily harbored within the customer's CubeSat without the shell and, had more time been available, the team would have addressed this in a more official capacity.

C. Data and Power

Ben Pearson, Evan Johnson

The data and power transfer susbsystem was broken into two very distinctive parts. The first, the cable containment tubes, has been described in the previous section. The second was the wiring itself, responsible for transferring power and signals between the CubeSat and instrument - for which the team used 28 AWG Kapton insulated twisted pairs with silver plated shielding from AccuGlass.

The AccuGlass wiring was purchased COTS to satisfy a need to route data and power between the main CubeSat bus and the instrument at the end of the boom. However, the twisted pairs needed additional work performed upon them to properly integrate into the architecture without causing snags, breaking on deployment, or tangling on themselves. The solution described in the design portion of this paper, the data coils, was achieved by placing a pair of cables side-by-side, perpendicular to the direction of extension, and temporarily holding them in place in a coiled configuration. Segments of heat shrink were then placed around the parallel cables which were temporarily being held in a tight, coiled configuration. The heat shrink was then contracted around the coiled cables forcing them to stay in the coiled shape. Segmentation of the heat shrink allowed for more compact coiling as well as decreasing the force needed to pull the data coils out of the coil tubes. Each of the heat shrink pieces were cut to be 8mm long and separated by roughly 8mm along the length of the wire. This length was decided on after several heat shrink separation lengths were tested, with 8mm giving the best packing volume and coil rigidity. Note Figures 31 and 32 below to see this in detail.

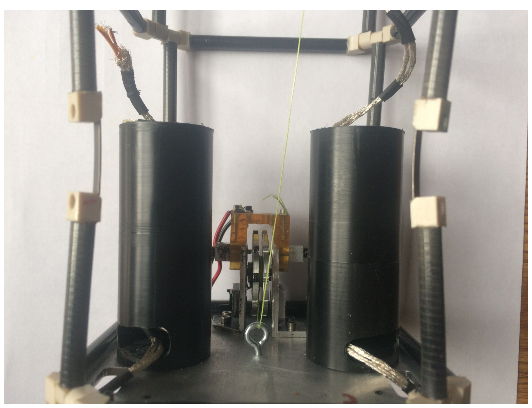


Fig. 31 Outside View of Cable Coils. One Wire Deployed.

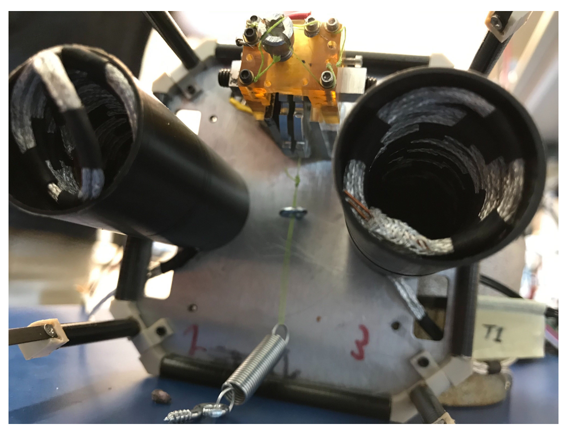


Fig. 32 Top-down View of Cable Coils.

D. Software

Roger Heller

Actual development of the test software proceeded with a “crawl, walk, run” methodology. In other words, small developmental iterations were accumulated over time to eventually meet the needs of the project. Early in development, the software subteam identified MATLAB App Designer as the best choice for creating a clear, easily usable interface for test personnel. This tool is based off object-oriented programming that can be easily modified to incorporate new methods, which are essentially functions defined in a special format called a class definition or *classdef*. Therefore, development workflow generally began by developing a standalone function that could later be shoehorned into a *classdef* method for use by the app. For example, one early script simply captured the steps required to configure the Arduino Due for use, which is to say selecting the correct comm port for the laptop to communicate with the microcontroller, which pins to configure as digital inputs or outputs, etc. Later, a modified version of the same script was inserted into the code for the app and used in testing. Similarly, the temperature-sensing thermistors, burn wire relay, and revolution counter IR LED/transistor circuits were all first tested with standalone MATLAB functions that were modified or outright copied for use in the final code. A representative screen of the software in operation is presented in the figure below, but the reader should reference the software itself, included in the data packet, to better understand its structure and function. Note that the temperature graph scrolls dynamically and the output field above the green “Deploy" button displays helpful program information.

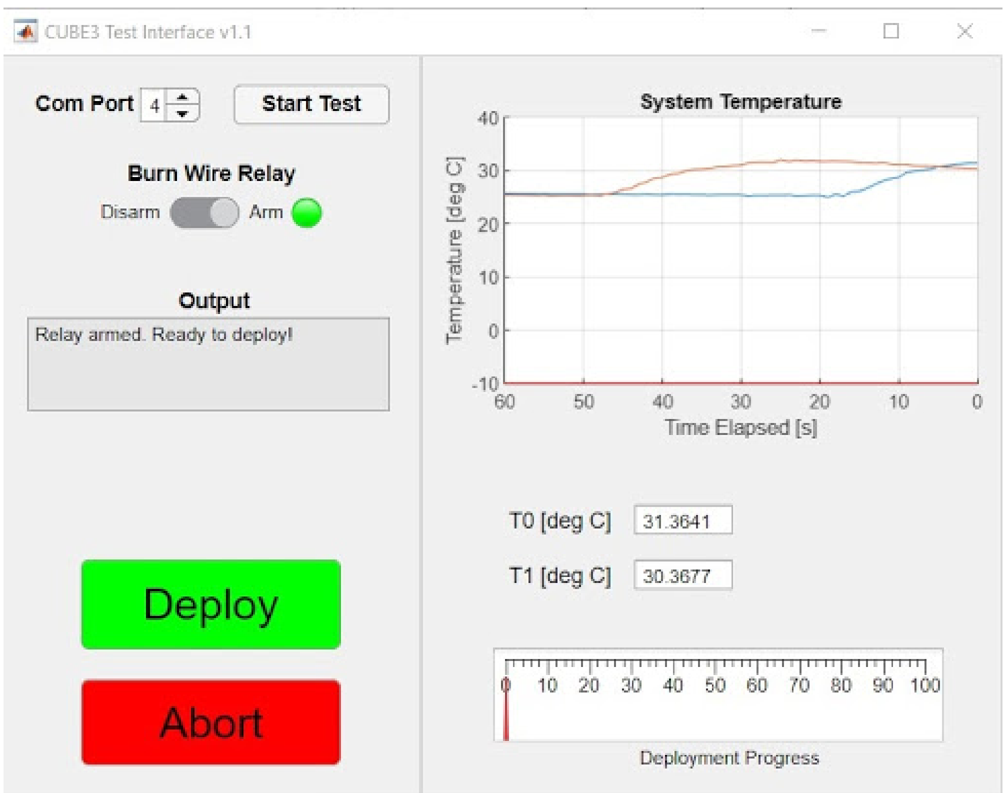


Fig. 33 CUBE3 Test Interface v1.1 software screenshot.

The technique for measuring temperature follows a standard methodology for using thermistors. Thermistors fall under the category of variable resistors, and the variance in their resistance is a function of temperature. Therefore, placing a thermistor in series with a known passive resistor creates a simple voltage divider circuit, where the voltage across the thermistor can be expressed algebraically.

$$V_t = \frac{R_t}{R_t + R_2} V_S \tag{3}$$

In this expression, V_t is the voltage across the thermistor, R_t is the resistance of the thermistor, R_2 is the other passive resistor in series with the thermistor, and V_S is the source voltage. If V_S is held at a constant voltage, and V_R is measured directly, R_t can be solved for as the only remaining variable term in that expression. Once the thermistor resistance is known, the temperature can be solved for via the Steinhart-Hart Equation per the manufacturer's direction in [11], given below.

$$T = \frac{1}{A + B\log(R_t) + C[\log(R_t)]^3} \tag{4}$$

In this equation, T is the thermistor temperature and R_t is its resistance, while A, B, and C are constants based on empirical data for the specific thermistor. In this case, the thermistor manufacturer provided a table of resistance ratios at given temperatures. The team identified a temperature range of interest and used this to identify an upper, lower, and middle resistance ratio that could then be fed into Stanford Research System's Thermistor Calculator [12] to generate the needed coefficients. Importantly, the impact of going outside the bracketed temperature range is a gradual increase in error for the calculated temperature. In the vicinity of the midpoint, the thermistor calculation was observed to be very accurate, on the order of 0.1 °C without any calibration. Further refinement could yield even more accurate temperature readings with this hardware configuration, but this precision more than met the functional needs of the project.

In software, MATLAB simply commanded the Arduino Due's built-in Analog-to-Digital Converter (ADC) to measure the voltage across each thermistor at regular one second intervals. The Due responded with a voltage measurement, which the MATLAB method then fed into the equations given above to calculate the thermistor temperature.

The circuit intended to measure the rotation of the spool followed a similar approach. Provided that the IR LED was powered in line with a current-limiting resistor, every rotation of the spool would expose the IR-sensitive phototransistor to alternating reflective and absorptive regions. The circuit used for this project placed the phototransistor in series with 5 kΩ of passive resistance in order to limit current through the circuit. Accordingly, the Arduino's ADC was able to directly sample the voltage across the phototransistor. As the spool rotated, the phototransistor would change from high to low, and the change in voltage was measured by the ADC.

The software that measured this process was accordingly simple. During the deployment process, the changes from low to high voltage across the phototransistor, in this case quantified as exceeding 1.0 V, caused the software to count a revolution. The software would then wait, continuously commanding voltage measurements, to observe a drop below the threshold voltage. Once this occurred, the cycle repeated, up to a maximum number of revolutions determined by the length of restraining cord wrapped around the spool.

Finally, the software that controls the burn wire relay is extremely straightforward. When the test conductor presses the "Deploy" button on the MATLAB interface, the software first performs two checks. In the first place, the software verifies that an arming toggle switch is in the "Armed" position, which functions as a safeguard against unintentional deployment. The software then compares the latest temperature calculation against a desired minimum value. If the temperature is not above that minimum, the software displays an error message but takes no further action. A later version of the code might give the test conductor the option to override, but that remains as future work. Presuming the checks both pass, the MATLAB software commands a digital input/output (IO) pin on the Arduino to be switched to a high voltage. This pin is connect to the control input of the solid state relay. A semiconductor device within the relay completes the circuit between the relay output pins, and current is free to flow between them. Once the software detects the first revolution of the restraining cord spool via the method described above, the relay control pin is commanded off, breaking the circuit between to the relay output pins. This software and hardware interaction was first tested by turning an LED on and off via the relay before its output was connected to an external power supply that fed a constant current to the burn wire for the full deployment test.

The test electronics in their final configuration are shown below. Note that the thermistors, IR LED, and phototransitor are not visible in the image. The IR LED and phototransitor terminate the grey, blue, and black wires exiting the top of the image. The thermistor cables attach to the multi-color wire ribbon exiting the bottom left of the image.

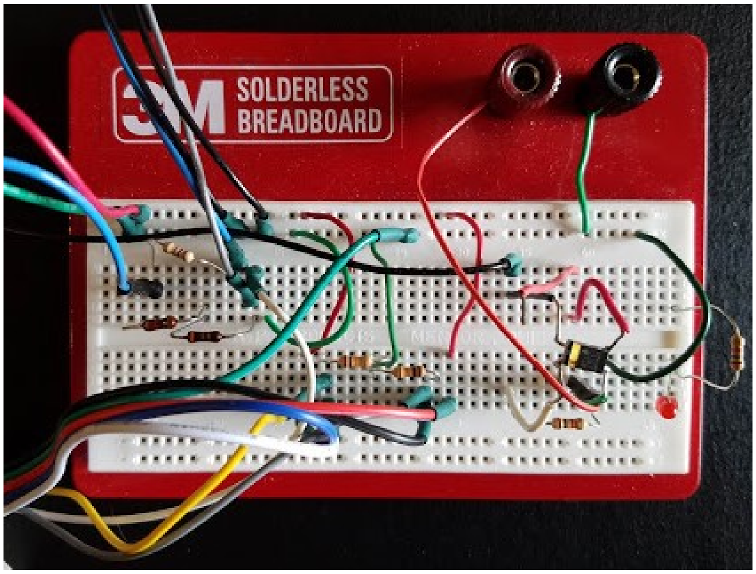


Fig. 34 Test electronics breadboard.

E. Test Rigs

Ben Pearson

Unfortunately, the team did not get full use out of the test equipment that it created, but all were fully completed. Chiefly, these components took the form of apparatuses to interface with the vibe tables that the team had access to. The first such construct had dual use, it was primarily a plate with a bolt pattern interface to allow a complete, deployed boom to attach to the slower horizontal vibe table for resonance testing. This component was the easiest metal part that the team made all year, as it was simply a square piece of scrap aluminum into which a correct bolt pattern needed to be drilled. The part was large enough to sit squarely on parallels in a vice without risking interference. For these tests, the boom itself was attached using 3D printed PLA cuffs screwed to the vibe plate. As is often the case, this 3D print method was chosen for its simplicity in a situation where robustness was not key. The team also manufactured minor attachments for this plate to allow for interface with the far higher-quality vertical vibe table. These tests never came to fruition, but a bolt pattern was drilled into connecting bars that was consistent with the vibe table bolt pattern and would have allowed for small-scale testing. Again, the manufacturing process for these was a simple matter of drilling holes into scrap aluminum with the correct dimensions. A figure of this plate with vertical vibe table attachments and a single boom bay is featured below. The PLA collars are featured in bright green. The plate itself was detached from the extrusions in the rear for use on the horizontal vibe table.

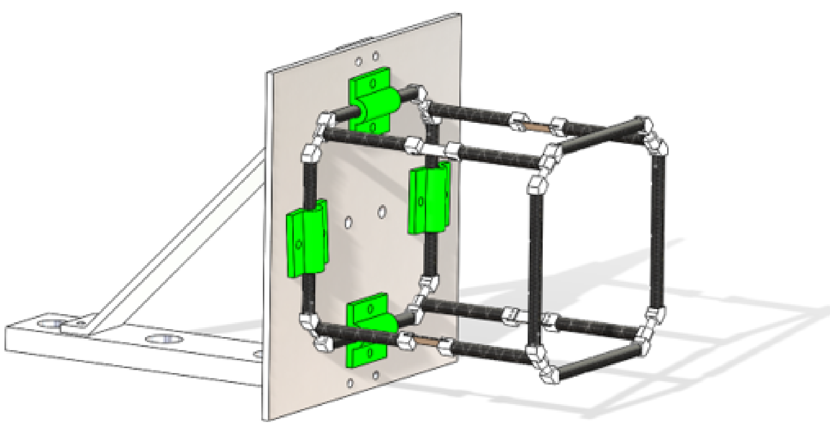


Fig. 35 Vibe Table Plate for Resonance Testing

The second of these vibe table apparatuses never saw any utility, but was designed to connect a fully collapsed boom to the vertical vibe table for launch environment testing. The entire construct is a strategic joining of four more pieces of scrap aluminum with bolt holes drilled into it in alignment with the profile of the table. The raised bars on the top level prevent interference between the table itself, and the boom interface to its bottom plate and the test rig. Both the test apparatus and the interfacing vibe table bolt pattern are shown below in Figures 36 and 37 respectively.

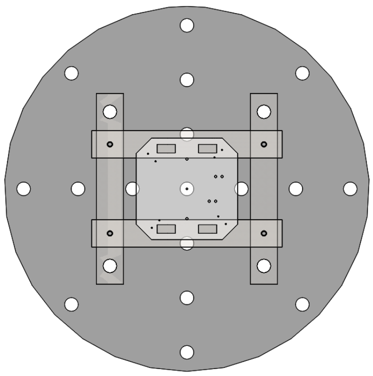


Fig. 36 Vertical Vibe Table Profile with Test Apparatus and Boom Bottom Plate Overlay

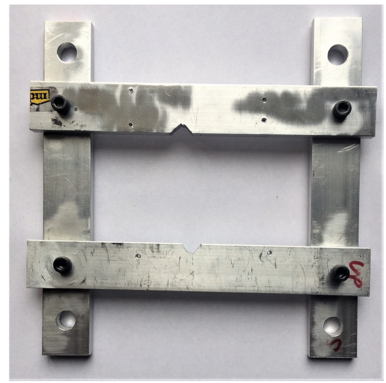


Fig. 37 Vertical Vibe Table Attachment

F. Deployment System

Ben Pearson

The deployment system was the biggest source of trouble to the manufacturing team by a long shot, in part because of schedule compression due to time spend on structural development and in part because component quality was inadequate without being realized, but mostly because of poor planning and design work. So much focus had been applied to development of the primary boom structure that production of a proper manufacturing plan for the deployment system fell by the wayside, and suffered because of it. These lapses were in no way helped by a machine shop which had become busy and this added difficulty to otherwise routine machine use.

In reality, none of the parts involved in this system were any more difficult than any challenges the team had overcome before. The spool walls were simple blocks of aluminum clamped on their side in the CNC, cut in full, and then 'tophatted' in a knee-mill. Bearings were pressed into the sockets to accommodate the upcoming spool axes, and holes were drilled in the wall bases to align with the interface on the bottom plates.

Production of the burn box was not much more challenging. The team received a small, charitable donation of polysulfide plastic scrap from Bioserve as material with which to construct it. Its simple geometric nature meant that it was a near-trivial effort to properly shape using the knee-mill.

The real difficulty emerged for this system while constructing the spool faces. Initial attempts to create these faces seemed successful and, per recommendation, were fulfilled by placing aluminum rod segments into a lathe chuck to sit within a vice in the CNC. The spool segments were then faced using a lathe which gripped the axle with a collet.

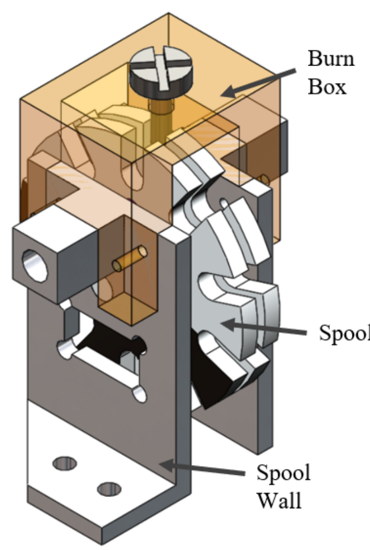


Fig. 38 Primary Deployment System

It was not until assembly of the broader system, right before it was needed, that the team realized that one of these spool parts seemed to have a bent axle - which made the whole setup function incorrectly. The source of this bend was a mystery, compounded by the production of a second part with the same defect. The first spool, after all, seemed fine. To address this issue the team drafted a very rudimentary fishbone, or Ishikawa, diagram - replicated in Figure 39 below. Concerns were arranged by major manufacturing phase. The axle deflection could have been caused at the end, by simple manual force in the assembly phase. It could have arisen because of an overzealous first contact in the lathing step, as the otherwise completed part was faced. Most likely however, a misalignment would have occurred during the primary part manufacturing process within the CNC. With so many moving parts, and a slightly novel configuration, even the practiced team could have been careless in its work.

Realistically though, the successful part and the unsuccessful parts had been developed too far apart, and all of the CNC variables had changed by the time the issue needed to be addressed. It is likely, the team feels, that a tool misalignment was the real culprit. However, time did not allow for experimentation and exploration here. Every aspect of the CNC was reset, and extra care was taken to prevent faults in the other branches of consideration. The matter was resolved for the fourth spool, and the team was able to conduct relevant tests with a delay of a couple of weeks.

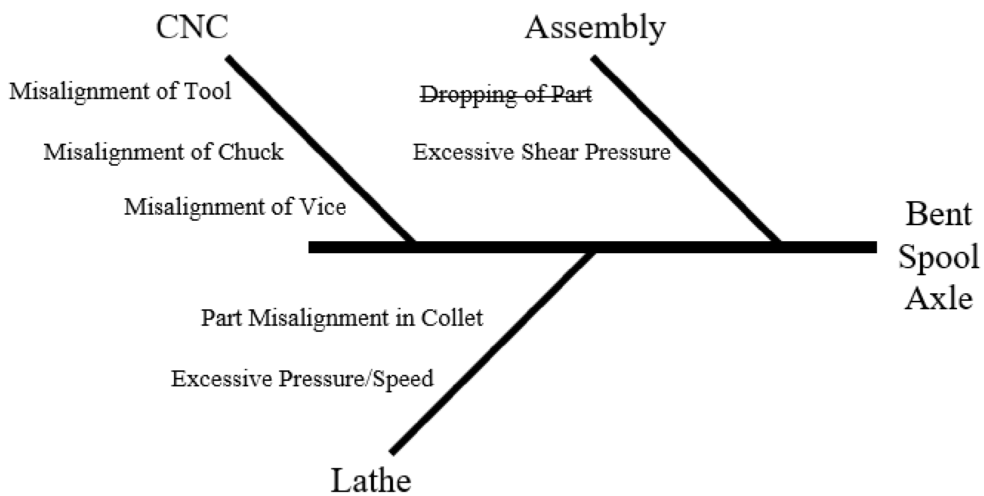


Fig. 39 Spool Axle Bend Ishikawa (Fishbone) Diagram

G. Manufacturing Purchasing List

Ben Pearson

The following describes the material needed to create one single PEEK boom and assumes a reasonable degree of error in the manufacturing process. A Delrin version of the boom requires a simple switch of the two materials. Since price is less a concern for Delrin, a purchase of simple bars is recommended - rather than the cost-conscious sheets the team cut up for PEEK. One boom requires 30 - 40 bars of 6 x 0.375 x 0.375 inches of either. The provided PEEK solution here is theoretically capable of producing 64 bars - not including losses from cutting.

This table does not include tools, though the manufacturing team recommends stocking up on carbide tips and an extra 0-80 screw tap. It also does not include the parts for the deployment system. For these parts the team was largely able to use scrap aluminum from around the shop. Delrin would be an adequate stand-in for the polysulfide burn box. Unfortunately, 30ft of Nitinol was the minimum available from the listed source. This should be enough for three to five such booms.

Table 9 Manufacturing Purchases

Line Item	Part	Source	Part Count	Cost per	Total Cost
Carbon Fiber Tubes	Longerons/Battens	Goodwinds	12	$17.99	$215.88
Carbon Fiber Tubes	Corner Rods	McMaster	5	$2.57	$12.85
Delrin Rod	Cable Coil Holster	McMaster	1 ft	$7.00	$7.00
Nitinol	Hinges	Confluent	30 ft	$295.80 / 30 ft	$295.80
Armstrong A-12	Epoxy	Ellsworth	1	$45.29	$45.29
PEEK (3/8")	Connectors	McMaster	1	$408.90	$408.90
Screws	Screws	McMaster	2 (50 per box)	$7.71	$15.42
Nuts	Nuts	McMaster	2 (50 per box)	$5.34	$10.68
Titanium Sheet	Top & Bottom Plates	McMaster	2	$12.97	$25.94
PLA Filament	Tooling Jigs	Amazon	1 kg	$17.99	$17.99
Wires	Cable Coil	AccuGlass	30 ft	$116.00 / 15 ft	$232.00
Heat Shrink	Cable Coil	DigiKey	5 ft	$5.76	$5.76
				Total:	**$1,293.51**

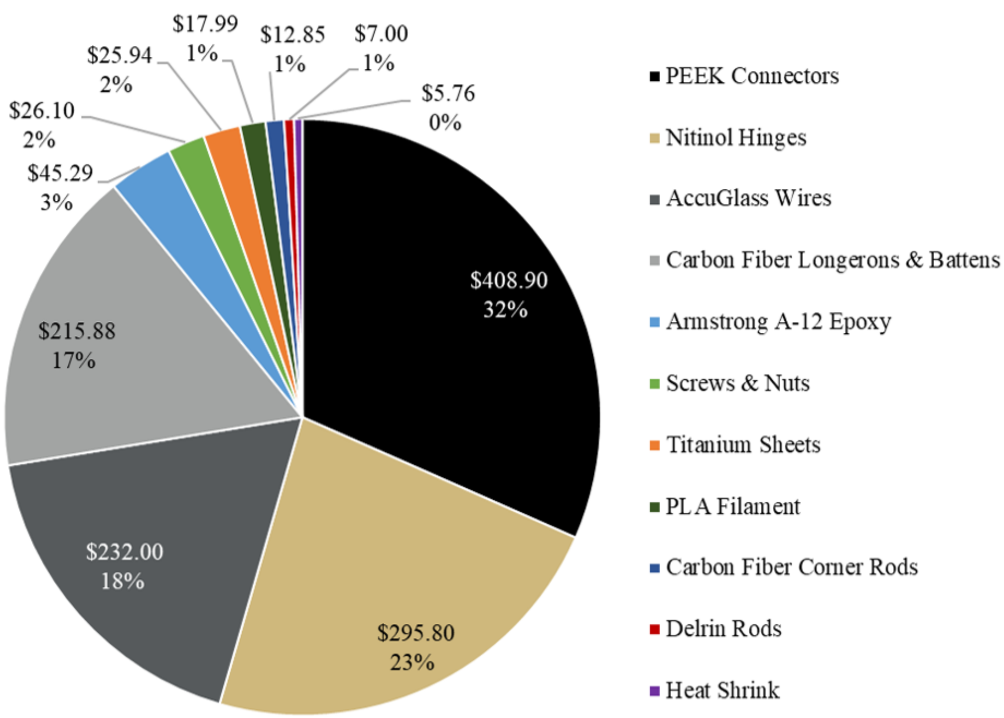


Fig. 40 Single Boom Purchasing Breakdown

5. Verification and Validation

A. Preliminary Testing

Evan Johnson, Venus Gonder

1. Epoxy Test

This test was conducted in order to find the best design for the plug section of the PEEK connectors, the "plug" being the top right portion of the connectors in figures 8 to 10. Three different designs were tested, one with a slot cut, one with a slot as well as a thinner cross section, and one unchanged plug. Three of each plug design were tested with an axial tension force as this was the force the team expected the connectors to be under most often. The regular cylindrical plug held an average of 12.1 kg before failure, the slit and thinned plug held 11.2 kg before failure, and the slit held only 7.9 kg before failure. The unchanged plug design held the most weight, this is most likely due to the surface area of the plug to which the epoxy adheres.

2. Nitinol Test

The Nitinol test preformed used a two-bay boom in order to determine the force required to collapse the boom. The results of this test are in Figure 41. The spike seen in the data near one inch is likely due to an over-compression of the boom structure, the fairly constant result above one inch is the data used in other models. The test confirmed the team's suspicion that the Nitinol behaves non-linearly. Linear behavior would result in a linearly decreasing pushing weight with increasing height instead of the relatively constant force shown.

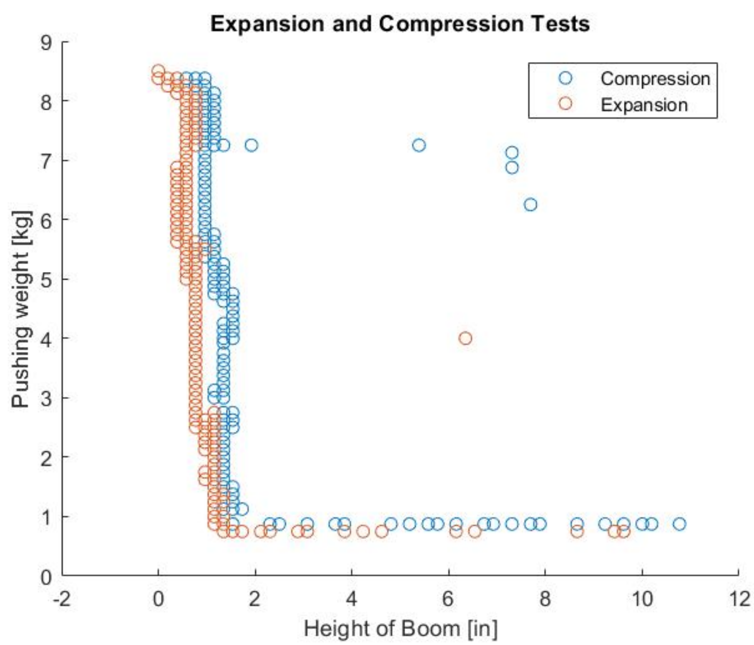


Fig. 41 Compression and Expansion Data.

3. Power Test

The purpose of the power test was to verify DR_1.3 was met. Specifically, the boom shall not use more than 30 Watts of power to fully extend. A simple pass/fail test was used to verify this requirement. Initial estimates put the resistance of the nichrome wire between 2 and 4Ω, dependant on the final length which would be used. Additionally the electrical team determined 800 mA of current was sufficient to melt the Polyethylene Burn Cord in roughly 2-3 seconds through preliminary testing. Current at 600 mA resulted in roughly a 30 sec deployment time, and current at 1000 mA resulted in a larger power draw. Using 800 mA of current and the highest estimated resistance, an estimated power draw of $P = I^2 \cdot R = 0.8^2 \cdot 4 = 2.56\ W$ was expected for the test.

The test utilized the deployment mechanism, a multimeter, current supply, and timer to verify DR_1.3. The deployment system was set up, and the resistance of the nichrome wire was measured. Current at 800 mA was then applied to the wire and simultaneously the timer was started. Once the deployment system released its pin, the timer was stopped and the current supply turned off. The results of the test are outlined below in table 10. The required deployment power was measured to be 2.30 W for 3 seconds, well below the allowable 30 W.

Table 10 Power Test Results

Test Number	Measured Resistance	Current	Time of Burn	Power
1	3.59 Ω	800 mA	3 sec	2.30 W
2	3.59 Ω	800 mA	4 sec	2.30 W
3	3.59 Ω	800 mA	3 sec	2.30 W
4	3.59 Ω	800 mA	3 sec	2.30 W
5	3.59 Ω	800 mA	2 sec	2.30 W
Avg	**3.59 Ω**	**800 mA**	**3 sec**	**2.30 W**

B. Functional Requirement Validation Testing

Michael Burke, Evan Johnson, Venus Gonder, Michael Strong, Britnee Staheli, Collin Doster, Roger Heller, Rowan Gonder

1. Resonant Frequency Tests

Requirements Under Test

- FR 6

Resonant Frequency Models

The resonant frequency modeling was performed using the SolidWorks simulation package, specifically the random vibration toolbox. Initial analysis was done using a simplified model in order to reduce the computer resources needed to run the simulations. The main assumption in the simplified model was that the longerons were continuous carbon fiber tubes, the Nitinol strips were excluded. All simulations were run using the highest fidelity blended-curvature mesh to ensure the results were as realistic as possible.

The initial results for the first resonant frequency of a 12 bay (1.2 meter) truss was 31.1 Hz in bending. Modeling of torsional frequencies was also performed but the first torsional resonant frequencies always occurred at least an order of magnitude higher than the bending frequencies. The team used this to justify only worrying about the first resonant frequency in bending. After further higher quality modeling was performed as well as testing the team has no reason to suspect that this decision was made incorrectly.

The final finite element modeling was done using an accurate model of the boom in SolidWorks. This model included all the required components, including the Nitinol. All material properties used in this model were gathered from reliable sources. This modeling was performed slightly differently than the first round. The modeling team ran eight different cases. Each case had one additional bay than the last, ranging from 1 to 8. The first resonant frequencies in bending for each case were recorded and can be seen in Table 5 and plotted in Figure 42. Only 8 bays were ultimately simulated because there were insufficient computer resources available to mesh larger models. The results were used to calculate a line of best fit using a modified least-squares method. This line was used to estimate a first resonant frequency in bending of just over 5 Hz with a full 12-bay boom.

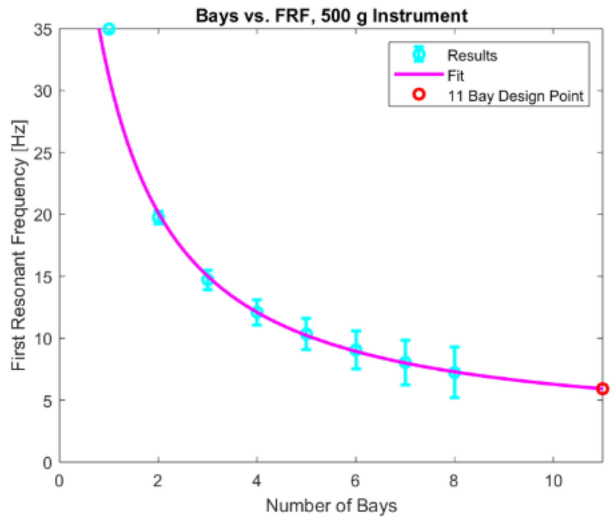


Fig. 42 Final Frequency Modeling Results

Required Resources

The list of required equipment needed to complete the tests that must be done in order to verify the design requirements of the sixth functional requirement are given below in Table 11.

Table 11 Equipment to Test FR 3, FR 9, and Subsequent DRs

Equipment Name	Level of Precision	Where to Obtain
Accelerometers	± 0.001 mm/s^2	AERO Department
Horizontal Shaker Table	.01 Hz	Electronic Shop
Impact Hammer	N/A	Electronic Shop

Test Strategy

Two different test were utilized to attempt to determine resonant frequency of the boom. The purpose of the tests was to not only attempt to find the resonant frequency, but also to validate the results of the models. If the models were deemed accurate with respect to the physical tests, it would allow the use of them in more complex testing environments (i.e. zero-g orbital conditions). The tests were designed to effectively validate the sixth functional requirement.

For both the tests, two accelerometers were attached to the eight bay boom. One sensor was attached to the payload, while the other sensor was attached to the aluminum base plate on the other end. The boom assembly was then suspended from the horizontal shaker table. These accelerometers were connected to a DAC unit to record data using the beam airplane VI used in ASEN 3112.

Driven Resonant Frequency Test

In the driven test, a function generator and amplifier were attached to the horizontal shaker table. Starting at 500 mHz, the frequency of the shaker table was increased in 100 mHz increments up to 5 Hz. At each 100 mHz increment, the vibration of the boom was allowed to reach steady state, at which point the data was saved.

Impulse Hammer Resonant Frequency Test

Once this test was completed the horizontal shaker table arm was restrained with the deployed boom still attached to start the impulse test. With the baseplate secured the boom was then hit with a soft mallet and the natural response of the boom was recorded. Mathematically, the frequency response of the boom to an impulse of infinitely brief duration should due only to the boom's structure, and any amplitude spikes in the frequency domain should reveal the resonant modes of the boom.

Specific Requirement Validation

FR 6: By performing the compression and tension impact and driven response tests a resonant frequency estimate of the boom structure's first modal frequency was determined. This functional requirement gave a lower bound for acceptable first mode resonant frequency of 2.5 Hz. The resonant frequency result was compared to this limit to determine whether or not this functional requirement was met.

Pass/Fail Criteria

Given below in Table 12 are the pass and fail criteria of the requirement analyzed in this test. Also, given in the last column of this table is the pass/fail result for the requirement determined through the analysis and tests that were completed.

Table 12 Pass/Fail Criteria for Resonant Frequency Test

ID	Pass Criteria	Fail Criteria	P/F Result
FR 6	First mode resonant frequency is above 2.5 Hz.	First mode resonant frequency is below 2.5 Hz.	Undetermined

Test Results

The results of the two different tests failed to agree with each other, despite meticulous testing plans for both. The discrepancy is believed to have been caused by a number of reasons, including unexpected external vibrations.

Driven Resonant Frequency Test

The results from the driven test seem to indicate that there is a first resonant frequency at 2.6 Hz. The team analyzed the data at each 100 mHz interval for peaks in displacement between the two accelerometers. This displacement was then normalized and compared with all other peaks. The results are shown below in Figure 43

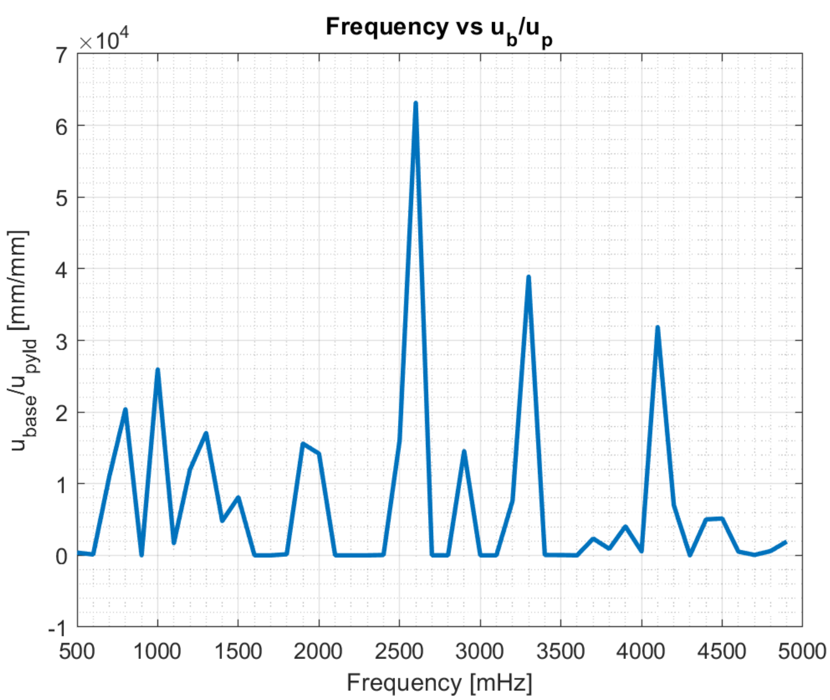


Fig. 43 Driven Test Frequency Results

Impulse Hammer Resonant Frequency Test

The accelerometer data recovered from the impulse hammer resonant frequency test was analyzed using MATLAB's built in Fast Frequency Transform (FFT) tool to convert the time-domain data into the frequency domain. On the principle that the impulse response of a system should be the transfer function of the system itself, the frequency response of the boom to a single impulse should capture only the boom's natural response to the strike. The results (shown in Fig 44) indicate that the first resonant frequency of the structure is at 0.56 Hz after the displacement was normalized with reference to the displacement of the baseplate.

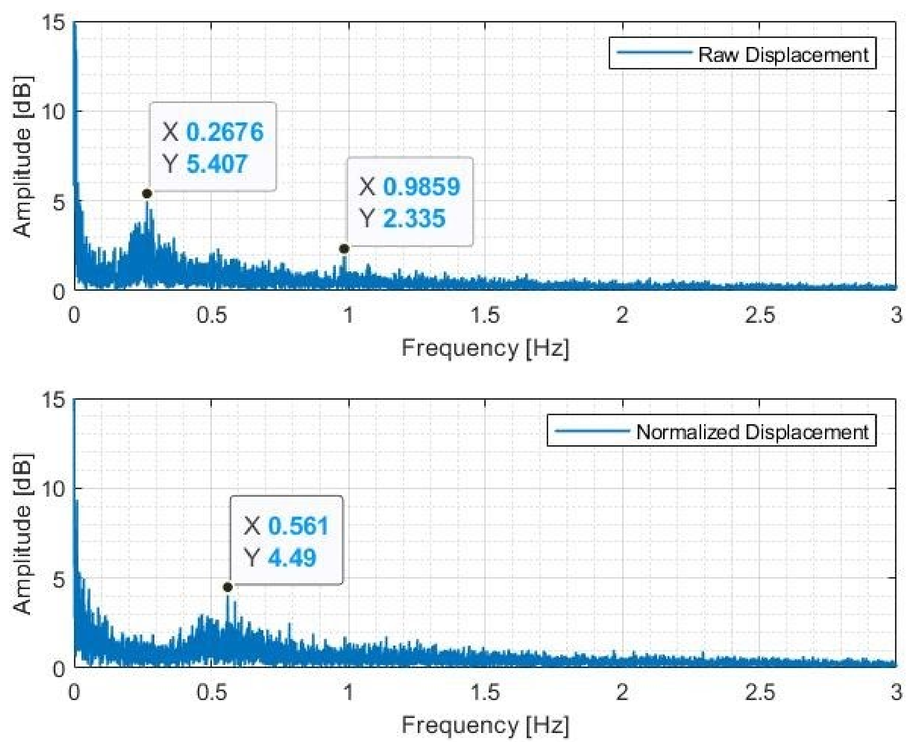


Fig. 44 Impact Test Frequency Results

2. Mass Dimension Test

Requirements Under Test

- FR 3, DR 3.1, DR 3.2, DR 3.3, DR 3.4
- FR 9

Required Resources

The list of required equipment used to complete the tests that were done in order to verify the design requirements tied to the third and ninth functional requirements are given below in Table 13.

Table 13 Equipment to Test FR 3, FR 9, and Subsequent DRs

Equipment Name	Level of Precision	Where to Obtain
Electronix Express Calipers	± 0.01 cm	Within Senior Project Tool Box
Acculab SV-50 Scale	± 10 g	Electronic Shop

Test Strategy

For the initial setup the undeployed boom was rested horizontally on a table with enough room for dimensional measurements to be completed. The first measurement obtained was of the z-axis or the length of the boom, which is the axis along the longest dimension starting from the base plate. The next measurement made was of the x-axis or the height of the boom. This axis corresponds to one of the two smaller sides defined by the right hand rule based off the z-axis. The last measurement made was of the y-axis or the width of the boom.

After these initial dimensional measurements of the undeployed boom assembly were completed, measurements of the accommodating guide rails were performed. Following the same axis definition used for the undeployed boom assembly, the three different axial dimensions were obtained for each of the four separate guide rails.

Following the completion of all the dimensional measurements, the final task completed was weighing the entire system, minus the attached instrument, in the undeployed state. This was as simple as placing the full boom assembly onto a scale and recording the mass shown.

Specific Requirement Validation

FR 3: By performing the tests required to validate the four subsequent design requirements of this one functional requirement the needed tests to validate this requirement were completed.

> **DR 3.1:** By performing the test that measured the z-axis of the full undeployed boom assembly an understanding of the total length was determined. The length of the built system was then compared to the maximum allowable length of 15 cm to determine whether or not this design requirement was met. By verifying this measurement and proving this requirement passes one fourth of the functional requirement was passed.
>
> **DR 3.2:** By performing the test that measured the x-axis of the full undeployed boom assembly an understanding of the total height was determined. The height of the built system was then compared to the maximum allowable height of 10 cm to determine whether or not this design requirement was met. By verifying this measurement and proving this requirement passed one fourth of the functional requirement was passed.
>
> **DR 3.3:** By performing the test that measured the y-axis of the full undeployed boom assembly an understanding of the total width was determined. The width of the built system was then compared to the maximum allowable width of 10 cm to determine whether or not this design requirement was met. By verifying this measurement and proving this requirement passed one fourth of the functional requirement was passed.
>
> **DR 3.4:** By performing the test that measured the size of the accommodated guide rail space an understanding of the total rail dimensions that are accommodated was determined. These accommodations were then compared to the actual rail dimensions specified in the NanoRacks IDD mechanical specifications document to determine whether or not this design requirement was met. By verifying these various measurements and proving this requirement passes one fourth of the functional requirement passes.

FR 9: By performing the test that weighed the full boom assembly, minus the attached instrument, an understanding of the total mass was determined. With the mass of the built system found it was then compared to the maximum value of 1.5 kg to determine if this functional requirement passed or failed.

Pass/Fail Criteria

Given below in Table 14 are the pass and fail criteria of each of the six requirements analyzed within this particular test. Also, given in the last column of this table are the pass/fail results for each requirement determined through the analysis and tests that were completed.

Table 14 Pass/Fail Criteria for Mass/Dimension Test

ID	Pass Criteria	Fail Criteria	P/F Result
FR 3	All four design requirements of this functional requirement pass.	One or more of the design requirements of this functional requirement fail.	Pass
DR 3.1	The measured length of the full undeployed boom assembly is less than or equal to 15 centimeters.	The measured length of the full undeployed boom assembly is greater than 15 centimeters.	Pass
DR 3.2	The measured height of the full undeployed boom assembly is less than or equal to 10 centimeters.	The measured height of the full undeployed boom assembly is greater than 10 centimeters.	Pass
DR 3.3	The measured width of the full undeployed boom assembly is less than or equal to 10 centimeters.	The measured width of the full undeployed boom assembly is greater than 10 centimeters.	Pass
DR 3.4	The full boom assembly accommodates the NanoRacks guide rail dimensions of 6 millimeters by 6 millimeters.	The full boom assembly does not accommodate the NanoRacks guide rail dimensions of 6 millimeters by 6 millimeters.	Pass
FR 9	The measured mass of the full boom assembly with the instrument unattached is less than or equal to 1.5 kilograms.	The measured mass of the full boom assembly with the instrument unattached is greater than 1.5 kilograms.	Pass

Test Results

Given below in Table 15 are the test results from performing the previously described test.

Table 15 Test Results for Mass/Dimension Test

ID	Expected Result	Result
DR 3.1	Length = 15 cm	Length = 14.99 cm
DR 3.2	Height = 10 cm	Height = 9.95 cm
DR 3.3	Width = 10 cm	Width = 9.95 cm
DR 3.4	Guide Rail Space = 6 mm x 6 mm	Guide Rail Space = 6 mm x 6 mm
FR 9	Mass < 2 kg	Mass = 0.89 kg

3. Cable Routing Test

Requirements Under Test

- FR 2, DR 2.1, DR 2.2

Required Resources

The list of required equipment needed to complete the tests that must be done in order to verify the design requirements and specific requirements tied to the second functional requirement are given below in Table 16.

Table 16 Equipment to Test FR 2 and Subsequent DRs

Equipment Name	Level of Precision	Where to Obtain
Arduino Due	~20 Hz	Checked out from Trudy Schwartz
Voltage supply	± 0.1 V ± 0.01 A	Electronics Shop
Multimeter	± 0.1 Ω ± 0.01 A ± 0.1 V	Electronics Shop
Function Generator	N/A	Electronics Shop

Test Strategy

This section outlines the general steps to follow for each sub-test performed. This will result in the most efficient and effective tests for validating each of the three requirements. The team was able to complete 2 out of the 3 planned sub-tests. An analytical model was put together and used to gather the information that would have come out of the third sub-test. The first sub-test involved deploying the full boom assembly and verifying through inspection that all the cables and their corresponding wires were not damaged or became unconnected from their attachment point during the deployment process. This sub-test was completed successfully after the deployment test.

The next sub-test performed involved testing the continuity of each cable. This was used to verify that power and signals could be sent along the length of the boom. Each cable was successfully verified to maintain continuity. In the case of the power cable, the shielding was also verified to maintain continuity between the bottom and top of the boom as a means of maintaining a common spacecraft ground. This sub-test verified the cables remained intact from an electrical standpoint. Completion of this test theoretically ensures data and power are able to be sent along the length of the boom.

The last sub-test, which was not able to be performed, involved sending and receiving a differential signal along the three data cables and sending and receiving power along the power cable. The differential signal was to be generated by a function generator set to output a square wave. This square wave would then be sent along each data cable, one at a time, and read using an oscilloscope. The oscilloscope readings in conjunction with the function generator would then be used to characterize the attenuation and maximum digital data rate of each data cable. The oscilloscope readings would have been used to verify through demonstration that a differential signal was indeed propagating along the data cable. A voltage source was to be used to send power along the power cable. A multimeter would verify this output at the opposite end of the power cable.

In lieu of the third sub-test, a predictive model was designed to estimate the maximum digital data rate results. It is important to note that it is safe to assume the cables are capable of delivering power and data in at least some capacity. This assumption can be made as the continuity check, in sub-test 2, was successfully completed. The specifics of the signals however are unknown as it was never verified through testing. The analysis that is performed here is used to estimate the signal's specifics that the team was unable to measure.

Specific Requirement Validation

FR 2: By performing the tests required to validate the two subsequent design requirements of this one functional requirement the needed tests to validate this requirement are completed.

> **DR 2.1:** By analyzing the differential signal cables following deployment it can be determined whether any damage is sustained during deployment. Then, by performing a test on each cable that verifies a signal can still be sent through the internal wires it can be reported to the team whether or not the cables are still functional. This will allow for a determination of if this design requirement is met and can be passed. By verifying that the wires remain functional and proving that this requirement passes, one half of the functional requirement passes.

> **DR 2.2:** By analyzing the power cable following deployment it can be determined whether any damage is sustained during deployment. Then, by performing a test on this cable that verifies power can still be transported through the internal wires it can be reported to the team whether or not the cable is still functional. This will allow for a determination of if this design requirement is met and can be passed. By verifying that the three-wire power setup remains functional and passing this requirement, one half of the functional requirement passes.

Pass/Fail Criteria

Given below in Table 17 are the pass and fail criteria of each of the three requirements analyzed within this particular test. Also, given in the last column of this table are the pass/fail results for each requirement determined through the analysis and tests that were completed.

Table 17 Pass/Fail Criteria for Cable Routing Test

ID	Pass Criteria	Fail Criteria	P/F Result
FR 2	The two design requirements of this functional requirement pass.	One or more of the design requirements of this functional requirement fail.	Pass
DR 2.1	The 3 separate differential signal cables are not damaged during deployment, and can carry the necessary data when the boom is fully deployed.	The 3 separate differential signal cables are damaged during deployment, or they cannot carry the necessary data when the boom is fully deployed.	Pass
DR 2.2	The three-wire power setup is not damaged during deployment, and they can successfully transport 15 V at 0.5 A when the boom is fully deployed.	The three-wire power setup is damaged during deployment, or they cannot successfully transport 15 V at 0.5 A when the boom is fully deployed.	Pass

Predictive Model for Sub-Test 3

The analysis to estimate results of sub-test 3 is organized in 4 distinct steps. It is assumed that differential signals imply digital signals and thus square wave signals. The analysis performed will therefore aim to find the highest data rate a single twisted pair cable may be capable of passing. The first step involves generating an equivalent circuit model of a single cable from the coil cable assembly. This circuit is purposely designed to depend on a single cable's cross sectional characteristics. The second step calculates the attenuation the circuit equivalent model generates on a sinusoidal signal. The third step estimates the shortest rise time this attenuation allows for. Lastly, the rise time can be used to estimate a maximum data rate based on the period of an estimated square wave signal.

Step 1. Circuit Equivalent Cable Model:

The first step is to redefine a single cable with a circuit equivalent model. Starting from the data coil containing two twisted pair cables, a single cable is taken out. The characteristics of a cross section of the cable were assumed to be uniform along its length and used to generate a circuit equivalent model. The circuit model chosen to represent the cable is a lossy transmission line equivalent circuit, extremely common in the RF world. This circuit realization process is shown in figure 45. The dimensions of the cable were estimated from the manufacturer's specification sheet with a = .321 mm, d = 2.16·a, and D = 1.375·d. The dielectric in the cable is assumed to be air. While there is a thin layer of Kapton wire insulation, the majority of the volume within the shielding is air therefore, $\epsilon_0 = 8.854 \cdot 10^{-12}$ F/m, $\mu_0 = 4\pi \cdot 10^{-7}$ H/m, and $\sigma_0 = 10^{-12}$ S/m.

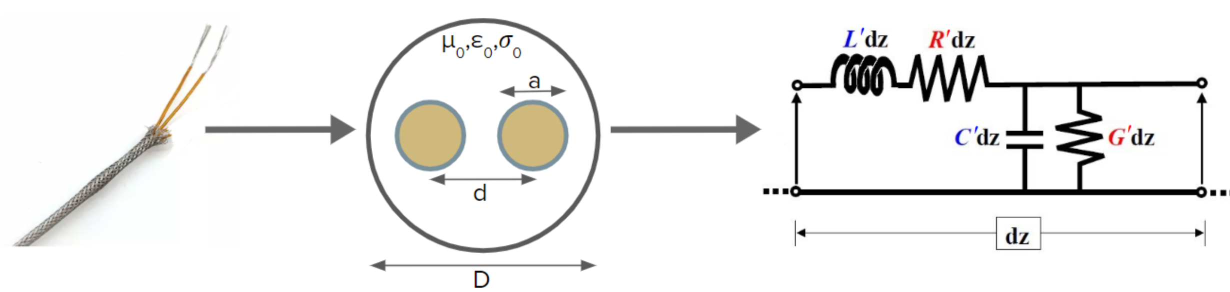


Fig. 45 Twisted Pair Equivalent Circuit Model

The equivalent circuit is defined by the resistance, conductance, inductance, and capacitance per unit length of the cable (R', G', L', C'). Two different models were used to compute these values, shown in table 18. The first model is a simple two wire line model normally made with the assumption of d >> a in figure 45 and without shielding. This model is used as a first order approximation as it is easily derivable from the E and H fields surrounding the wires. The second model [8] takes into account losses due to the wire shielding. The circuit characteristics both of these models estimate, fully define the lossy transmission line circuit. The circuit can then be used to replace the twisted pair cable and allows for simpler signal analysis.

Table 18 Equivalent Circuit Parameters

Model	R'	G'	L'	C'
Two Wire Line [7]	$\frac{2R_S(f)}{\pi a}$	$\frac{\sigma_0}{\epsilon_0}C' = 2.35$ pS/m	$\frac{\mu_0}{\pi}ln(2d/a) = 0.534\mu$H/m	$\frac{\pi\epsilon_0}{ln(2d/a)} = 20.8$ pF/m
TLM Model [8]	See Eq 5	$\frac{\pi\sigma_0}{osh^{-1}(a/d)} = 2.50$ pS/m	$\frac{\mu_0}{\pi}cosh^{-1}(d/a) = 0.503\ \mu$H/m	$\frac{\pi\epsilon_0}{cosh^{-1}(d/a)} = 22.1$ pF/m

$$R'(f)_{TLM} = \frac{2R_s(f)}{\pi a}\Big(1 + \frac{1+2(d/a)^2}{4(d/a)2}(1-4(d/D)^2)\Big) + \frac{8R_s(f)}{\pi D}(d/D)^2\Big(1+(d/D)^2 - \frac{1-4(d/a)2}{8(d/a)^4}\Big) \tag{5}$$

The key takeaway from the circuit parameters is that the resistance per unit length, R', is dependant on frequency through $R_s(f)$. $R_s(f)$ is given by $R_s(f) = \sqrt{((\pi\mu_c f)/(\sigma_c))}$. This frequency dependence is due to the skin effect occurring at high frequencies [7]. The end result of the skin effect being the majority of current traveling near the surface of the conductor within a depth equal to $\delta = \sqrt{1/(\sigma_c \pi f \mu_c)}$. With σ_c being the conductivity of the conductor, f the frequency of a sinusoidal signal propagating, and μ_c the permeability of the conductor. As frequency increases the current depth, δ, decreases ultimately decreasing the area, A, in which current can travel through, as resistance in general is given by $R = L/(\sigma_c A)$.

Step 2. Circuit Attenuation:

Using the equivalent circuit model, the voltages along the circuit can be solved to find how a signal may propagate through the circuit. The voltage along the circuit propagating in the z direction is given by a second order differential equation with one solution given by a sine wave, equation 6 [7]. The propagation of the sine wave is characterized by the propagation coefficient, γ, shown in equation 7 and is dependant on the circuit's parameters outlined in table 18.

$$V(z) = V_+ e^{-j\gamma(f)z} + V_- e^{+j\gamma(f)z} \tag{6}$$

$$\gamma(f) = \alpha + j\beta = \sqrt{(R'(f) + j\omega L')(G' + j\omega C')} \tag{7}$$

The propagation coefficient can be seen to contain a real and imaginary part. The imaginary portion determines the phase of the propagating wave in the z direction. The real part of the propagation coefficient, α, however causes attenuation of the signal as $e^{-\alpha z}$.

In order to give the team confidence in the models generated, this computed attenuation was compared to a common Cat5 cable. The attenuation is compared instead of the data rate as digital data rates are directly dependant on the encoding scheme used. The attenuation of a Cat5 cable [9] was used as it is a common unshielded twisted pair cable used for data transfer. Both models were compared to Cat5 standards and the results shown in figure 46.

The results of the comparison give the team confidence in the models used. There is agreement from 1 MHz all the way up to 100 MHz. The largest difference is seen in the two wire line model which is expected as this is a coarse approximation of the two transmission lines being studied.

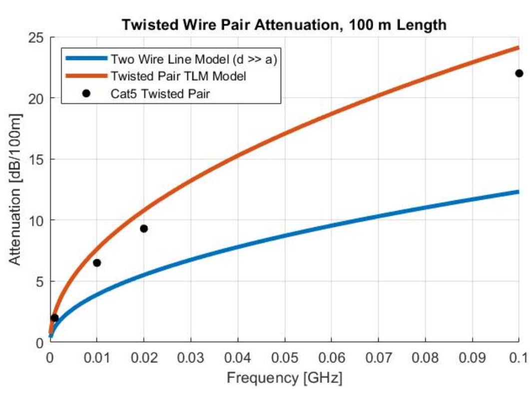


Fig. 46 Attenuation Comparison

With confidence established in the models used, the attenuation as a function of frequency is shown in figure 47. The length of the twisted pair line is now taken into account to give an attenuation in dB instead of dB/length. The results of the TLM model will be carried forward as it is a more accurate model of the cable being used. The 3 dB bandwidth of the line from the TLM model is computed to be 8.22 GHz. While this is much higher than a Cat5 cable rating, 100 MHz, the cable being studied is much shorter than the rated length of Cat5 cables, 100m.

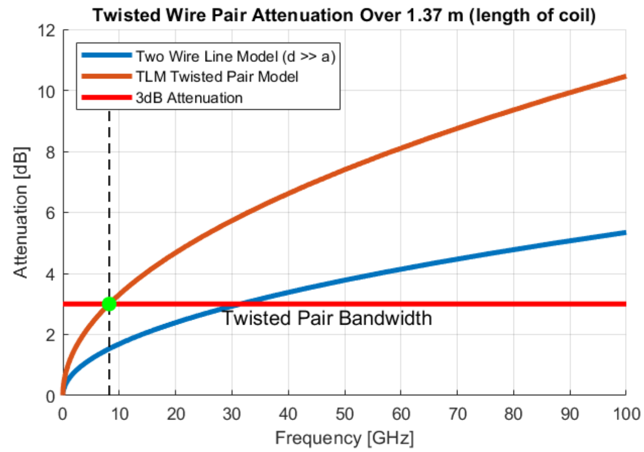


Fig. 47 Attenuation Increase With Frequency

Step 3. Estimated Shortest Rise Time:

Keeping in mind the end goal of this analysis is finding the highest data rate capable of being sent, a digital signal can be characterized by its rise time. The rise time in the case of a 10-90 rise time, R_{10-90}, is the time it takes for a square wave (waveform of a digital signal) to go from 10% to 90% of its final value. The attenuation the circuit model causes can be used to estimate the shortest rise time that can be accurately sent through the line. A common rule of thumb used to estimate rise time is given by $RT_{10-90} = 0.35/BW$ [10]. Using the bandwidth computed in the previous section, the shortest 10-90 rise time that can be sent through the twisted pair line is 42.6 ps.

Step 4. Highest Digital Data Rate:

Using the the 10-90 rise time computed and making an approximation of a digital signal, the data rate can be computed. If the RT_{10-90} is approximated to be 7% of the period of the digital signal [10], then the digital signal period can be estimated to be $RT_{10-90}/7\% = 0.61$ ns. The frequency of this signal is given by 1/period and is found to be 1.64 GHz. This correlates to a 1.64 Gb/s data rate if a single bit represents one bit of data.

It is very important to understand the assumptions made in this analysis. The largest assumption made is a constant cross sectional area of the cable. Variation in this cross section alters the attenuation of the signal and violates assumptions made in deriving the equations in Table 18. This analysis also does not take into account impedance mismatches between sources at the bottom or top of the boom. Lastly, the analysis does not take into account coupling or electromagnetic interference that may be present. Shielded cable was chosen to mitigate these negative effects however future modeling and testing would be needed to validate this mitigation assumption. In conclusion, in lieu of sub-test 3, an analytical model was used to estimate the maximum data rate of a digital signal that can be sent along a single twisted pair cable. This data rate for a single cable is estimated to be 1.64 Gb/s and should be verified, future tests allowing.

4. Full Deployment Test

Requirements Under Test

- FR 1, DR 1.1, DR 1.2, DR 1.3, DR 1.4, SR 1.4.1, DR 1.5
- FR 4, DR 4.1, DR 4.2, SR 4.2.1, DR 4.3
- FR 5, DR 5.1

Full Deployment Model

The mathematical model used to estimate performance during the full deployment test was based off a simplified mass-spring system. In this model the mass of the CubeSat bus is assumed to be much greater than the boom and instrument, effectively being inertially fixed rather than free to displace as the boom deploys. The first iteration of the model replaced the Nitinol hinges with linear springs, although this assumption was known to be faulty from the results of the Nitinol compression tests described above. Therefore, although the model depicts spring elements, the calculations derived from this model actually assumed a constant force from the Nitinol in accordance with the compression test results. Similarly, tension in the restraining cord was captured as a constant tension term since this force would be due to the friction brake applying a constant torque on the restraining cord spool as it rotated. Friction internal to the boom, for example in the surfaces of its joints sliding past one another, was captured in a single term. Finally, the power and data cables were replaced by linear springs in tension, an effect meant to capture the force of stretching their coiled shape as the boom expands. The model and its associated free body diagram (FBD) are presented below.

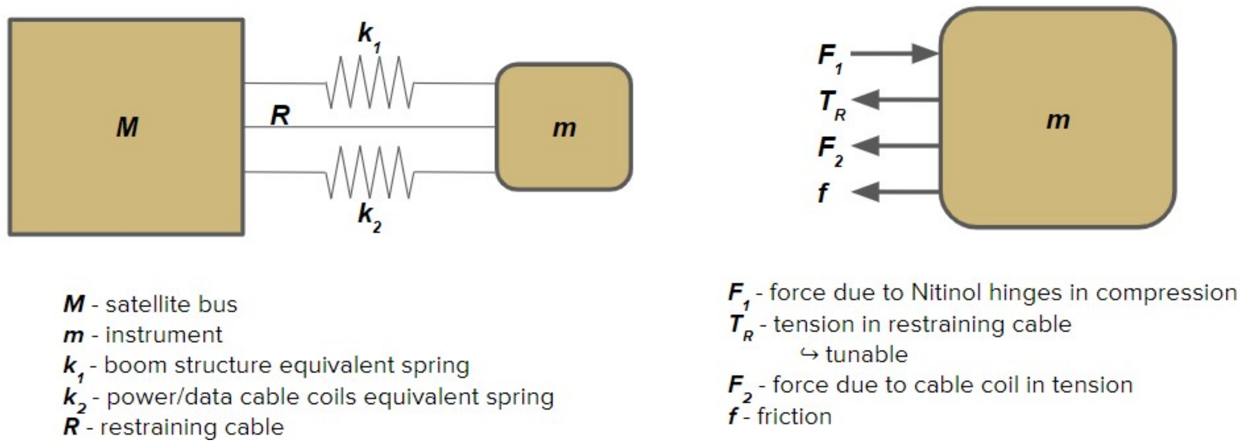


Fig. 48 Simplified mass-spring model for full deployment.

Calculations using this model yielded several important metrics to compare against experimental results. First, the maximum g-loading can be calculated in straightforward fashion from Newton's second law to estimate an initial load of 1.1 g immediately after release. Replacing the spring model for the Nitinol with a constant force and ignoring the effects of friction and the power and data cables allows for a direct application of the kinematic equations for constant-force motion, which can then be solved for the time it would take for the payload to reach its maximum displacement, i.e. for the boom to be fully extended. This calculation predicts a deployment time of 0.38 s. Finally, the energy required to compress an individual bay can be calculated as the integral of the force over the compression displacement, which is by definition the work done in compressing the bay and thus equivalent to the energy stored in the bay by the work-energy theorem. This integral was accomplished by application of MATLAB's *trapz()* function to the force data collected during compression of the two-bay structure. With that number in hand and assuming the mass of the boom to be negligible relative to the payload mass, energy methods can be brought to bear on the question of the payload's velocity immediately before the boom reaches maximum extension. Since the potential energy of a single compressed bay is known from the compression work integral, conservation of energy predicts that the payload must have equivalent kinetic energy at the end of the exchange. In that case, $PE_1 = KE_2 = \frac{1}{2}mv_2^2$, where PE_1 is the potential energy stored in the Nitinol before release, KE_2 is the kinetic energy just before full extension, m is the mass of the payload, and v_2 is the final speed of the payload. Since PE_1 and m are known constants, solving for v_2 is trivial. That calculation yields an estimate of 4 m/s for the final speed of the payload when the boom reaches its full extension.

Interestingly, this presents a new challenge: if the payload snaps to the end of the boom at 4 m/s and decelerates quickly, the g-loading at the end of the boom may exceed the 10 g limit for the payload. For example, if the interaction takes 1 ms, the g-loading would be $\frac{4}{10^{-3}} = 4000$ m/s^2, or roughly 400 g! Therefore, one critical objective for repeated full deployment testing must be to tune the friction brake such that enough of the potential energy of the compressed Nitinol hinges is dissipated as heat, meaning that the payload would reach full extension at a more sedate speed that is less likely to tear the boom apart.

Required Resources

The list of required equipment used to complete the tests that were done in order to verify the design requirements and specification requirements tied to the first, fourth, and fifth functional requirement are given below in Table 19.

Table 19   Equipment to Test FR 1, FR 4, FR 5, and Subsequent DRs

Equipment Name	Level of Precision	Where to Obtain
Timer	± 1 s	Any Cellular Devices
Westward 16 ft Tape Measure	± 1 cm	With Senior Project Tool Box
Sorensen XPH 35-4D Power Supply set as Current Supply	± 0.1 A	Electronics Lab
Keysight 34461A Digit Multimeter set as Ohmmeter	± 0.01 Ω	Electronics Lab
Accelerometer	± 0.1 g's	Electronics Lab
Lab Computer with Labview VI software	N/A	Electronics Lab
Arduino Due Microcontroller (as mock flight computer)	N/A	Check out from Lab Director
Screwdriver	N/A	With Senior Project Tool Box
Hex Wrench	N/A	With Senior Project Tool Box

Test Strategy

For the initial setup the undeployed boom was rested horizontally on a surface with enough room for full deployment to occur. The accelerometer was then mounted and turned on in order to record acceleration of the boom during deployment. An instrument mass simulator was then attached to the instrument attachment plate. Finally a Lego roller was attached to the instrument mass simulator to aid in the deployment process and avoid the sliding friction that would be induced.

The next step after setup and equipment acquisition was completed was to start the test by sending the command from the Arduino (mock flight computer) to the boom assembly that started the deployment process. At the same time a timer was started to record the required time for full extension to be reached. During deployment the deployment verification mechanism sent deployment status confirmation to the Arduino. Once the last deployment status confirmation was received by the Arduino and processed the timer was lapped to measure how long it took for any oscillations that developed to be damped out. During this period of time it was also determined whether or not power was still being drawn by the deployment mechanism through analysis of the current power draw of the full boom assembly from the power source.

Once any oscillations were damped out a measurement of the full boom extension was completed. The data from the accelerometer was then analyzed to determine the acceleration experienced by the instrument during deployment. Following this measurement and analysis the boom was then stowed through the help of multiple team members. This test was completed only twice before the reduced schedule was put into place, but allowed for some useful data to be gathered.

Specific Requirement Validation

FR 1: By performing the tests required to validate the five subsequent design requirements and one specification requirement tied to this one functional requirement, the needed tests to validate this requirement were completed.

DR 1.1: By confirming before the full deployment test that an instrument could successfully be connected to the attachment plate on the boom assembly, it was determined that this requirement was verified, therefore allowing one fifth of the functional requirement to be passed.

DR 1.2: By performing the test that measured the length of the boom after full deployment, an understanding of the total distance between the attachment point and CubeSat body was determined. The length of the full boom extension was then compared to the minimum allowable distance of 60 cm to determine whether or not this design requirement was met. By verifying this measurement and proving this requirement passed, one fifth of the functional requirement was passed.

DR 1.3: By performing the test that measured both the resistance of the wire used in the deployment mechanism and the current needed to burn the polyethylene rope, an understanding of the total power needed during deployment was determined. The value for power was then compared to the maximum allowable power of 30 W to determine whether or not this design requirement was met. By verifying this measurement and proving this requirement passed, one fifth of the functional requirement was passed.

DR 1.4: By performing the test that measured how long it took the boom to reach full extension, an understanding of the total deployment time was determined. The deployment time was then compared to the maximum allowable time of 2 minutes to determine whether or not this design requirement was met. By verifying this time measurement and proving this requirement passed, along with the subsequent specific requirement, one fifth of the functional requirement was passed.

SR 1.4.1: By performing the deployment test and recording the acceleration of the attachment plate with an accelerometer, the maximum acceleration that was experienced by the attached instrument was determined. The maximum acceleration was then compared to the maximum allowable acceleration of 10 g to determine whether or not this specification requirement was met. By verifying this measurement and proving that this requirement passed, half of the design requirement that this specification requirement is attached to passed.

DR 1.5: By performing the test that measured how long it took for any oscillations that develop to be damped out, an understanding of the total time for damping was determined. The damping time was then compared to the maximum allowable time of 2 minutes to determine whether or not this design requirement was met. By verifying this time measurement and proving this requirement passed, one fifth of the functional requirement was passed.

FR 4: By performing the tests required to validate the three subsequent design requirements and one specification requirement tied to this one functional requirement, the needed tests to validate this requirement were completed.

DR 4.1 By sending a command that started the deployment process from the Arduino to the full boom assembly it verified whether or not the boom could successfully start deploying by a command from Ground Support Equipment or a spacecraft computer. By verifying that the command was received and that the deployment process was started this design requirement was met and proved that one third of the functional requirement was passed.

DR 4.2: By executing the test required to validate the one subsequent specific requirement tied to this design requirement the needed test to validate this requirement is completed. By validating the test for the specific requirement of this design requirement, one third of the functional requirement passes.

SR 4.2.1: By waiting for the boom assembly to send the deployment status confirmation back to the Arduino to confirm the state of deployment, rather than just visually inspecting it, it proved that the deployment verification mechanism worked and was capable of completing its task. By showing that the deployment verification mechanism was operational and could properly identify the state of deployment it was determined that this specification requirement was met and helped to prove that the design requirement that this is attached to passed.

DR 4.3: By performing the analysis of whether or not power was still being drawn by the deployment mechanism after the deployment verification signal came through proved that power was successfully shut off. By analyzing the whole system being tested and validating the state of power drawn by the boom assembly from its power source following full extension, it was determined that this design requirement was met and proved that one third of the functional requirement passed.

FR 5: By performing the tests required to validate the one subsequent design requirement of this functional requirement, the needed tests to validate this requirement were completed.

DR 5.1: By performing the full test strategy defined here twice it showed that the full boom assembly was capable of being re-stowed following a deployment, and that re-deployment could occur following a re-stow. By performing the re-stow and re-deploy capabilities it verified that this requirement is met and proved that the functional requirement that this was tied to passed.

Pass/Fail Criteria

Given below in Table 20 are the pass and fail criteria of each of the fourteen requirements analyzed within this particular test. Also, given in the last column of this table are the pass/fail results for each requirement determined through the analysis and tests that were completed.

Table 20 Pass/Fail Criteria for Full Deployment Test

ID	Pass Criteria	Fail Criteria	P/F Result
FR 1	The five design requirements and one specific requirement of this functional requirement pass.	One or more of the design requirements or the specific requirement of this functional requirement fail.	Undetermined
DR 1.1	An instrument of 500 g and 8x8x8 cm can be fastened to the attachment plate.	An instrument of 500 g and 8x8x8 cm can not be fastened to the attachment plate.	Pass
DR 1.2	The measured distance of the fully deployed boom is greater than or equal to 60 cm.	The measured distance of the fully deployed boom is less than 60 cm.	Pass
DR 1.3	The deployment mechanism uses less than or equal to 30 W of power during deployment.	The deployment mechanism uses greater than 30 W of power during deployment.	Pass
DR 1.4	The entire deployment process takes less than 2 minutes.	The entire deployment process takes greater than or equal to 2 minutes.	Undetermined
SR 1.4.1	The acceleration experienced by the attached instrument during deployment is less than or equal to 10 g's.	The acceleration experienced by the attached instrument during deployment is greater than 10 g's.	Pass
DR 1.5	Any oscillation that is developed within boom structure is damped out in under 2 minutes.	Any oscillation that is developed within boom structure is damped out in over 2 minutes.	Undetermined
FR 4	The three design requirements and one specific requirement of this functional requirement pass.	One or more of the design requirements or the specific requirement of this functional requirement fail.	Fail
DR 4.1	The deployment process can be started by a command sent by the spacecraft computer.	The deployment process can not be started by a command.	Pass
DR 4.2	A confirmation of deployment status can be sent by the full boom assembly to the spacecraft computer.	A confirmation of deployment status can not be sent by the full boom assembly to the spacecraft computer.	Pass
SR 4.2.1	The full boom assembly can successfully identify the deployment status of the boom arm.	The full boom assembly can not successfully identify the deployment status of the boom arm.	Fail
DR 4.3	Following the deployment process power to the deployment mechanism can successfully be turned off.	Following the deployment process power to the deployment mechanism can not successfully be turned off.	Pass
FR 5	The one design requirement tied to this functional requirement passes.	The design requirements tied to this functional requirement fails.	Pass
DR 5.1	Multiple re-stows and re-deploys occur during repeated tests.	The boom can not be re-stowed once it is deployed, or it can not be re-deployed once re-stowed.	Pass

Full Deployment Acceleration Analysis

A video analysis of the full deployment was used to determine maximum acceleration which was imparted on the payload during deployment. Using this method, a maximum of 1.6 g was determined to occur at around halfway through deployment. Using the process described in the ASEN 2003 Bouncing Ball lab document, the full speed video was able to be analyzed by tracking a single point on the payload through the video. In this case, this point was the corner of the payload closest to the camera. This point was chosen as a point easily visible throughout the test even though the structure turned off course due to uneven friction on the testing surface. Using the video tracking software allowed the team to get data on the position of the payload through time, using this data the acceleration was able to be found through using the MATLAB *diff()* function. The data shown below in Figure 49 displays the acceleration of the payload from this analysis. A teardrop accelerometer was also added to the payload as described in the test plan. The data collected is shown in Figure 50.

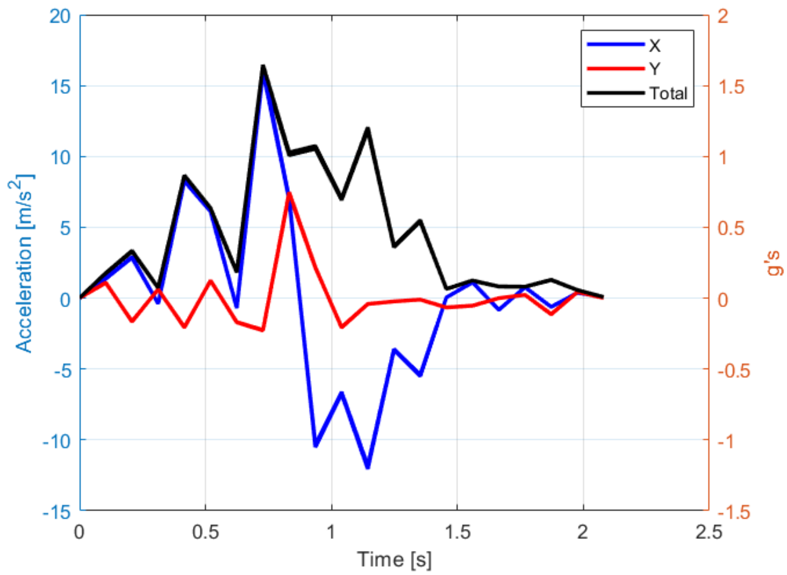


Fig. 49 Payload Acceleration Through Deployment

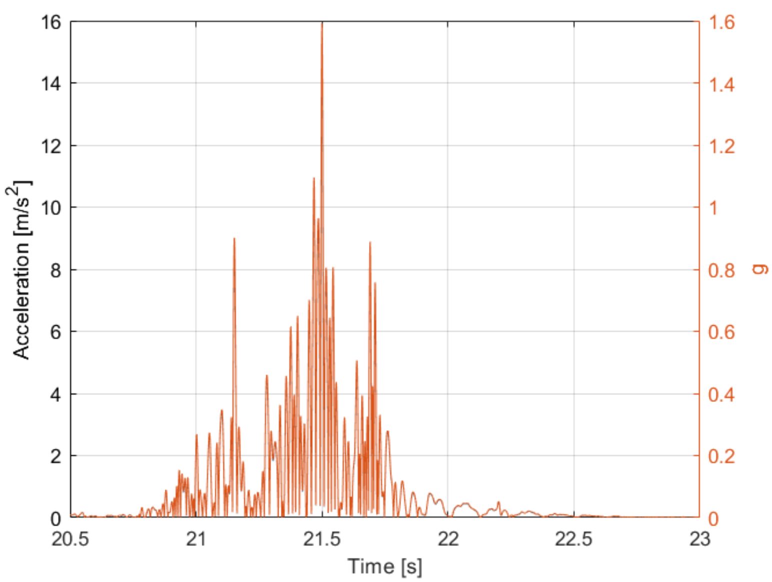


Fig. 50 Teardrop accelerometer results

Test Results

Given below in Table 21 are all the test results the team was able to gather from the two tests performed along with the associated requirement that the result is linked to. The last column of the table indicates if the gathered result results in a pass or fail of the associated requirement. Note that not every result that was initially planned to be gathered was able to be gathered due to the reduced schedule and the need to perform more full deployment tests.

Table 21 Test Results for Full Deployment Test

ID	Gathered Result	P/F Result
DR 1.1	An instrument of the proper weight and dimensions can be attached.	Pass
DR 1.2	Fully extended the boom is 68.5 cm long.	Pass
DR 1.3	The deployment power required is 2.3 W for 3 seconds.	Pass
SR 1.4.1	A maximum of 1.6 g's is inflected onto the instrument due to deployment.	Pass
DR 4.1	Deployment can be started from a command sent by a flight computer.	Pass
DR 4.2	Deployment status can be identified and sent back to the flight computer.	Pass
SR 4.2.1	Due to reliance of Arduino ADC deployment was not detected because sampling rate and spool deployment rate were misaligned.	Fail
DR 4.3	Following deployment power to the deployment mechanism was turned off.	Pass
DR 5.1	Multiple re-stows and re-deploys can occur.	Pass

5. Launch Environment Test

Requirements Under Test

- FR 7, DR 7.1

Required Resources

The list of required equipment needed to complete the tests that must be done in order to verify the design requirements of the seventh functional requirement are given below in Table 22

Table 22 Equipment to Test FR 2 and Subsequent DRs

Equipment Name	Level of Precision	Where to Obtain
UD Vibration Shaker Table Model S202	0.1 Hz	AERO Department

Test Strategy

This section outlines the general steps to follow for each sub-test to be performed. This will result in the most efficient and effective tests for validating the functional and design requirements.

The boom structure must be securely attached to the baseplate for this test, the bolts must be secured before the test can begin. The boom must be in the stowed configuration with the deployment mechanism secured prior to the beginning of this test. Once these areas have been checked the baseplate can be attached to the vibration shaker table's platform. With the boom properly attached the shaker table can be turned on and the control software booted up. During the test the controller should remain at the controls ready to stop the test in case of a failure of the deployment system and the testing team should remain at least 2 meters away from the boom. Begin a sweep of frequencies from 0 to 3000

Hz. The displacement of the platform should remain between 1 and 2 inches throughout the test. Once the sweep up to 3000 Hz has finished, sweep back to 0 Hz. After this has been completed turn off the shaker table and remove the baseplate from the shaker platform. Ensure that the boom has remained securely fastened to the baseplate during test, if necessary tighten connection and note that this system will need further iteration and testing. Perform a full deployment of the boom structure and check the boom for damage.

Specific Requirement Validation

FR 7: By performing the test required to validate the subsequent design requirements of this one functional requirement the needed tests to validate this requirement are completed.

> **DR 7.1:** By performing a 10 g vibration test on the undeployed boom structure it is possible to simulate the launch environment. Once the boom has been tested up to 10 g vibrations the state of the boom will prove whether the boom passes or fails this design requirement.

Pass/Fail Criteria

Given below in Table 23 are the pass and fail criteria of both requirements analyzed within this particular test. Also, given in the last column of this table are the pass/fail results for each requirement determined through the analysis and tests that were completed. Note that both are undetermined since this test was not actually completed and only analysis was performed.

Table 23 Pass/Fail Criteria for Launch Environment Test

ID	Pass Criteria	Fail Criteria	P/F Result
FR 7	The design requirement of this functional requirement passed.	The design requirement of this functional requirement failed.	Undetermined
DR 7.1	The boom assembly remains intact, undamaged, and deployable after enduring 10 g vibrations in a test environment	The boom assembly does not remain intact or becomes damaged or undeployable after enduring 10 g vibrations in a test environment	Undetermined

Restraining Cord Analysis

Analysis of the restraining cord was done to determine its strength and resilience through a flight scenario. This was using force analysis through a free body diagram, shown in Figure 52, and the plotting tool through MATLAB, shown in Figure 51. An assumption was made about the system in that forces only acted in the vertical-direction, or along the cord. This was made because cord was sheer resistant and the force needed to cut the cord was much greater than the restrainig force. The correlation between acceleration and force is shown through the dotted black line where the initial force of 11.12 N is from the Nitinol hinges. This gives the y-intercept. The maximum amount of restraining force was given at just under 89 N. Thus the absolute maximum g-force that the restraining cord can maintain was calculated to be 15.87 g. The blue line, labeled '10-12 g range' is aptly named as the customer dictated that this would be the range that the CubeSat would experience upon the launch environment. It is shown to be well within tolerances and at the maximum expected 12 g, with a comfortable factor of safety of 1.27.

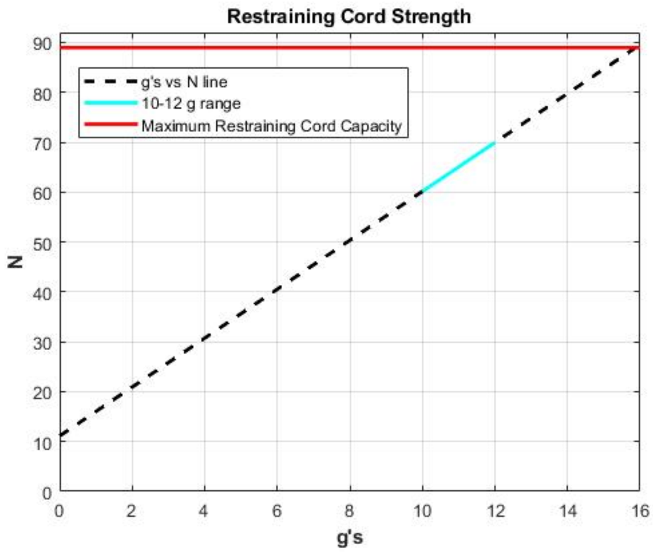


Fig. 51 Restraining Cord Strength

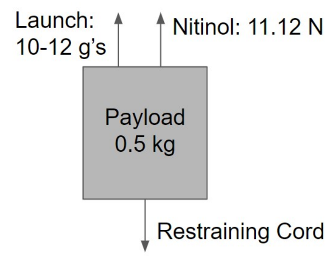


Fig. 52 Restraining Cord FBD

Test Results

Due to the coronavirus-induced restrictions, actual launch environment testing was not performed as planned. As such, no other results are available at this time.

6. LASP Thermal Chamber Test

Requirements Under Test

- FR 8, DR 8.1

Thermal Model

Per supplier provided information, the super-elastic properties of Nitinol are no longer present at temperatures less than -10 °C. To this end, it was important that on-orbit temperatures be calculated, if possible, so as to determine whether a heating unit would be required for the boom. If the temperature of the boom throughout multiple orbits never went above the -10 °C minimum, then a heating unit would have to be found and included in the design. However if the temperature rose above -10 °C during an orbit, a restriction on the time of deployment to temperatures above -10 °C could be included.

While there exists extensive records on the temperatures a CubeSat in LEO experiences, all of these satellites incorporated heating units of some kind, reducing the usefulness of the data. As such, it was determined that thermal modeling would be required before any sort of thermal chamber testing was performed. AGI STK was used to create a simple shell model of the CubeSat in orbit. From it, a wide range of temperatures were provided. However, the simple shell model created by AGI STK could not account for fact that essential part of the boom, the Nitinol hinges, were encased within the CubeSat structure, hidden from direct view of the heat sources on orbit. A concentric cylinder thermal model was devised in MATLAB. Complex view-factor equations were used to determine the amount of heat transfer between the inner cylinder and the outer cylinder. Using re-arranged equations found in NASA documentation, the amount of heat in and heat out on orbit was calculated. From this, the temperature of the boom structure was found for each part of the orbit. For both the AGI STK and the MATLAB models, a few assumptions were made: the orbital altitude was 500 km, the amount of heat generated by the CubeSat was negligible, and the orbit was in line with the solar ecliptic plane, meaning that the CubeSat would be full eclipsed from the sun by the Earth for just under half of its ~90 minute orbit. The results are shown in Figure 53.

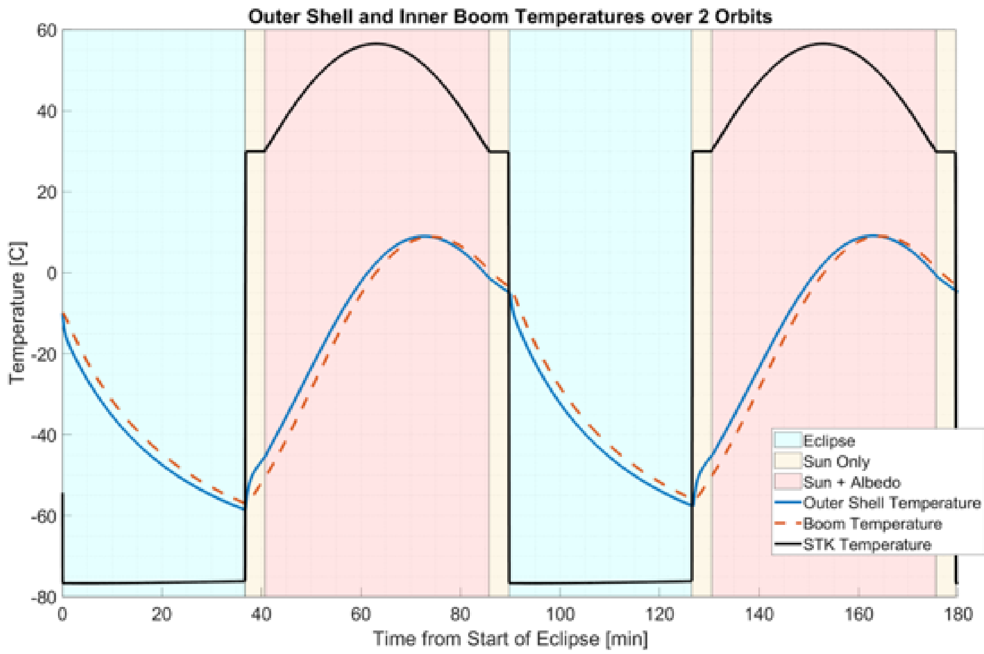


Fig. 53 AGI STK and MATLAB Thermal Models

Required Resources

The list of required equipment used to complete the tests that had to be done in order to verify the design requirement tied to the eighth functional requirement are given below in Table 24.

Table 24 Equipment to Test FR 8 and Subsequent DRs

Equipment Name	Level of Precision	Where to Obtain
Big White Thermal chamber	± 1 °C	LASP
Thermistor	± 1 °C	LASP
Thermocouples	± 0.1 °C	LASP

Test Strategy

The thermal tests for CUBE^3 utilized the Laboratory for Atmospheric and Space Physics (LASP) Big White thermal chamber in order to verify that the boom was capable of surviving the expected temperature minimums. It should be noted that these tests were performed on a modified 2-bay structure rather than the unmodified 8-bay structure due to size constraints of the thermal chamber. However, it was determined that a 2-bay system would provide all the necessary information about survivability.

The first step of the process involved having all parts of the 2-bay system being cleaned by LASP personnel prior to boom assembly in a clean room. The next step was to transport the assembled boom to the thermal chamber without allowing any contamination to occur. Once there, the boom was inserted into the chamber and the necessary thermocouples were installed. Next, the deployment mechanism for the test was installed. The deployment mechanism consisted of a fishing line fixed on one end to the attachment plate and on the other end to a 25 pound weight outside the chamber. The line was tightened until the 2-bay structure was fixed in the collapsed position. After securing the deployment mechanism in place the remaining steps, including software initialization, were carried out.

After all setup was completed the thermal chamber was closed up and the testing begun. The first cycle of this test consisted of a survival cycle where the chamber was cooled down to -60 °C and held there until the entire boom reached equilibrium, which was determined by the present thermocouples. During this cycle the boom was closely monitored and visually inspected for any occurring deformations. After it was determined that the whole boom had reached the

-60 °C threshold the next cycle was started. This cycle consisted of heating the chamber to -10 °C and holding until the whole boom reached -10 °C, which will again be determined by the thermocouples. Just like the first cycle the boom was closely observed for any deformations. Once it was determined that the boom was at the -10 °C threshold the deployment process was started. This process consisted of releasing the tension in the fishing line and waiting for the boom to deploy. During the deployment process any deformations observed in the structure were documented, as well as the general deployment performance. Following deployment, which was determined through visual inspection from the lack of boom extension, the last cycle was started. This last cycle consisted of cooling the chamber back down to -60 °C and holding it there until the boom reached -60 °C, again continuously monitoring and visually inspecting for any deformations. After completion, the chamber was reheated to the ambient temperature and the test was concluded. This testing procedure was completed again for deployment temperatures at -5 °C, 0 °C, 5 °C, and 10 °C.

Specific Requirement Validation

FR 8: By performing the tests required to validate the subsequent design requirement of this functional requirement the needed tests to validate this requirement were completed.

DR 8.1: By performing multiple tests that analyzed the thermal response of this two bay system, the team developed an understanding of ability to withstand the thermal fluctuations of the space environment.

Pass/Fail Criteria

Given below in Table 25 are the pass and fail criteria of both requirements analyzed within this particular test. Also, given in the last column of this table are the pass/fail results for each requirement determined through the analysis and tests that were completed.

Table 25 Pass/Fail Criteria for the Thermal Chamber Test

ID	Pass Criteria	Fail Criteria	P/F Result
FR 8	Boom assembly components do not break, decay, or reduce functionality as a result of time spent in the space environment.	The boom assembly components break, decay, or reduce functionality as a result of the time spent in the space environment.	Pass
DR 8.1	Boom assembly components do not break, decay, or reduce functionality as a result of thermal fluctuations.	Boom assembly components break, decay, or reduce functionality as a result of thermal fluctuations.	Pass

Test Results

From these tests the team hoped to not only gather the required analysis to verify the specific design requirement in question, but also gather the required information about deployment restraints based on temperature. Given below in Table 26 are the deployment results from each of the five thermal chamber tests performed. Note that full deployment was only reached at the 10 °C deployment temperature. This temperature was then used by the team as the deployment temperature restraint given to the customer. Another key result to come from these thermal chamber tests was that no component damage was ever observed within the two bay system due to the thermal fluctuations inflected. This is what gave the team the confidence to pass the requirements under test for this particular test.

Table 26 Thermal Chamber Deployment Test Results

Temperature	No Deployment	Partial Deployment	Full Deployment
-10 °C	X		
-5 °C	X		
0 °C	X		
5 °C		X	
10 °C			X

6. Risk Assessment and Mitigation

Ben Pearson

As in any project, the team expected to encounter a certain degree of uncertainty and risk in its many operations. These challenges encompassed every level of the project development process, so they were planned for and alleviated in order to avert both critical failures and last minute scrambles. It should be emphasized, especially, that although this project is one which is very mechanical and very development oriented, the array of risks to it extended far beyond the physical action of sticking small bits of material together. Throughout the development process the team expected to encounter fundamental concerns about material supply line, capabilities of personnel, testing ability, and the prospect of simply running out of money. Additionally, the prototypes and final products faced a similar array of physical concerns. For example, the space environment may produce unexpected degrees of damaging radiation and temperature flux, or the deployment conditions may be more challenging to handle than the customer believes. mitigation of these concerns, and the myriad of others, is clearly crucial to both the maturation of this design, and its success once deployed in a real-world application.

Figure 57 below is a comprehensive matrix of the team's major concerns before mitigation attempts had been made. Many were in the region of 'middling concern', but there remained a single 'major concern' - the failure of Nitinol hinges. Not listed in this matrix is the prospect of team member absence, loss, or unforeseen personnel challenges. These issues remained realistic prospects, but were chiefly mitigated by strong interpersonal communication, and the presence of multiple levels of leadership within key project areas.

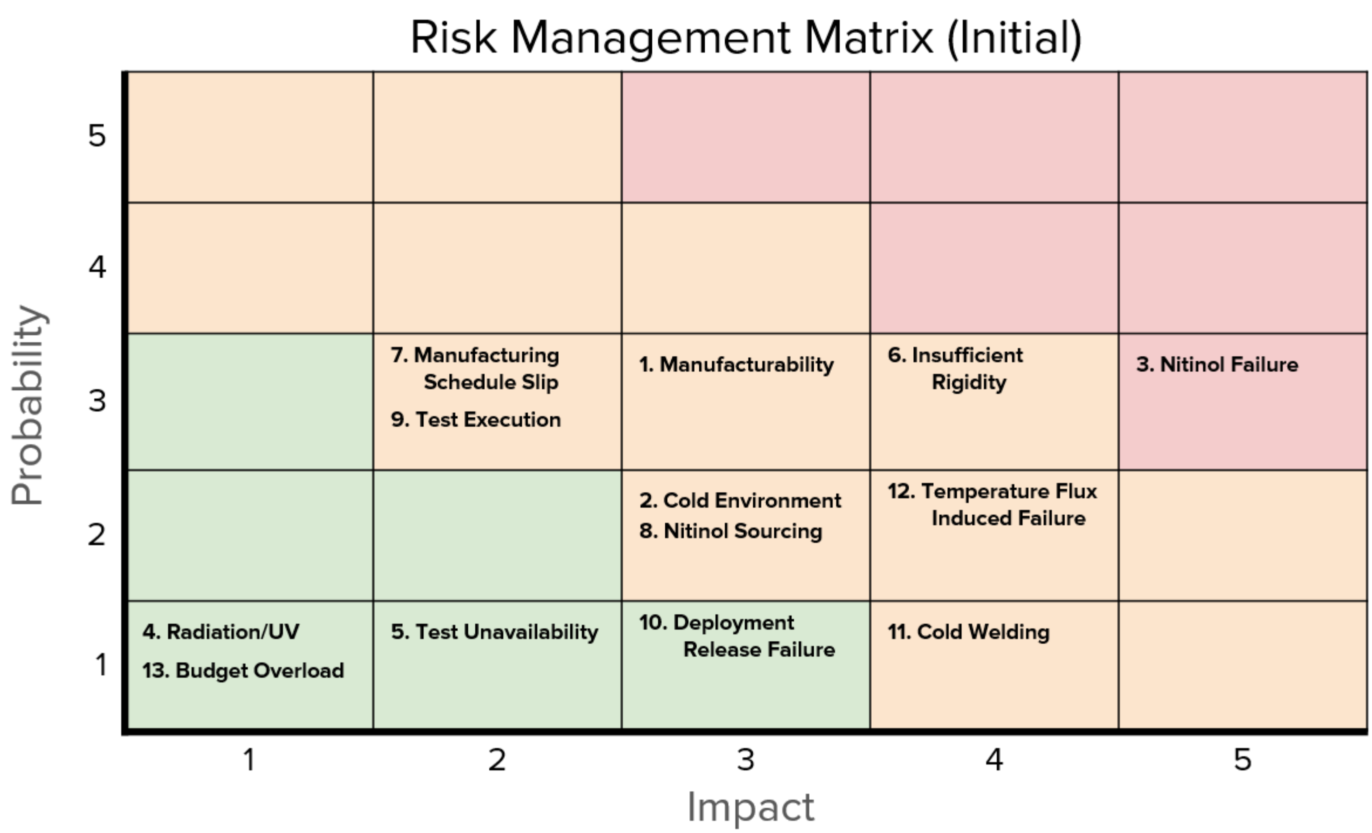


Fig. 54 Major Team Risks - Unmitigated

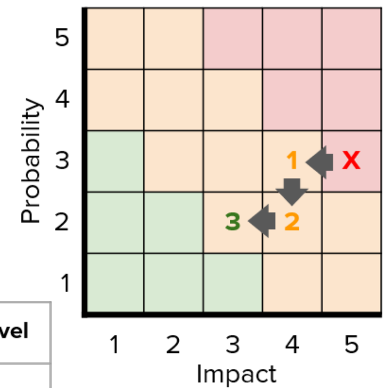
As indicated, the team's greatest concern before mitigating efforts was the unknown properties and capabilities of the Nitinol hinges used to deploy the boom. In short, because it is such a strange material, it was unclear what effects usage in the proposed manner would have upon it. Fundamental material testing was the most valuable way to alleviate concerns, but design contingencies like the addition of torsion springs were also ready to be implemented in case it was proven to be non-viable as a stand-alone option. Figure 55 below lays out both the steps taken to reduce this risk, and the schedule of its implementation. The steps taken, reduced this risk to a low-medium level of concern - which is a substantial improvement.

Risk Mitigation - Nitinol Failure

Risk Overview:
Nitinol is an unusual material with equally unusual properties. It may warp or kink in the space environment, failing to deploy as expected.

Risk Level:
High

Risk Type:
- [x] Technical
- [ ] Schedule
- [ ] Cost



#	Mitigating Action	Mitigation Effects	Status	Adjusted Level
1	Re-sizing and alteration of strips	Changes lower the minimum allowable temperature, increase rigidity, lower bending radius, and add to expected deployment force	Completed	Medium
2	Rigorous testing	Experimentation at varied temperature levels and loading situations supports expectations	Ongoing	Medium
3	Addition of torsion springs	Helps jumpstart deployment and attain final few degrees of rotation	Ongoing	Medium

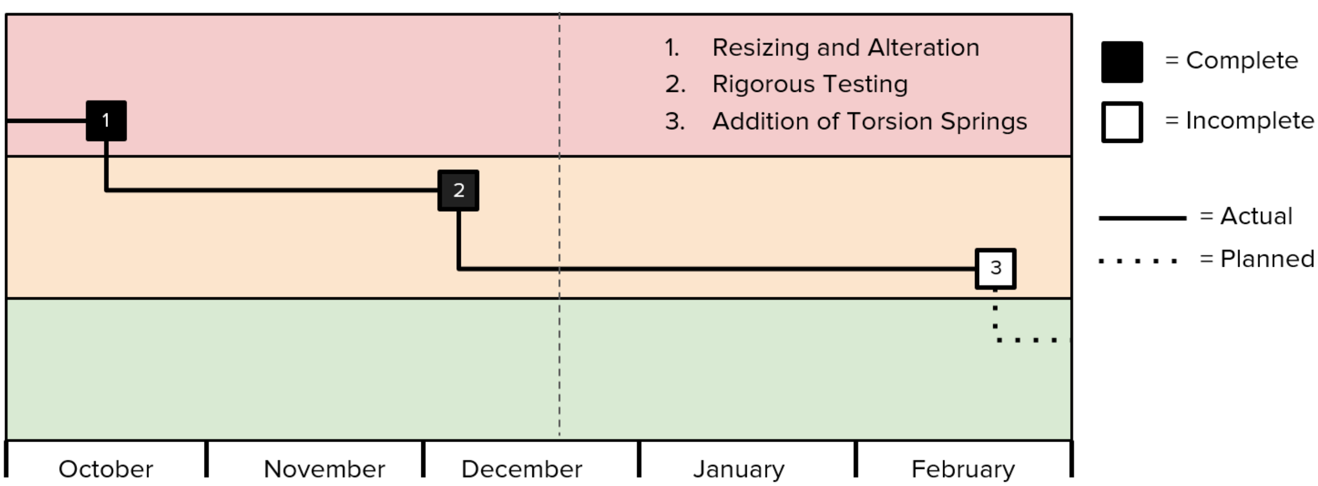


Fig. 55 Nitinol Failure Risk Assessment and Mitigation Schedule.
Note: Addition of Torsion Springs Deemed Unnecessary

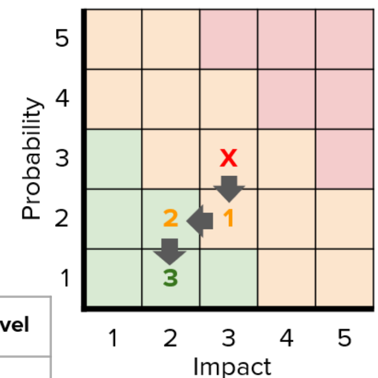
Early in the design process, the team recognized that the high number of very small parts could pose a significant risk to its ability to actually construct the boom. The high complexity of this concern touched on, and compounded, a wide array of preexisting concerns also, like budgetary and scheduling constraints. The immediate response, once the severity of these possibilities was made clear, was to redesign the parts to minimize their points of failure, and maximize the team's chance of physically being able to create the components with available (rather than specialized) tooling. A major additional step taken, external to changing the parts themselves, was development of a series of jigs and softjaws. These allowed teammates with less manufacturing experience to participate more fully in the process and improved both the speed and the accuracy of part creation. The figure immediately below, again, outlines this mitigation process, which reduced this risk from a risk score of 9 (high-medium) to a 2 (low).

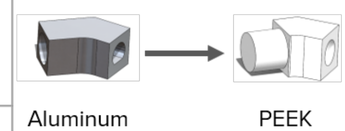
Risk Mitigation - Manufacturability

Risk Overview:
Some components are small and hard to manufacture. It is possible that parts may be prohibitively challenging to produce, at necessary tolerances, with available resources.

Risk Level:
Medium

Risk Type:
- [x] Technical
- [ ] Schedule
- [ ] Cost





#	Mitigating Action	Mitigation Effects	Status	Adjusted Level
1	Part redesign	Removal of problem areas minimizes chance of mechanical failure, and reduces the complexity of individual steps	Completed	Medium
2	Change of part material (PEEK)	PEEK plastic is easy to work with, and less likely to damage tools	Completed	Low
3	Extra focus on jig design	Increases preparedness, part uniformity, and manufacturing speed	Completed	Low

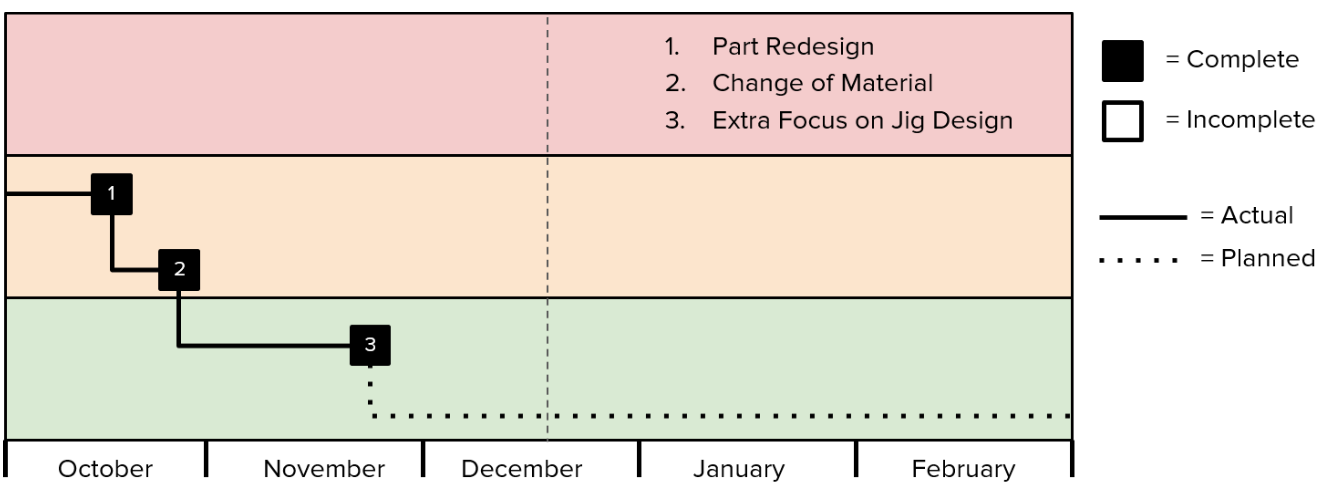


Fig. 56   Manufacturability Risk Assessment and Mitigation Schedule

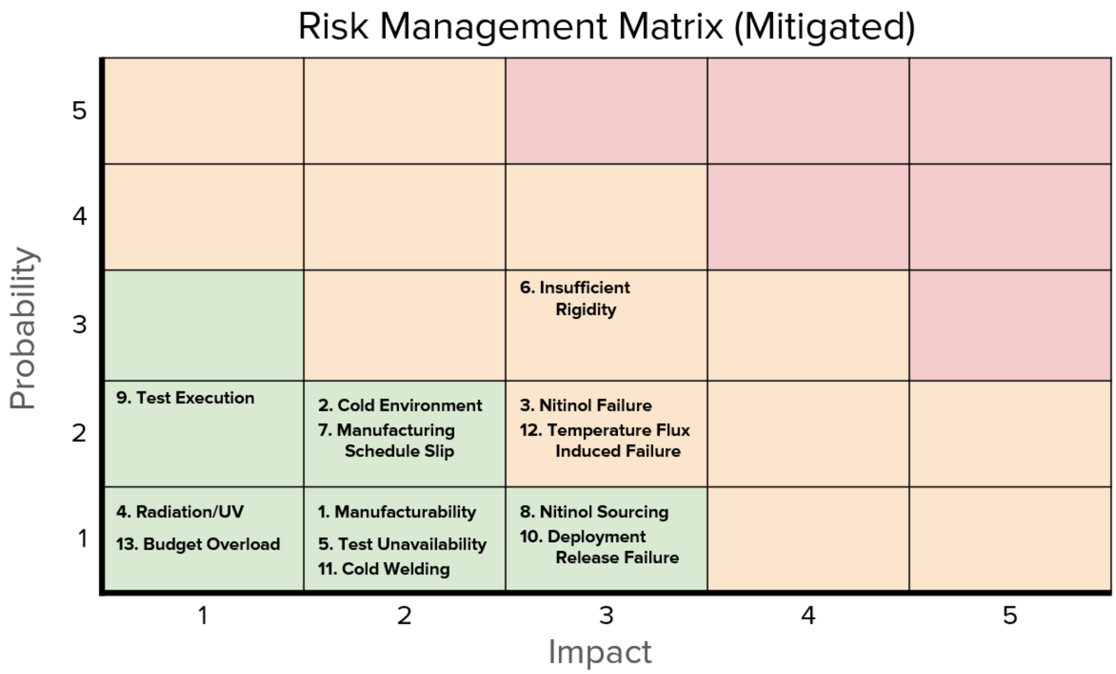


Fig. 57 Major Team Risks - Mitigated

Risk mitigation efforts were conducted for all listed concerns and prospective situations, and in doing so the risk levels for every single one dropped, such that the majority lay in the low region. On all fronts, efforts continued such that the team was prepared should any come to fruition, and extensive testing was conducted to ensure that the team was aware of any concern-validating (or alleviating) results. The one remaining standout issue (with a medium-high risk score of 9) was that of insufficient rigidity. The team reached its limit in how well the system could be modelled, and the best way forward was to test a prototype as early as possible and assess its response to the experimentation.

The team recognized the merits of remaining vigilant in its preparedness for further risks to arise and appreciated that certain intangible risks remain inherent for every project. The big snowstorm over Thanksgiving break, for example, set the team back at a crucial time, and only quick thinking and planned contingencies were responsible for the partial salvage. The full table below lists the broad-stroke contingencies and implementations to best mitigate all identified risks at time of testing.

Table 27 Complete Major Risk Mitigation Contingencies

#	Concern	Explanation	Risk Mitigation Strategy
1	Manufacturability	Some components were small and hard to manufacture. It was possible that parts may be prohibitively challenging to produce, at necessary tolerances, with available resources.	The components of concern were generally the hinge connectors (not the tubing), which were redesignable to reduce the part manufacturing difficulty. Also, simplifying jigs smoothed the physical process. Had these steps not improved things, manufacturing may be outsourceable to a better equipped shop, and 3D printing was another viable fallback.
2	Cold Environment	Thermal modeling struggled past early stages. The team could estimate the temperature of the CubeSat surface at steady state, but the internals were a little different. A too-cold interior on an ongoing basis would have prevented ANY hinge mechanism from functioning.	Simple models indicated a high likelihood that there would at least be windows of deployable opportunity. However, a heater would have been a relatively simple addition to the structure if necessary. The team discussed the definition of ‘deployment time’ further with the customer, and he agreed that the spacecraft could be tasked with oversight duties here.

3	Nitinol Failure	Nitinol is a strange alloy, with very limited literature on it. The team needed an opportunity to experiment with it. It may be have been inadequately 'springy' (unlikely), or it may have warped/kinked in the space environment (more likely).	Contingencies depended on severity of failure. If it turned out that Nitinol was rendered unusable should it reach a certain low temperature (especially with such a small turning radius), then it would have been replaced as a concept with a steel torsion spring hinge design. It could also have been simply supported by a torsion spring, or more rigid elements.
4	Radiation/UV	The UV and radiation problems of space are well documented. Either could cause part failure in the long term. This would be most likely to impact thinner, and more variable components like the Nitinol hinges.	A big 'upside' of this issue is that it would strike long after actual deployment, and would impact one piece at a time. An advantage of having four struts is that the other three will continue to function even if one fails. Should it have proven problematic with further analysis, there are volume and mass allowances available to add foil shielding. Tests were performed with separated struts to assess impact.
5	Test Unavailability	The team was in contact with LASP for TVAC and had strong connections within the AERO building for vibe table testing, but these could have become less viable in the event of a crisis or shift in regulations.	There existed a few thermal chambers around campus, and Bioserve had a potentially accessible vacuum chamber. Together, these testing environments would be of comparable quality.
6	Insufficient Rigidity	Throughout the project, models were optimistic, but they were all idealized to an extent. Actual boom rigidity was known to be lower than modeled, and it was possible that the first mode will be below 2.5 Hz.	Reinforcement and analysis of Nitinol hinges was expected to be important if prototyped bays seemed problematic. There are a few cables and wires running between the top and bottom of the boom which could have been altered to improve rigidity if necessary. The hinge pieces themselves may also have been reinforced if complexity proved to be a non-limiting factor.
7	Manufacturing Schedule Slip	The team expected to enjoy a long and iterative manufacturing process. This was compounded by part complexity and COTs shipping delays. If the team had started work in the spring semester, it would have had to have been super-humanly efficient with its time and resources.	The best way to mitigate time constraints for manufacturing was to employ the abilities and resources of all team members. A highly organized and synchronized effort was be the team's best weapon against a slipping schedule. The team began the manufacturing and ordering process long before the spring semester started.
8	Nitinol Sourcing	The Nitinol strips which the team used were sourced by one or two specific companies which had been challenging to contact, and are tough to find elsewhere. Even Nitinol wires of verifiable quality were hard to come by.	Ordering these parts early in the process was beneficial to guaranteeing component access, and allowing for alternative avenues of approach if access turns out to be impossible. The team also looked into communications with material-specializing professors for custom and reputable vendors. The team acquired the Nitinol in the middle of Fall semester, however, which made this risk a non-issue.

9	Test Execution	Setup for the zero-g vibe table test was quite a lengthy process, potentially requiring the construction of a secondary support structure. The team was confident in its ability to execute, but there remained room for issues to arise in this more challenging test operation.	The team addressed this concern by compiling a complete plan early on, and began construction of necessary parts, and preliminary testing, before the spring semester.
10	Deployment Release Failure	The deployment release mechanism, the burn rope, had substantial heritage and is a simple concept. However, the team did not have experience with the materials involved or the exact methodology, which added risk.	The team expended significant energy on testing this mechanism, and investigating ideal materials. The team also verified that the materials involved do not experience major changes or alterations in a space environment. Had it been proven to be non-viable, then motorized pin pulls or other break-methods were available as contingencies. The team was likely to implement a redundant burn system with more time available.
11	Cold Welding	Cold welding is a notorious problem for metal components in space. Had the team not exercised adequate caution, pieces could become fused and whole bays may fail to deploy.	Efforts were be made to reduce the number of metal components contacting each other, but some were unavoidable. The team looked into the applicability of oxide coatings, annodizations, and more physical barriers for the necessary parts.
12	Temperature Flux Induced Failure	The best and worst case temperature scenarios on orbit were over 100 K apart, which lent a significant possibility to expansion and contraction of very finely toleranced interfaces. Had these factors been too substantial, components could have crack, or fixed.	Significant attention was been paid in choosing materials for which the coefficient of thermal expansion is more limited. PEEK was not expected to fluctuate much, and carbon fiber even less so. However, the team also conducted preliminary thermal tests on components before committing to building the full set, and designed the tolerances to account for both analytical and tested requirements.
13	Budget Overload	The team remained well within its expected budgetary constraints for its duration, however, if manufacturing had taken a sudden turn for the worse and had need to outsource it, or if Nitinol costs had been much higher than expected, then the costs of certain processes could have inflated exponentially.	Obviously the first course of action was to avoid this situation. Careful planning mitigated surprises, and alternative component design or supplier choices limited budgetary explosions. Had budgetary excesses become an unavoidable certainty, the team had connections to a number of aerospace companies which might have been willing to contribute, and the school had funding options for research purposes also.

Though some concerns, like cold welding and UV/radiation protection, are design challenges which will not be fully realized unless the boom finds its way to space, the mitigating efforts have driven their chances acceptably low. As such, the team considers that most of these risk limiting effects to have been successful, and hindrances to schedule, quality, and cost in this project process were minimal.

Some planned strategies were unnecessary, which is normal to find at the end of a project period. The issue of Nitinol sourcing, for example, was completely resolved early on in the schedule, and a failure of the material itself never occurred, which meant full mitigation efforts, though planned, did not have to be enacted. Similarly, temperature flux induced failure never evolved into major issues that the team had to overcome, and the risk mitigation plans for those particular areas never had to be initiated. It should be noted though that, in all of these cases, the insistence on rapid preparedness, early construction, and preliminary testing of the boom significantly reduced concerns the team had for these issues early on. This was complemented by extra attention paid in the design process to these potential concerns.

Because the risks were identified early, it was possible to create baseline designs with them in mind and get out way ahead of them.

The manufacturability risk item also benefited from these practices. After having initially designed boom components prior to a complete risk assessment, parts were found to be over-complicated, challenging to create, and of considerable risk to the schedule. As previously stated, parts were overhauled with these in mind, and subjected to both material and geometric alterations. Additionally, risk management processes insisted on a complete manufacturing plan early-on, which helped to identify areas of remaining concern.

Despite these efforts, there did exist a minor oversight in risk mitigation whilst manufacturing the deployment system. So much attention had been paid to the primary boom structure, by a number of subteams, that attention was fully diverted from the complexities of the release spool and its accompanying system. Though these parts were small, and seemed simple at face value, they took a lot longer to perfect and actually produce than had been expected - and the result was a manufacturing schedule slip of a couple weeks for those parts in particular. Thankfully, mitigation efforts for the manufacturing process as a whole had provided the team with a manufacturing margin of reasonable size, and this slip did not cataclysmically derail the critical path.

Naturally though, a risk mitigation conversation could not be completed without addressing the oversight of a global pandemic, or its impacts to project schedule and completion. Because of the COVID-19 pandemic, the team was unable to properly execute the remainder of its tests (cited risk #9). Again though, because of risk-mitigation induced pace, this was a situation for which this particular team was reasonably well positioned - having completed a significant number of its tests (at least at the baseline level). As such, there might be a consideration that the 'natural disaster' risk had been mitigated somewhat by default (lessons were learned after delays caused by the Thanksgiving-week blizzard), but to suggest that anyone was really prepared for this specific eventuality would be disingenuous.

7. Project Planning

A. Organizational Chart

Rowan Gonder

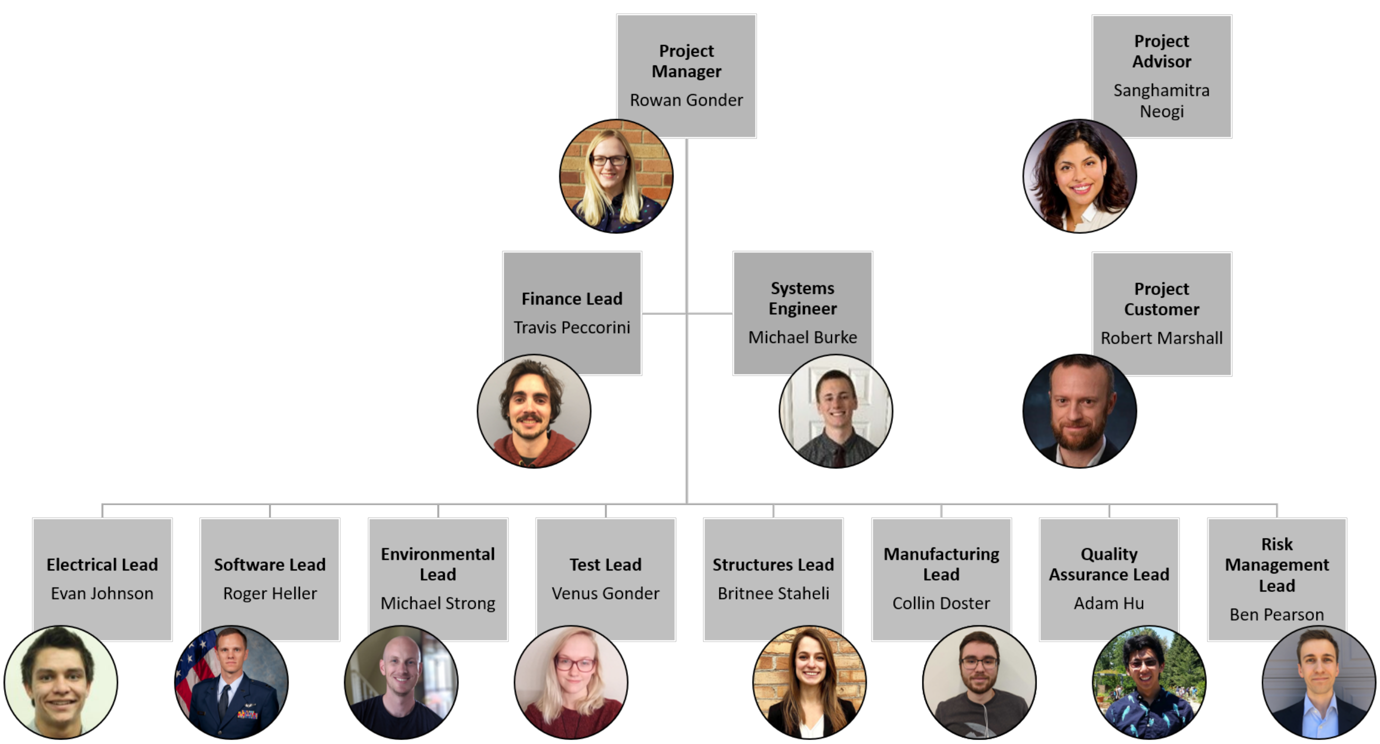


Fig. 58 Team Organizational Chart

In Figure 58 above, the team structure is outlined. The project advisor was professor Sanghamitra Neogi as she had a lot of insight into the analysis needing to be done for this project. The project customer was professor Robert Marshall. The team members took rolls of project manager, finance lead, systems engineer, as well as sub team leads. There were a few unusual positions that were held by team members, and those with their purpose follow. First was the quality assurance lead, this was a necessary position due to the high degree of manufacturing and tolerancing required for the project. Next is an environmental lead, this position was decided upon after it was determined that the system's ability to survive the LEO environment was extremely important to project success. Finally, there was a risk management lead who was in charge of tracking risks through all areas of the project.

B. Work Breakdown Structure

Travis Peccorini

The following figure, Figure 59 shows the Work Breakdown Structure to depict the process through which our team navigated the different areas of the project. This version is slightly different than the one included in the FFR as it focuses on the deliverables associated with the Spring semester. One may notice that it is broken down in a very similar way to that of the Gantt Chart. This is to show the work products that resulted from the completion of the tasks outlined in each section of the Gantt Chart. The team was able to make substantial progress on a number of tasks and felt confident in our ability to finish if the semester had not been prematurely ended. The next steps would have been to continue and improve the testing procedures to obtain results with a higher level of confidence.

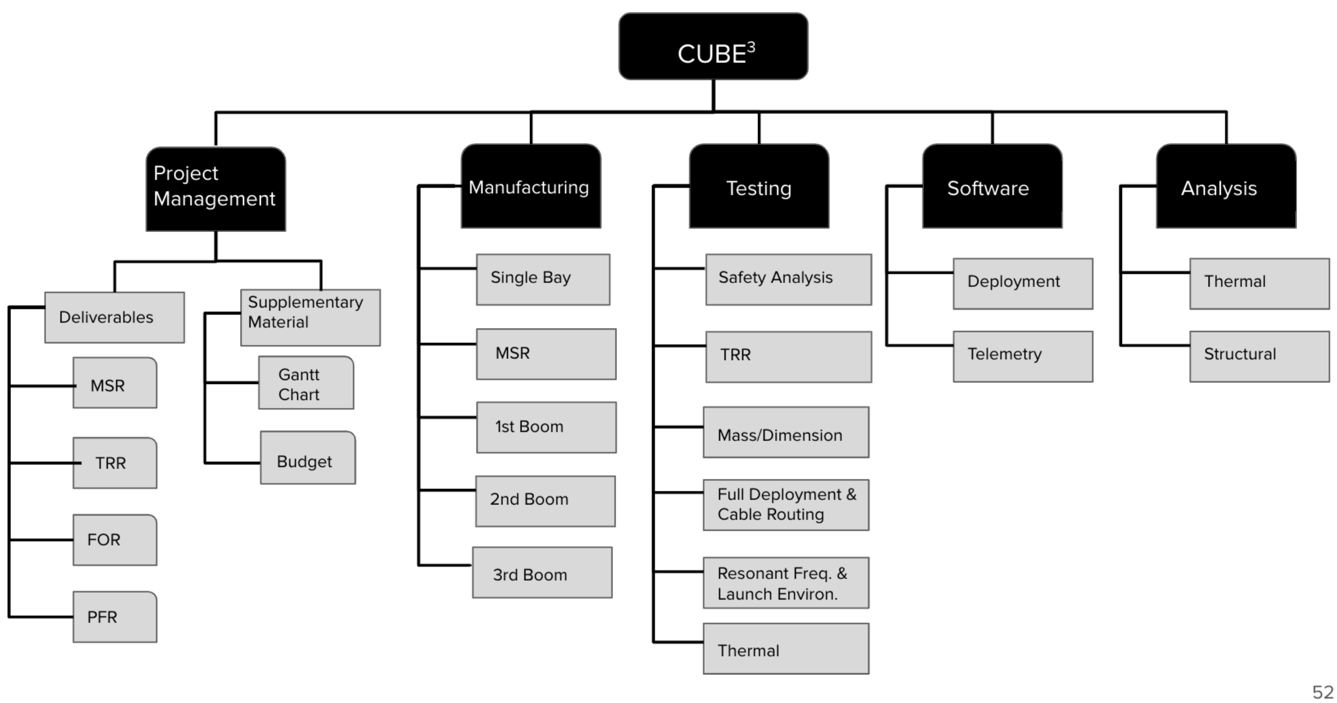


Fig. 59 Work Breakdown Structure

C. Work Plan

Travis Peccorini, Rowan Gonder

The following figures, Figure 60 and Figure 61 show the Gantt charts that were used by the team for the Fall and Spring semesters respectively. Since the team was able to remain ahead of schedule for the majority of the semester, a significant amount of testing was completed before the school was forced to close, and this is represented in the status of the Gantt charts.

Fig. 60 Fall Semester Gantt Chart

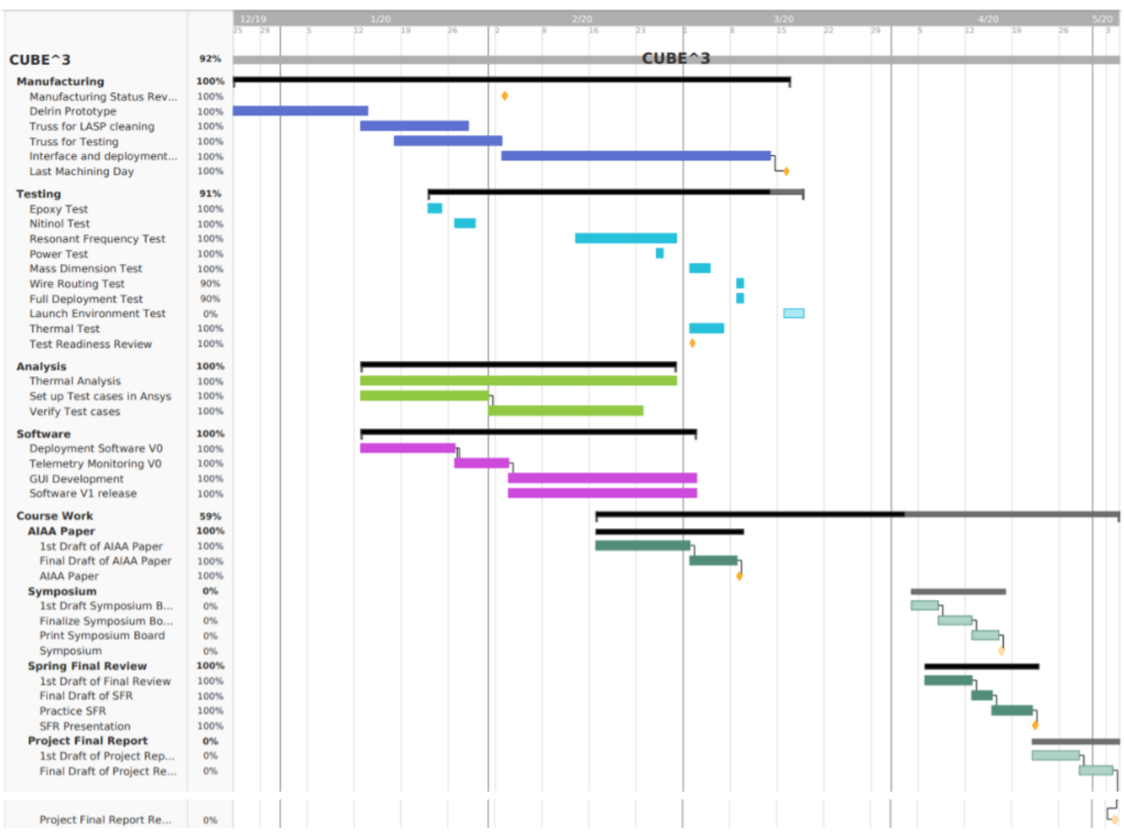


Fig. 61 Spring Semester Gantt Chart

D. Team Work Trends

Travis Peccorini

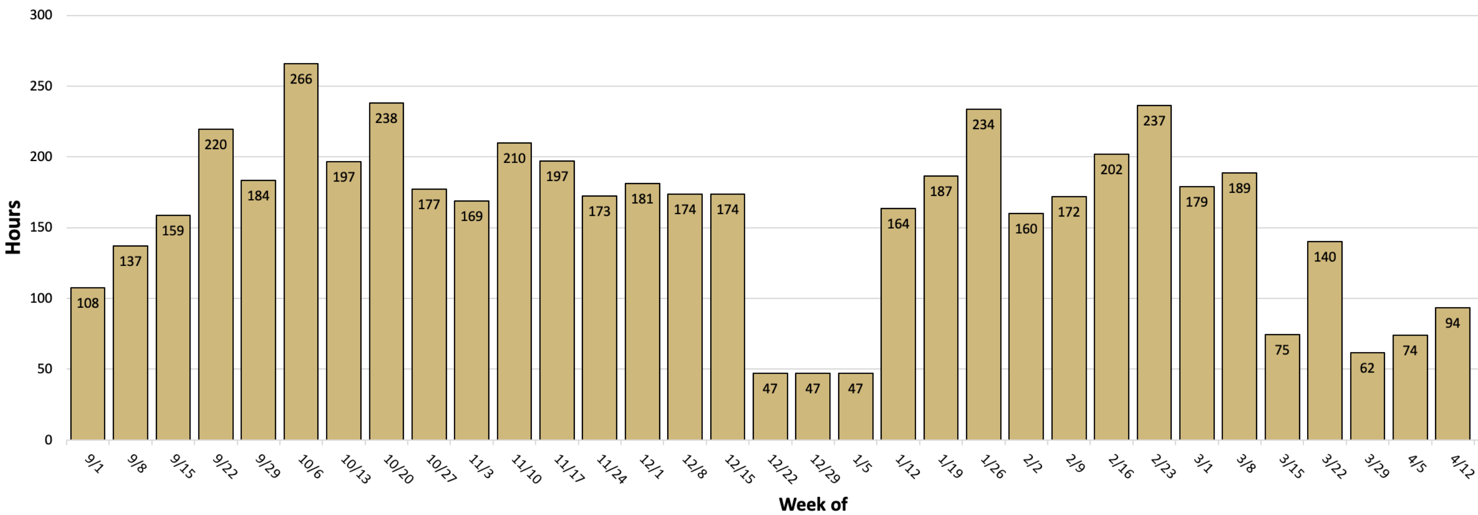


Fig. 62 Team Work Hours Per Week

Figure 62 represents the hours put in by the team on a weekly basis. This is to not only show the the amount of time and dedication our team has put in during the semester, but it also allows us to calculate the predicated industry cost for our project. We saw the greatest increase in workload around presentations, document due dates, and manufacturing processes. In order to address this, more time was allotted on the front end of these more time consuming tasks of design presentations and documents. For the majority of they year the team consistently remained at or above 170 hours per week. The 3 week span of only 47 hours per week represents winter break as a few members of the team pushed to get stay on track with manufacturing. After the pandemic forced the school to close, there was somewhat of a drop off in hours devoted to this project as the team was limited to strictly analysis work. With respect to industry cost, the average aerospace salary of $65,000 for 2080 hours of work was used to find that this project would cost approximately $164,594. If a 200% overhead is assumed, the expected industry cost of this project (salary + materials) is estimated to be $332,775.

E. Cost Plan

Travis Peccorini

Figure 63 represents what portion of the $5,000 budget was used during the project with respect to what was estimated at the time of CDR. Using the principles outlined in the NASA Standard Margin Analysis, a 20% contingency (standard for post-CDR) was applied to each item at the time of CDR. These contingencies resulted in an estimate of $3,887.83. Our finalized budget at the end of the year showed that we only spent $3,586.84, which put us $300.54 under our maximum expected value. These contingencies were able to allow the group to properly account for unexpected purchases without knowing where or when they would occur. The table shown in Figure 64 represents a breakdown of the different type of expenses accounted for and their associated contingencies compared to the final value. While the contingencies were able to provide a relatively accurate estimate for most purchases, the largest discrepancies occurred with the expenses associated with testing at LASP and the tools needed in the manufacturing process. After CDR, the team had decided to remove the TVAC from testing plans so the expenses needed for testing were cut by nearly 75%. On the other hand, the team significantly underestimated the additional tools needed to meet the manufacturing needs of this project. While the machine shop was extremely helpful throughout the whole process, the precision levels of this project required more unique tools than what was available for use. Finally, Figure 65 shows a visual representation of the percentage of project funds spend in each area. The largest portions were devoted to PEEK and carbon fiber which made up most of the structure of the three booms constructed. The remaining purchases ranged from approximately 5-10% of the total project budget.

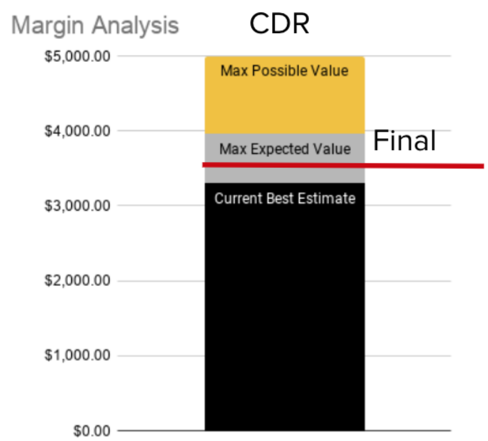


Fig. 63 Final Budget Compared to CDR Estimate

Line Item	CDR	+ Contingency	Final	Difference
Tooling	$43.66	$52.39	$272.04	$219.65
Hardware	$410.55	$492.66	$427.93	$64.73
Epoxy	$90.58	$108.70	$90.58	$18.12
PEEK	$540.95	$649.14	$770.66	$121.52
Carbon Fiber	$399.17	$479.00	$627.94	$148.94
Nitinol	$295.80	$354.96	$295.80	$59.16
Wiring	$300.00	$360.00	$338.34	$21.66
LASP	$750.00	$900.00	$175.00	$725.00
Test Equipment	$100.00	$120.00	$140.09	$20.09
Shipping	$300.00	$360.00	$273.46	$86.54
Machine Shop/Classes	$350.00	$75.00	$350.00	$75.00
Total	**$3,297.62**	**$3,887.38**	**$3,586.84**	**$300.54**

Fig. 64 Contingency Breakdown Comparison

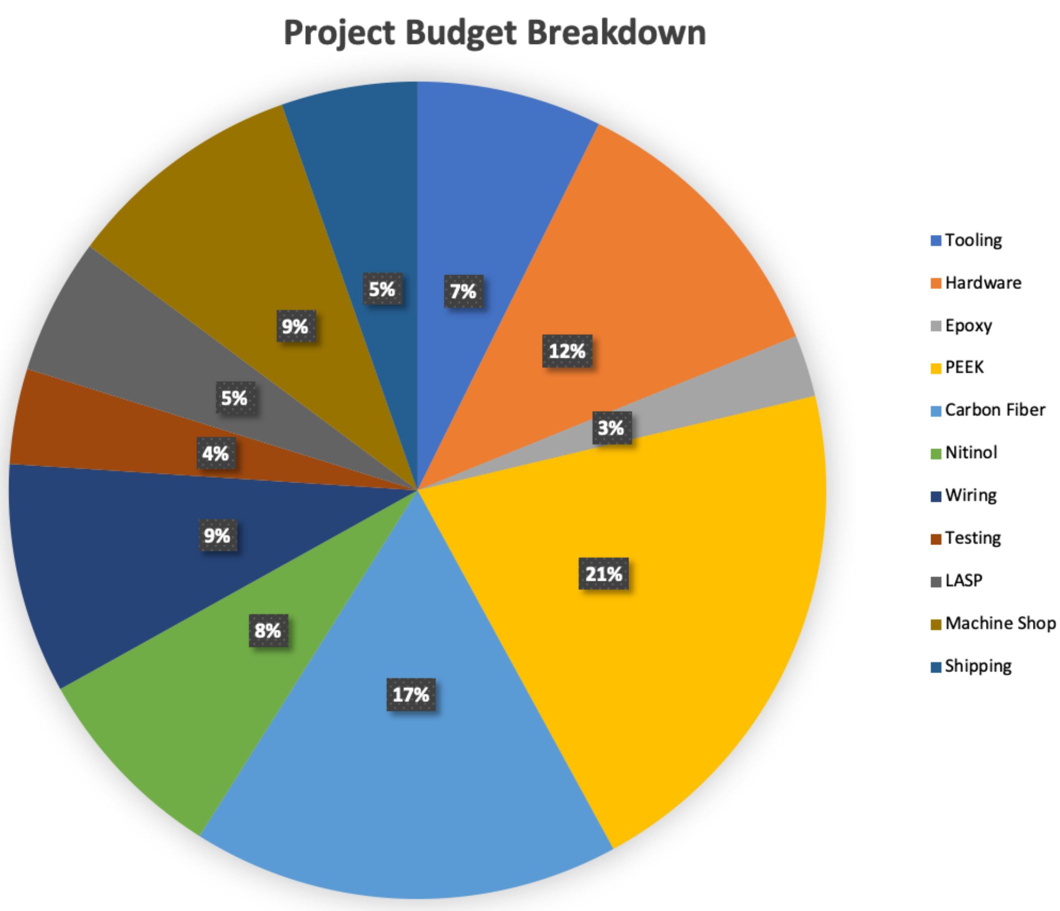


Fig. 65 Total Project Expenses

F. Test Plans

Rowan Gonder, Michael Burke, Venus Gonder

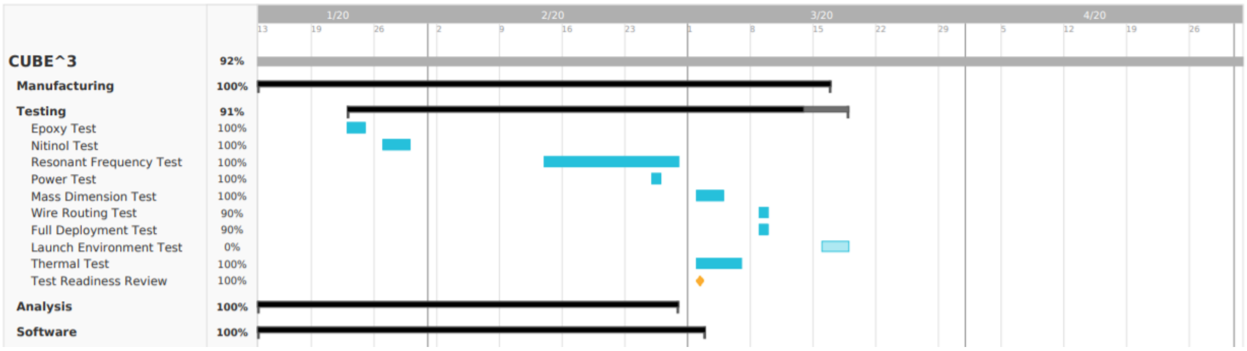


Fig. 66 Testing Schedule

Figure 66 above shows the testing schedule which the team followed. As can be seen, all tests were completed to some degree except for the launch environment test which was scheduled for the week after the stop work order was given. Below is a description of each test and what equipment and facilities were used.

1. Cable Routing Test

The facility used for this test was the ASEN electronics shop, access was gained through completion of the basic soldering workshop. To conduct this test, the following equipment was needed: Keysight 34461A Digital Multimeter, Sorensen XPH 35-4D Power Supply set as a Current Supply, Keysight 33220A Function/Arbitrary Waveform Generator, and an Oscilloscope. All equipment was found to be available in the lab. The last portion of the cable routing test was unable to be completed due to the team's reduced schedule.

2. Launch Environment Test

If this test were able to be completed it would have used the Aero department's Unholtz Dickie model S202 vibration shaker table located in the vibe room. Access to this machine was granted through KatieRae Willamson with a thorough scheduling plan.

3. Resonant Frequency

This test was conducted in the AERO Electronics Lab, access to this room was gained through completion of the basic soldering workshop. The equipment used included a mallet borrowed from the machine shop, two teardrop accelerometers checked out from the electronics shop and KatieRae Willamson, and a horizontal shaker table used with permission from Bobby Hodgkinson and KatieRae Willamson.

4. Full Deployment Test

This test was conducted in the AERO Electronics Lab, access was gained through completion of the basic soldering workshop. The equipment used was as follows: Sorensen XPH 35-4D Power Supply set as a Current Supply available in the electronics lab, Arduino Due microcontroller checked out from the electronics lab, a Westward tape measure from the project locker, a teardrop accelerometer checked out from the electronics lab and KatieRae Williamson, timers on personal phones, and a lego roller from a team member's personal collection.

5. Mass and Dimension Test

This test was conducted in the AERO Electronics Lab, access was gained through completion of the basic soldering workshop. The equipment used included Shars Aventor Calipers purchased with team funds and an Acculab SV-50 scale available in the electronics lab.

6. LASP Thermal Chamber Test

This test was conducted in the LASP thermal chamber room, the use of which was procured through contact with LASP staff as well as a LASP specific ESD training completed by some team members. The following equipment was available from LASP and used for the test: the Big White Thermal Chamber and thermocouples to measure the actual temperature within the chamber.

8. Lessons Learned

Ben Pearson, Rowan Gonder

The Lessons Learned for this project were, of course, innumerable. The team holds a view that this projects class alone was more educational than most others put together. Team members developed new analytical insights, experience compiling test plans, and practice working in a diverse group - to name just a few, broad didactic areas. Fundamentally though, the most crucial aspects of Lessors Learned tend to fit within the categories of Manufacturing, Test, and Project Process.

A. Test

The absolute, number one testing lesson that can be taken away from this project is that there should be a high emphasis on testing early and often. This is, of course, a mantra that engineers will hear often - but one that academic careers had not fully instilled until now.

Learning this lesson enabled the team to experiment with designs, materials, and testing processes early - which in turn directed future test plans and shaped expectations. By testing Nitinol in prototypes, the team developed baseline assumptions for requisite deployment and restraining forces. By exposing subteam members to vibe tables and necessary interfaces, the resonant frequency testing processes were much smoothed. Once manufacturing had completed some preliminary bays, the team was able to perform preliminary thermal tests and materials analyses laying groundwork and setting baseline expectations for higher fidelity assessments.

One area in which the team could perhaps have applied this lesson with a little more rigor was in supplementing system resonance analysis with progressive structural tests. Testing plans were completely thrown asunder by the coronavirus, but the team could have benefited significantly by testing sub-structures in alignment with smaller mathematical analysis and SolidWorks to validate results. This progressive methodology would have drastically improved the reliability of these comparisons, and a ramp-up test protocol would have meaningfully increased the team's credibility in its assertions.

The other big lesson learned for testing was that it is crucial to focus as much effort on developing a test system as it is developing the system being tested. It does not make sense to test a piece of equipment that costs $1,000 and hundreds on man hours with a rig which required 15 minutes and $3 to put together. This was a lesson which the team really should have learned earlier working with the vibe tables, but which was really pronounced when the team tried to use a Lego roller as a crucial part of the full deployment test. Granted, the team had not intended that this be the actual solution, but this specific example really drove the point home.

B. Manufacturing

Processes in preparation for, and in execution of, manufacturing tasks were the most time-consuming that the team experienced by a long shot. This was a very 'manufacturing heavy' project, and the subteam needed to work hard to deliver elements on time and of suitable, usable quality.

To this end, two fundamental lessons learned were that the more team members able to engage in tasks, the better, and that it really pays to have team members trained and practiced - to maximize interchangeability and flexibility. The subteam took steps to make sure that every process had backup members able to step into a task if primary members were unavailable, but failures occurred when those with the knowledge base felt it would be a waste of time to teach others the necessary methods.

The manufacturing subteam also very quickly learned the merits of maintaining a high pace, and producing prototypes to perfect processes. As a byproduct, the team was able to avoid the machine shop during times when all classmates were trying to cram in their last minute machine-time. For context, at peak production this team was operating all three CNCs, a lathe, and a knee-mill at the same time early in the semester - a literal impossibility mid-spring.

On a more granular level, the manufacturing subteam found that carbide tips are more than worth the extra expense and that, if funding is available, it helps a lot to have ownership of higher quality tools. As well as end mill bits and drill bits, the team purchased middle-quality digital calipers to facilitate Quality Assurance. In hindsight, this was an absolute necessity as attempting any degree of reasonable QA for these tiny parts would have been much more difficult with the stock calipers provided. The team also recommends, as it does for all analysis too, that future teams take full advantage of subject matter experts when developing processes. Consultation with machine shop employees and machinists provided a great deal of helpful guidance, and were excellent supplements to the team's existing knowledge.

The team also learned some lessons in the design process as they pertained to manufacturing. The first design pass on PEEK pieces produced parts which would have been very functional and effective for the primary boom structure, but they would have been almost impossible to manufacture at times, and would have taken far far longer to create. As such, the team's second-pass on components placed an added emphasis on machinability - ensuring that the entire life-cycle of PEEk parts was accounted for.

Finally, the biggest lesson learned was to implement a design freeze early so time was not wasted on creating parts which then became obsolete. This would also have forced the subteam to fully develop all parts of the design before diving in and getting lost in the manufacturing of a single component. This could have lead to a re-design of the burn-box which ended up failing on the full deployment test due to a last minute addition of a pin which was not fully understood. Lastly, this subteam ended up wasting time and resources on a test rig which was agreed by the team should not be made and was never used for anything more than displaying the project during the MSR. This could have been avoided with more stringent communication to the team and ensuring that all parts that were manufactured were agreed upon by the team as would have happened if the design freeze was accepted when issued.

C. Project Process

Project completion and the intermediate planning steps along the way were the biggest unknowns throughout the duration of this enterprise. This was for the simple reason that it was a first venture into a real engineering project for all team members, and because every project is different. Therefore the team learned a great many lessons in planning, risk development, accountability, and general cohesiveness through these nine months.

Efforts committed to aspects of project planning were continuous. At different phases of project development different methods worked better or worse, and this was all untested ground enough that project management required a little extra bandwidth for experimentation and evolution of requisite tools. Final mechanisms to this end included Gantt Charts and a custom progress tracking tool - which superseded a previous software intended to fulfill a similar role. This switch spoke to another important lesson in planning and tracking, which is that no matter how good the tool is, it will only be useful if team members use them effectively. CUBE^3 highly recommends drilling the importance of tracking and accountability through chosen tools into the heads of team members from an early stage. Having members consistently and continually relying on planning tools is an excellent way to stay organized. It is important to note that to have successful leadership there must also be successful followers and without actual 'power' in the project management role, the team must rely on individual's willingness to follow the agreed upon schedule and expectations, which was impossible to keep forthcoming through the entire year.

To this end, the team also found that verbal check-ins at meeting times helped to keep everyone on the same page, and engaged with the elements of the project which required most collaboration. Project Management through discussion with the team's advisor, augmented these check-ins with personal PowerPoint slides. These served the dual purpose of improving the quality of status updates, whilst acting as pipelines to facilitate slides in presentation deliverables.

A strong series of efforts by the Project Manager in creating a coherent project plan also eased and enabled an equally robust risk management effort - creating a positive feedback loop. The risk management work has been described at some length already, but the big top-line lesson learned from the process is that planning for every eventuality is immensely valuable and time saving along the line. Time spent planning for and mitigating potential challenges really is an investment that pays dividends. That said, it is also important to recognize that there is no possible way to anticipate every single thing that could go slightly wrong in a project. Margins must remain in expectations, and team members should expect to maintain a degree of flexibility and critical thinking to overcome problems, as this team did to achieve near-completion of a complex project in a challenging environment.

D. Project Specific

There are a few lessons learned which the team would like to be implemented in future iterations of this project. First, a complete re-design of the 'burn-box' system to release the spool and begin deployment. Second, to make this system fully space-ready the photo-diode gate should be replaced with a hermetically sealed and low-outgassing component. If future testing determines that the resonant frequency is not above requirements, the team suggests a re-build of the system with larger diameter carbon fiber and PEEK pieces. Our models suggest that this would be the easiest way to increase the first resonant frequency. If further issues occur, the choice of Nitinol could be analyzed and could be replaced with the shape-memory version or torsional springs. Finally, with a specific program in mind for this design's use, an analysis of whether a catbed heater would be required for the Nitinol to reach $10^{o}C$ needs to be undertaken.

9. Individual Report Contributions

Michael Burke: Concept of Operations, Project Deliverables, Functional Requirements, Requirements Flow-Down, Requirement Validation Testing, Test Plans, Editing

Collin Doster: Manufacturing, Modeling

Rowan Gonder: Abstract, Project Purpose, Functional Block Diagram, Full Deployment Acceleration Analysis, Organizational Chart, Test Plans, Lessons Learned, Editing, Data Package collation

Venus Gonder: Preliminary Testing, Functional Requirement Validation Testing, Editing

Roger Heller: Project Purpose, Software Design, Software Manufacturing, Resonant Frequency Test, Full Deployment Model, Editing

Adam Hu: Concept of Operations, Manufacturing, Launch Environment Test, Editing

Evan Johnson: Design, Manufacturing, Preliminary Testing, Functional Requirement Validation

Ben Pearson: Manufacturing, Design, Risk, Lessons Learned, Levels of Success

Travis Peccorini: Work Breakdown Structure, Work Plan, Team Work Trends, Cost Plan

Britnee Staheli: Design Process and Outcome, Functional Requirement Validation Testing - Resonant Frequency, Editing

Michael Strong: Functional Requirement Validation Testing - Resonant Frequency & Thermal Modeling, Editing

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