
# The Zenith Program

## Critical Design Review

**FAMU-FSU College of Engineering**

**2525 Pottsdamer Street**

**Tallahassee, FL 32310**

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# 1 Summary

## 1.1 Team Summary

### 1.1.1 Team Information

1.1.1.1 Team Name

This team has dedicated itself to laying the groundwork for continued yearly participation in NASA Student Launch and expansion into experimental liquid-fueled engine development by the parent AIAA chapter. To that end, the team has deemed itself the first year of FAMU-FSU AIAA's rocket development program, called the Zenith Program.

1.1.1.1 Mailing Address

Mail to: FAMU-FSU AIAA

2525 Pottsdamer Street, Suite B111

Tallahassee, FL 32310

### 1.1.2 Mentor Information

1.1.2.1 Mr. Tom McKeown

- **Title:** Board Member, Spaceport Rocketry Association (NAR #342 / TRA #73)
- **Email:** mckeownt@ix.netcom.com
- **Phone:** 321-266-1928
- **NAR Flyer Number:** 57205
- **TRA Flyer Number:** 01922
- **NAR/TRA Certification Level:** Level 2

### 1.1.3 Huntsville Travel Plans

The team intends to attend launch week at NASA MSFC in Huntsville.

### 1.1.4 CDR Completion Time

The team spent approximately 200 hours working on the CDR document.

## 1.2 Launch Vehicle Summary

### 1.2.1 Target Altitude

The target altitude for the Zenith 1 is 4600 ft AGL.

### 1.2.2 Final Motor Selection

The final motor selected is the Aerotech L850W.

***Table 1-1. Aerotech L850W Specifications***

| Motor Parameter | Value |
|---|---|
| Average Thrust | 850 N |
| Initial Thrust | 1,001 N |
| Maximum Thrust | 1,866 N |
| Total Impulse | 3,646 N-s |
| Burn Time | 4.4 seconds |

### 1.2.3 Vehicle Sections

The flight vehicle design is 99 inches in length with a body tube diameter of 6.18 inches and a total weight of 38.6 lbs. The static stability margin of the vehicle is 3.43 calibers and the max velocity the vehicle reaches is 545 ft/s. Section 3.1 expands further into the design of the vehicle, its subsections, and their weight distribution.

### 1.2.4 Vehicle Mass

***Table 1-2. Vehicle Masses***

| Vehicle State | Mass (lbm) | Mass (g) |
|---|---|---|
| Dry Mass | 33.671 | 15273 |
| Wet Mass | 38.625 | 17520 |

### 1.2.5 Recovery System

The recovery system consists of the TeleMega v4 dual-deployment flight computer which is capable of recording altimeter, GPS, and telemetry data. At apogee, a 24" high strength elliptical parachute will deploy. At around 550 feet above ground an 84" Iris Ultra elliptical main parachute will deploy. Ejection charges used are CO2 driven to avoid damaging the parachutes with hot gas produced by traditional black powder charges. The recovery system and all its relevant components are discussed further in Section 3.4.

***Table 1-3. Recovery System Components***

| Component | Part Selected |
|---|---|
| Primary Flight Computer | TeleMega V4.0 |
| Backup Altimeter | AIM4 USB |
| GPS Tracker/Locator 1 | TeleMega V4.0 |
| GPS Tracker/Locator 2 | Apple AirTag |
| Ejection Charges | Tinder Rocketry Raptor CO2 Ejection Charge |
| Drogue Parachute | Fruity Chutes Classic Elliptical 24" |
| Main Parachute | Fruity Chutes Iris Ultra Standard 84" |

### 1.2.6 Rail Size

The launch vehicle will utilize 1515 rails.

## 1.3 Payload Summary

The payload design has been greatly simplified since PDR to allow for more emphasis on the actual scored portion of the payload competition. Rather than deploying a mobile rover, the team has opted to create a static 3D printed camera housing, which will contain an Arduino Mega microcontroller, ArduCam mini camera, and stepper motor to drive the rotation of the camera. The camera housing has been designed as a pyramid, with a wide flat base to prevent tipping or rolling as it sets down on the ground under parachute. The microcontroller and camera are mounted to a 3D printed turret, driven by the stepper motor, with the camera protruding from the top of the pyramid into a protective plexiglass case.

# 2 Modifications to Proposal

## 2.1 Modified vehicle criteria

***Table 2-1. Vehicle Modifications***

| Description of Change | Reason for the Change |
|---|---|
| LEXAN nose cone camera housing removed. Nose cone will now be a completely ABS. | Reduce manufacturing/assembly complexity and prevent adhesive connection points between dislike materials |
| Nose cone bulkhead and shoulder now fixed in place and non-removable after epoxying. | No need for nose cone entry point due to determination of camera and camera housing. |
| Forged eye bolt connection to motor case in substitution of U-bolt/bulkhead configuration above the motor. | Decreases weight, increases lower payload bay cabin space, and shaves a few steps off of assembly process. |
| Centering rings cut to hold fin tabs. | Prevents fin tab connection via threaded rods and decreases compression acting on threaded rods. |
| Threaded rods shortened to run from aft end of vehicle to forward fin-cut centering ring. | Decreases compression on rods, decreases overall vehicle weight, and improves ease of assembly/disassembly. |
| Forward fin-cut centering ring epoxied into airframe while after centering ring is held in place via threaded rods. | Optimizes thrust distribution to airframe while maintaining modularity in removability of the aft centering ring. |
| Thrust Plate and Tail Cone will be printed as one component and held in via threaded rods. | Reduces weight, allows personal modifications, shortens build time, and allows motor retainer to be completely removed. |

## 2.2 Changes made to payload criteria

***Table 2-2. Payload Modifications***

| Description of Change | Reason for the Change |
|---|---|
| **FULL REDESIGN:** Rover concept replaced with static pyramid housing camera system | Reduce complexity. Focus solely on the assembly of the camera turret and coding of the microcontroller to receive and execute command string. Allow 2023/24 team to improve payload with knowledge gained. |
| Lens on ArduCam switched for fisheye wide angle | Initial lens did not meet NASA FOV requirement |

## 2.3 Changes made to project plan

***Table 2-3. Project Modifications***

| Description of Change | Reason for the Change |
|---|---|
| STEM Engagement delayed. Planning begins in January. Execution in February | More difficulty in finding points of contact and planning events than was initially anticipated |
| Full-scale manufacturing brought forward into early January | Parts list by vendor created and waiting for submission to ME department. Can begin ordering/building early for a test flight in early/mid-February. Gives margin for re-flight if any off-nominal event occurs |
| Payload manufacturing brought forward into early January | Payload requires more time for code debugging. Need to test receiving, decoding, executing commands over VHF. 3D print times for housing are longer than expected |
| Full-scale test flight brought forward into mid-February | Sub-scale flight had little to no margin for re-flight. Want 100% nominal full-scale so early first flight and backup dates are scheduled. |

# 3 Vehicle Criteria

## 3.1 Design and Verification of Launch Vehicle

### 3.1.1 Launch Vehicle Mission Statement

The mission of the Zenith Program's launch vehicle, the Zenith 1, is to reach within 5% margin of error of the targeted 4600 ft AGL apogee, safely recover the vehicle, and deploy a payload with a nominal dual deployment recovery while employing a modular and highly reusable design for future iteration and re-flight.

### 3.1.2 Launch Vehicle Success Criteria

1) The launch vehicle meets NASA requirements for starting static stability between 2-5 calibers, and simulations show the vehicle stays within the stability margin of 2-5 during the flight, regardless of launch angle or wind conditions.
2) The launch vehicle can be assembled and made launch-ready in under 2 hours.
3) The vehicle can remain launch-ready on the pad for a hold of up to 2 hours.
4) The motor ignites when the launch command is given and the 12V igniter initiates.
5) The launch vehicle achieves over 52 ft/s at rail exit to comply with NASA requirements.
6) The vehicle does not go supersonic.
7) Maximum velocity is within +/- 5% of OpenRocket prediction.
8) The vehicle apogee is within +/- 5% of 4600 ft AGL target.
9) The lower half of the rocket separates at apogee, deploying the drogue parachute while the upper payload bay remains pinned to the avionics bay.
10) The upper half of the rocket separates at 550ft, deploying the main parachute and payload.
11) All 4 independent ejection charges fire during the flight. The vehicle is not recovered with live charges endangering the team.
12) No section of the vehicle is ever jettisoned. All sections remain tethered together under parachute by the nylon recovery harnesses.
13) The vehicle impacts the ground inside a 2500 ft radius of the launch pad.
14) The descent from apogee occurs in under 90 seconds.
15) The vehicle impacts with KE of the heaviest section being under 75 ft-lb to comply with NASA requirements.
16) Ground impact causes no damage to the airframe, fins, internal structures, avionics, or payload.
17) Flight data can be extracted from the flight computers. Data is sampled across the entire flight profile.

### 3.1.3 Final Vehicle Design

The final design chosen for the Zenith Program will be 100 inches long with an estimated loaded weight of 38.23 pounds (17,485 grams) and an unloaded weight of 33.67 pounds (15,273 grams).

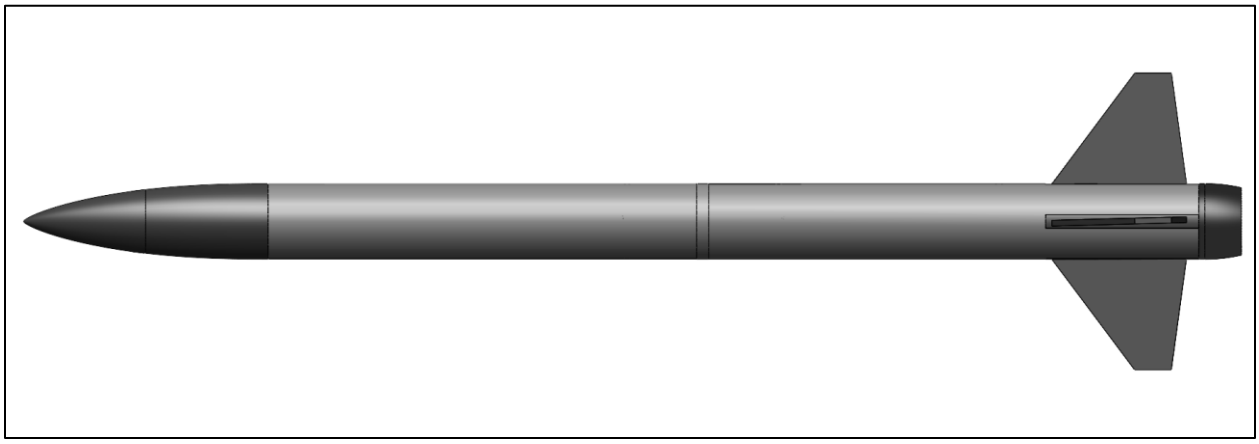


***Figure 3-1. Launch Vehicle Assembly***

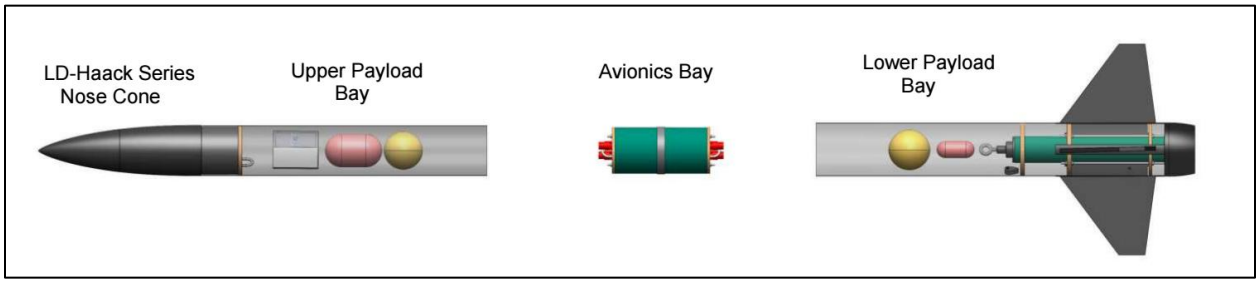



***Figure 3-2. Launch Vehicle Exploded/Transparent Assembly***

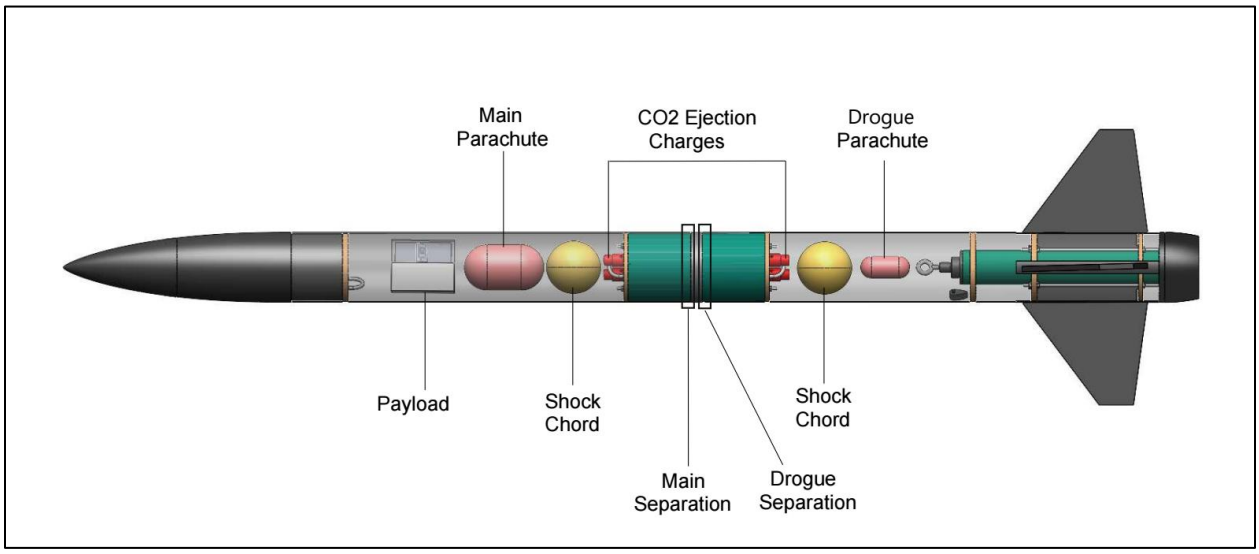


***Figure 3-3. Launch Vehicle Transparent Assembly***

#### 3.1.3.1 Nosecone Configuration

The final design for the nosecone configuration will be an LD-Haack Series with threaded shoulder attachment. The leading design presented in PDR included a nosecone with a camera housing unit to satisfy our faculty advisor's request of capturing the flight through video recording from inside the vehicle. However, after further discussion with our faculty advisor, it has been decided to leave out the camera housing due to manufacturing complexity and potential failure points. The nosecone will be printed from acrylonitrile butadiene styrene (ABS) and the camera housing was supposed to be made of LEXAN glass. Attempting to connect the two different materials raised concerns in terms of flight performance and structural integrity as the vehicle enters large speeds during flight. As the nosecone is positioned at the front of the vehicle, it will be undergoing many aerodynamic forces during flight, interrupting the structural integrity of the nosecone's profile could cause the nosecone to break during flight. Instead, the whole nosecone profile will be made of ABS material without any camera house.

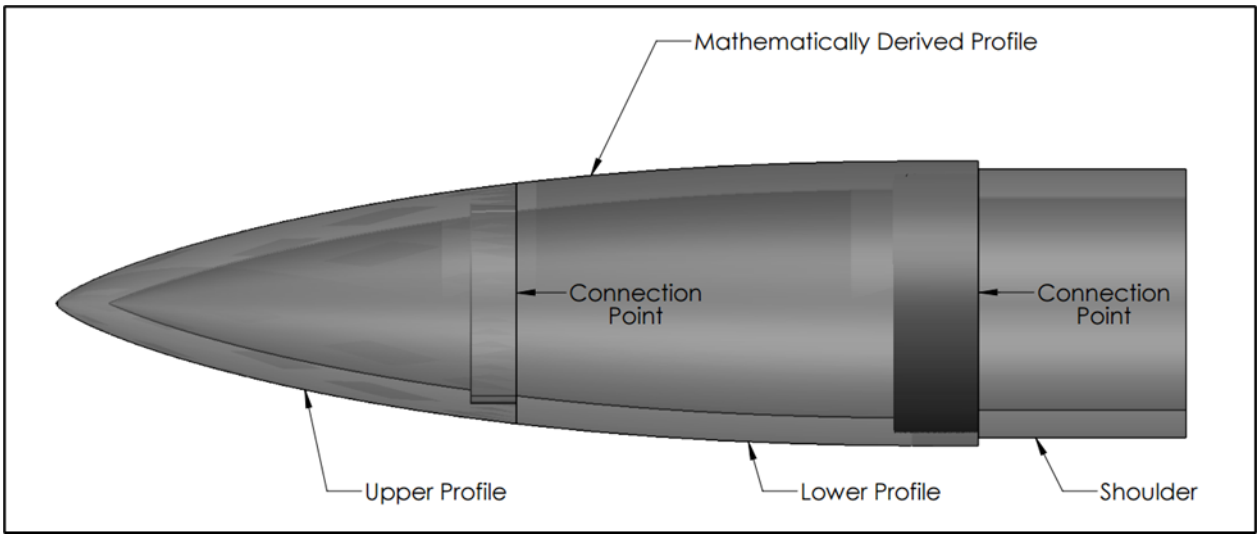



***Figure 3-4. LD-Haack Series Nosecone Assembly***

The nosecone configuration is separated into three sections: upper profile, lower profile, and shoulder. The configuration of the nosecone was ultimately separated into three sections for ease of manufacturing. The upper profile is connected to the lower profile by a cylindrical shoulder. The shoulder, receiving end, and connection faces between the two sections will be epoxied together. The lower profile is connected to the shoulder by a threaded cylindrical shoulder and the two sections will also be epoxied together. Shown below are dimensioned CAD drawings of each component and the full nosecone assembly. 3D printing specifications and notes have also been included in the drawings included in the drawings.

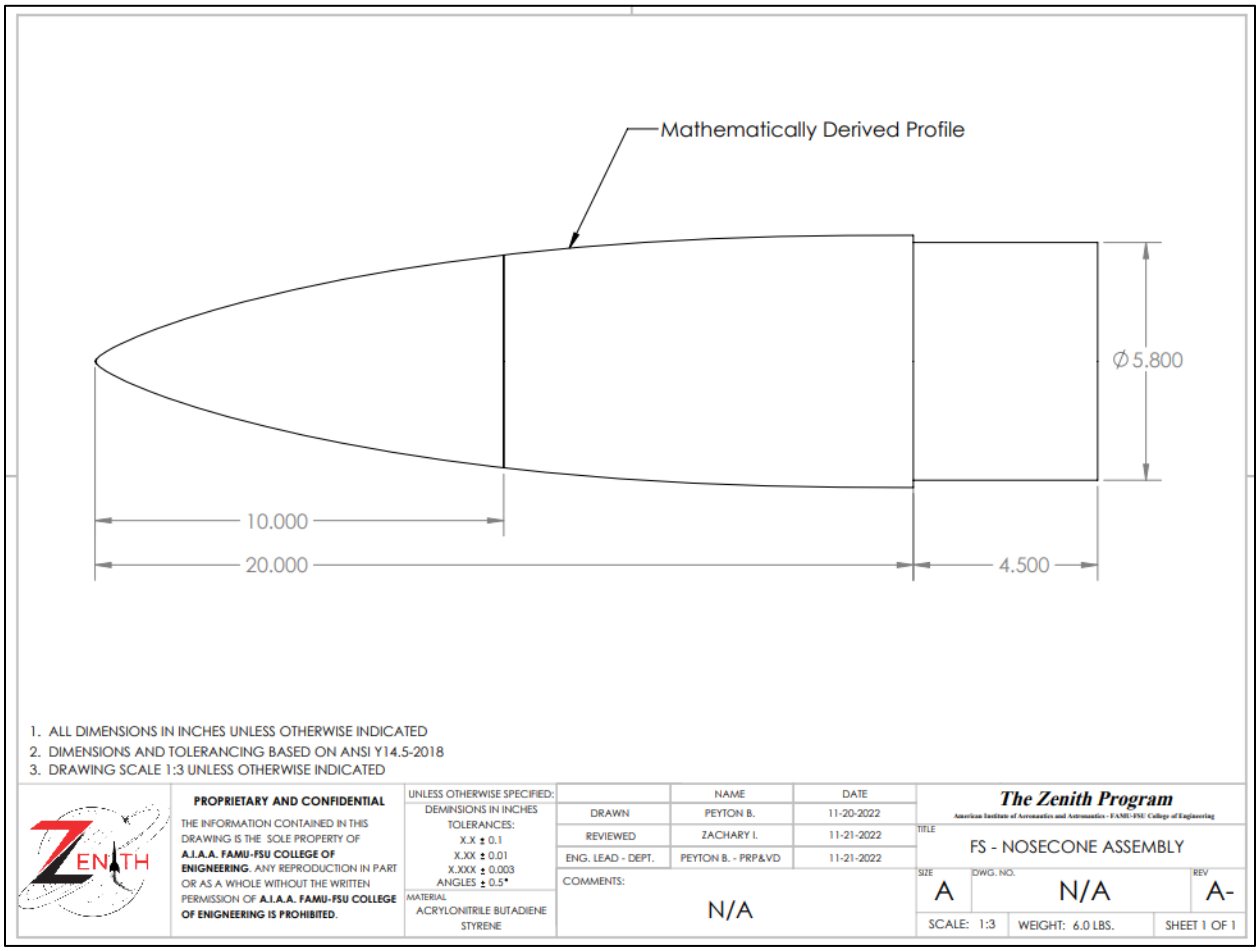



***Figure 3-5. LD-Haack Nosecone Assembly CAD Drawing***

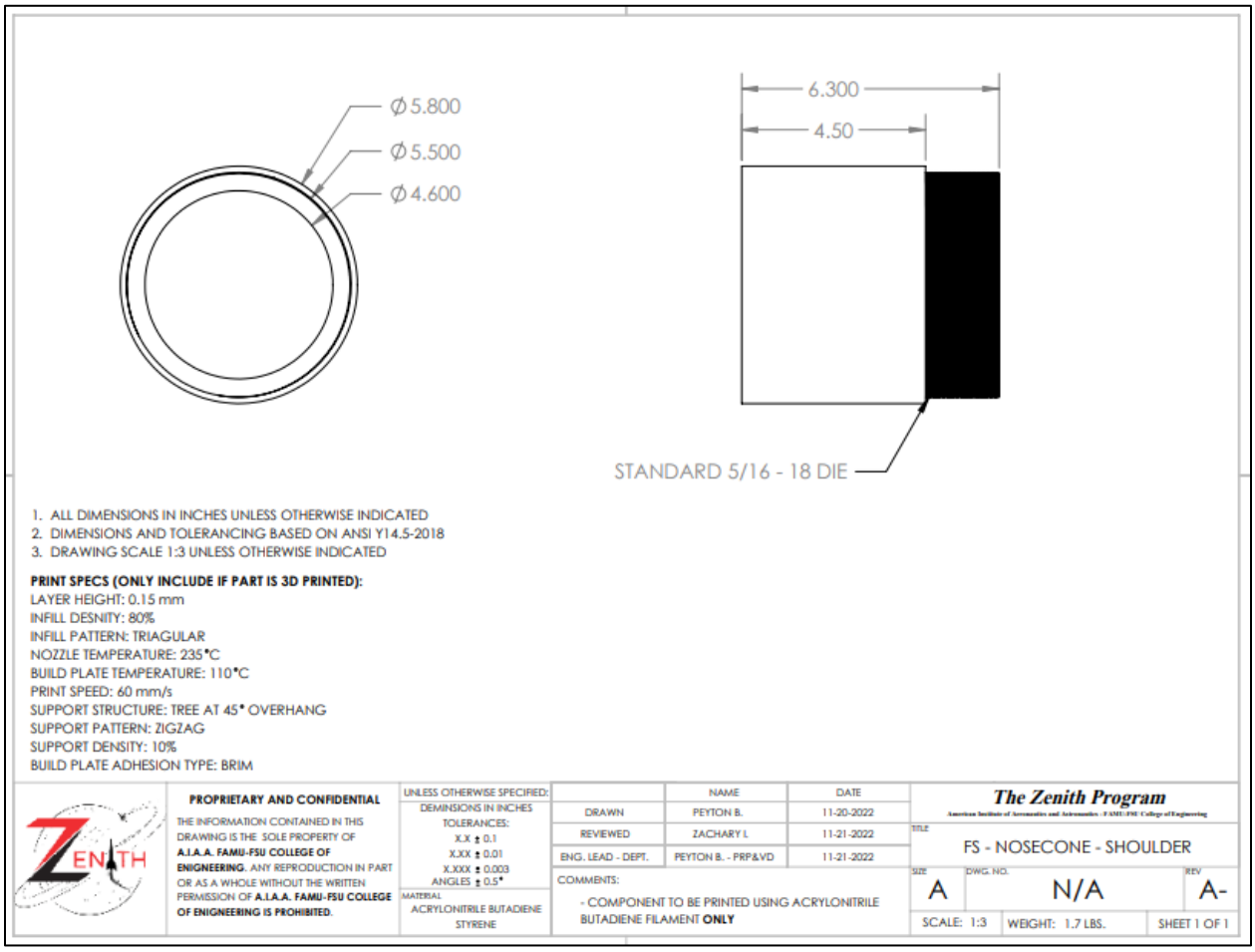



***Figure 3-6. Nosecone Shoulder CAD Drawing***

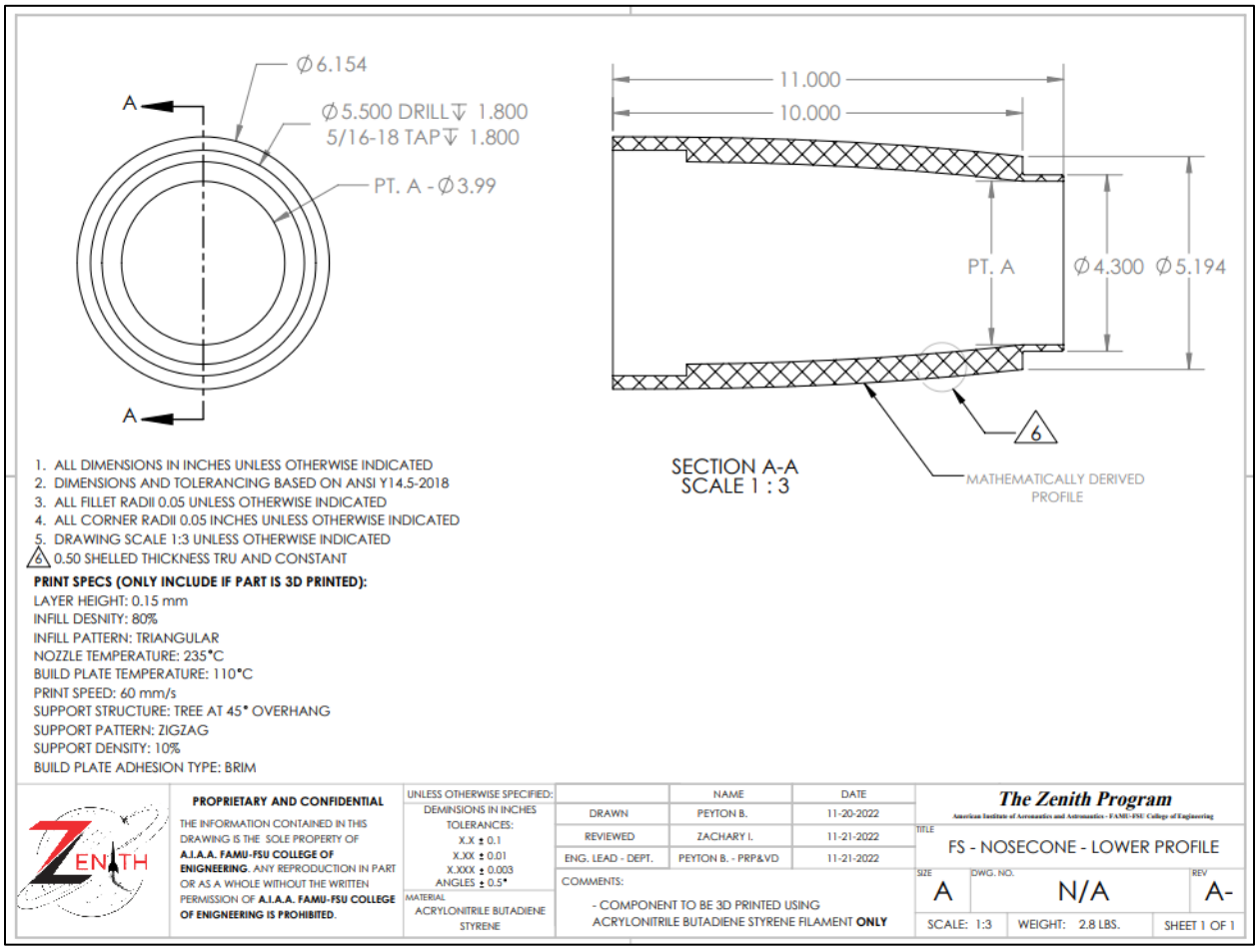



***Figure 3-7. Nosecone Lower Profile CAD Drawing***

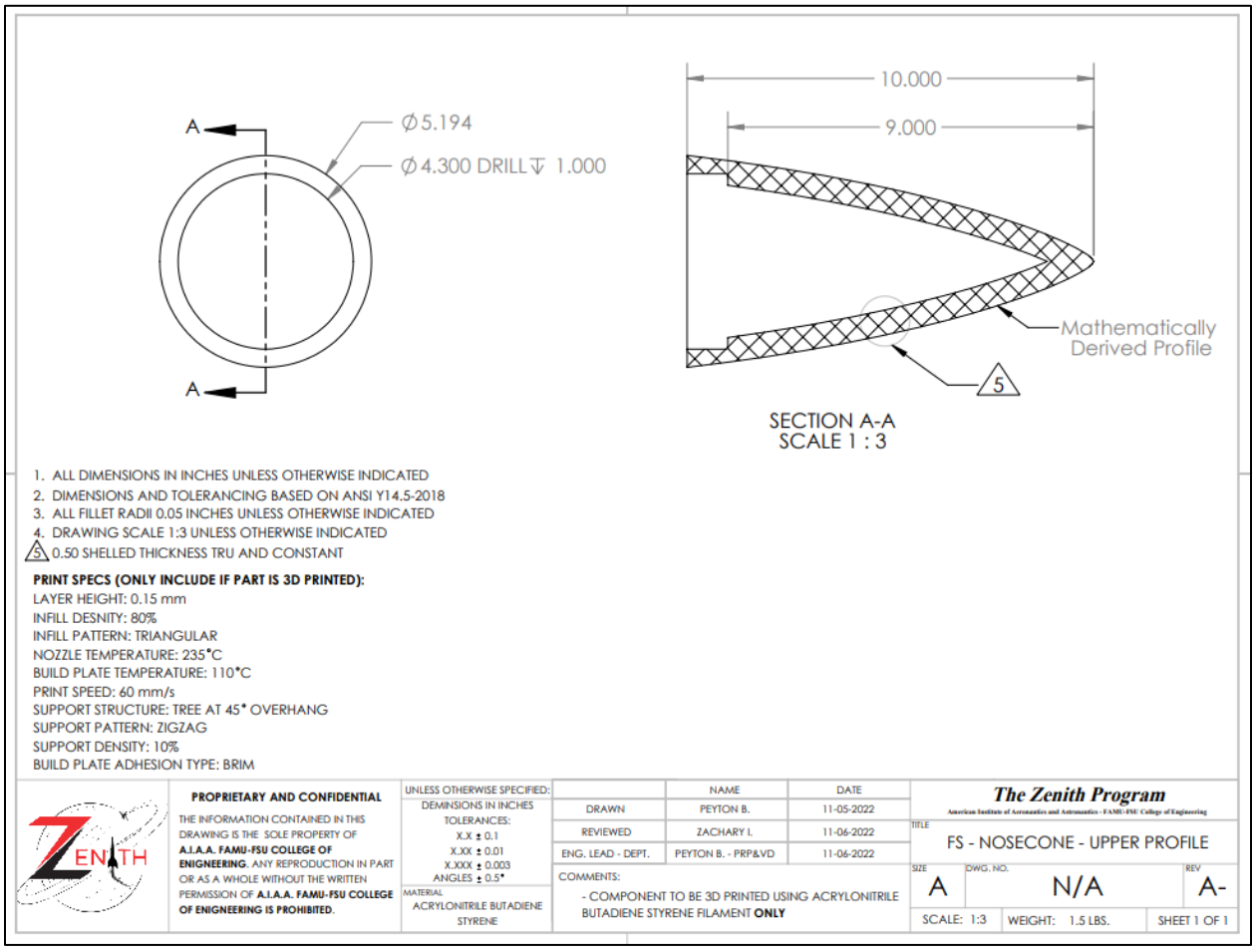



***Figure 3-8. Nosecone Upper Profile CAD Drawing***

### 3.1.3.2 Upper Payload Bay

The upper payload bay consists of a 35-inch-long blue tube airframe with a forward bulkhead that sits flush against the nosecone shoulder.

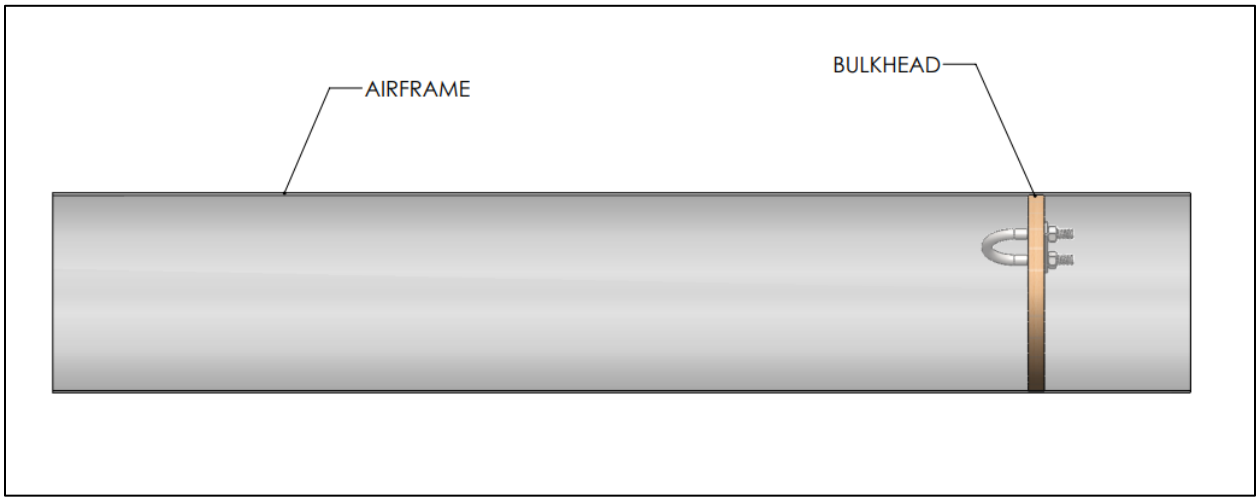



***Figure 3-9. Upper Payload Bay Assembly***

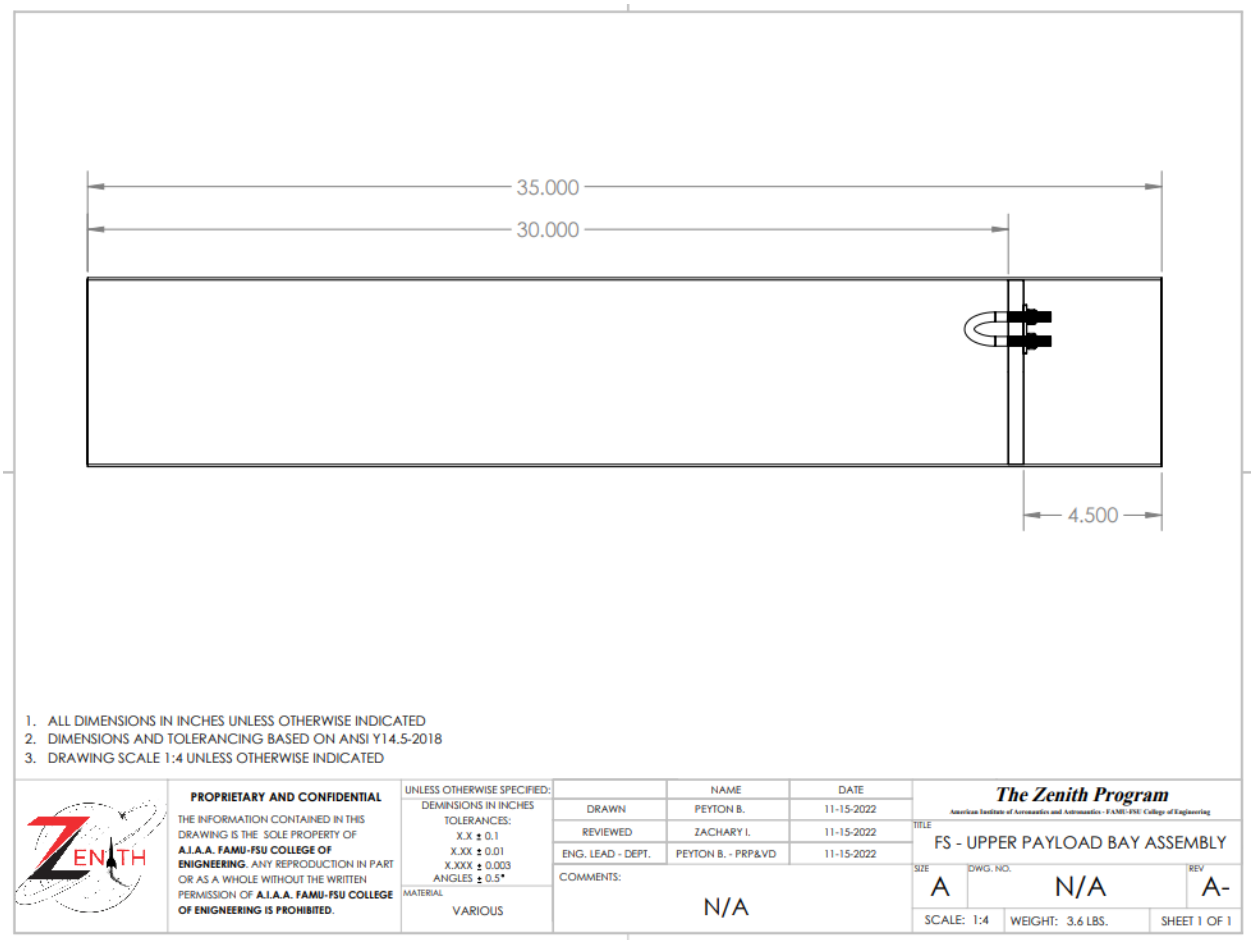



***Figure 3-10. Upper Payload Bay Assembly CAD Drawing***

(a) Upper Payload Bay Airframe

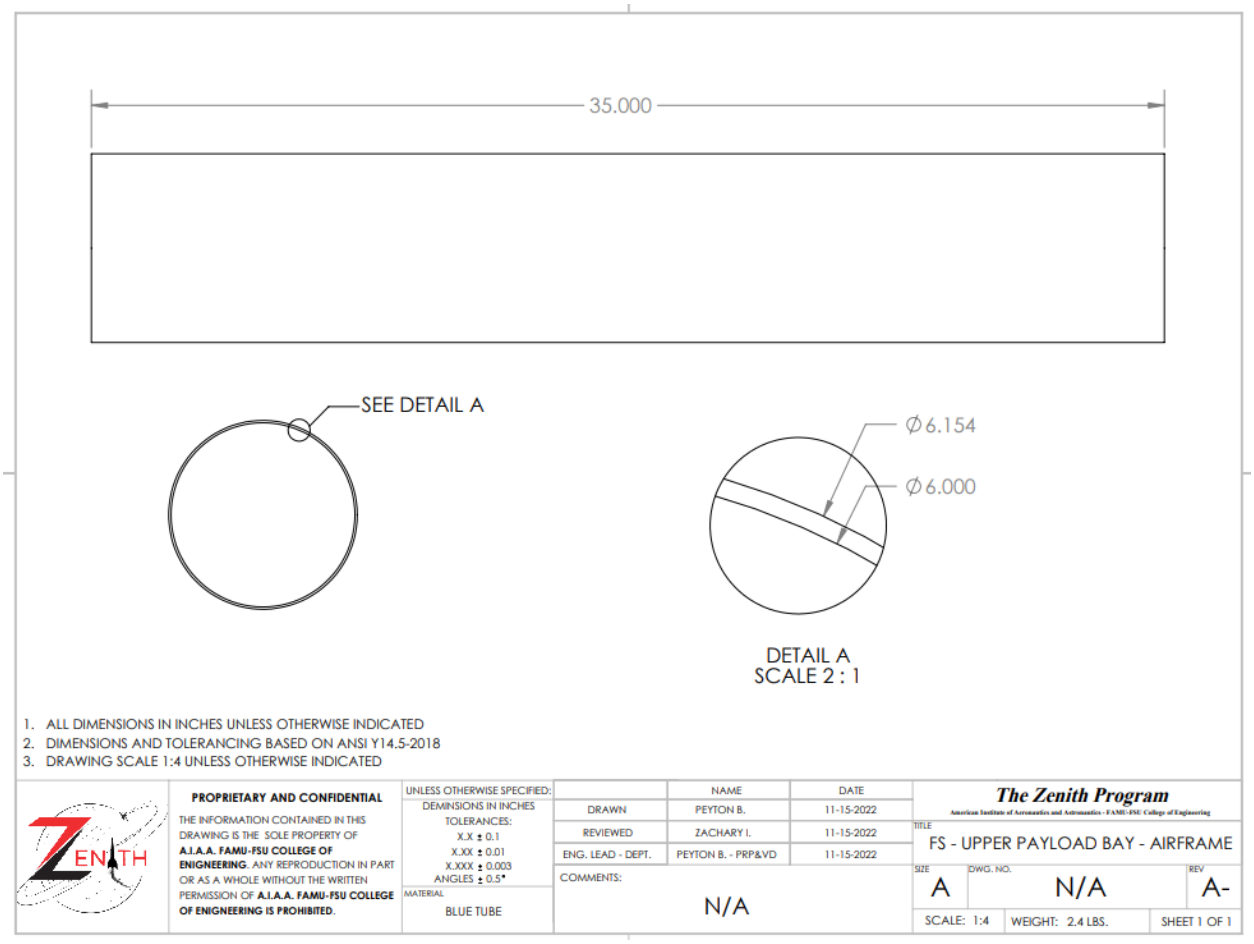



***Figure 3-11. Upper Payload Bay Airframe CAD Drawing***

(b) Updated Nose Cone Bulkhead

Originally, the nosecone bulkhead was designed with two holes for a bolted connection to the nosecone shoulder. However, now that the nosecone camera housing has been eliminated from the vehicle's design, bolted connection (which allowed access to the nosecone) is not needed. All other design aspects of the nosecone bulkhead have remained the same with a 5/16" U-Bolt and fastener plate configuration attached to the bulkhead for main parachute shock chord connection purposes. The ½" bulkhead is fabricated from Baltic Birch Plywood. Shown below are dimensioned CAD drawings of the nosecone bulkhead design and each of its components.

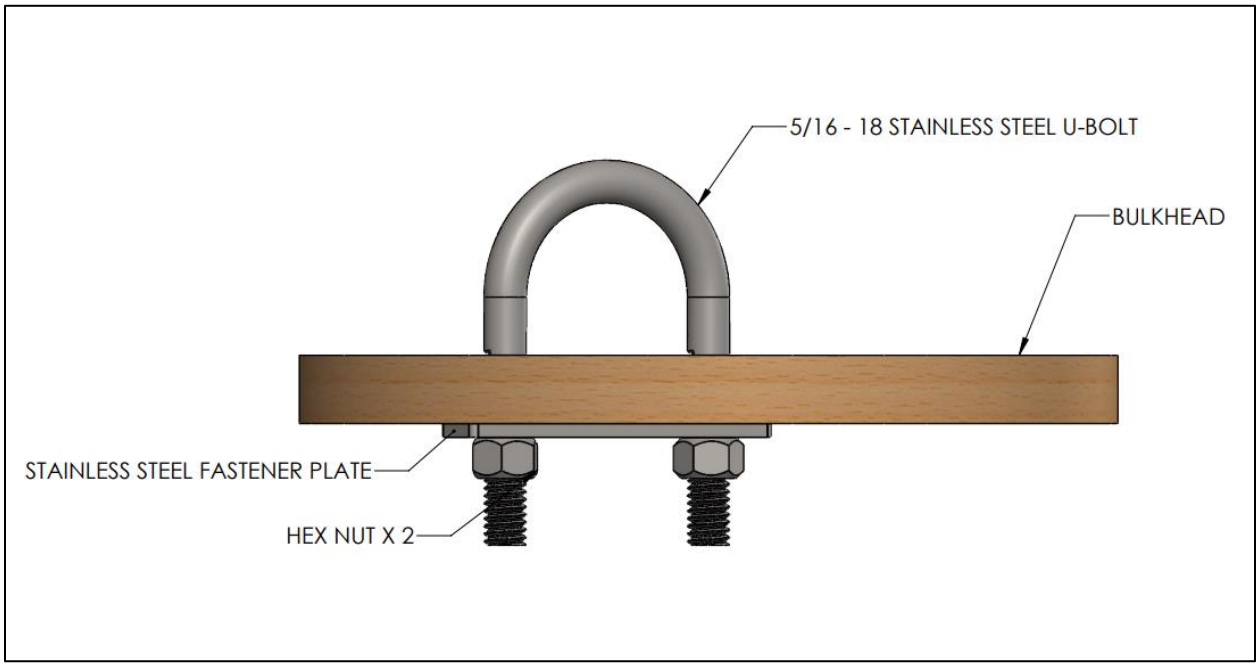



***Figure 3-12. Nosecone Bulkhead Assembly***

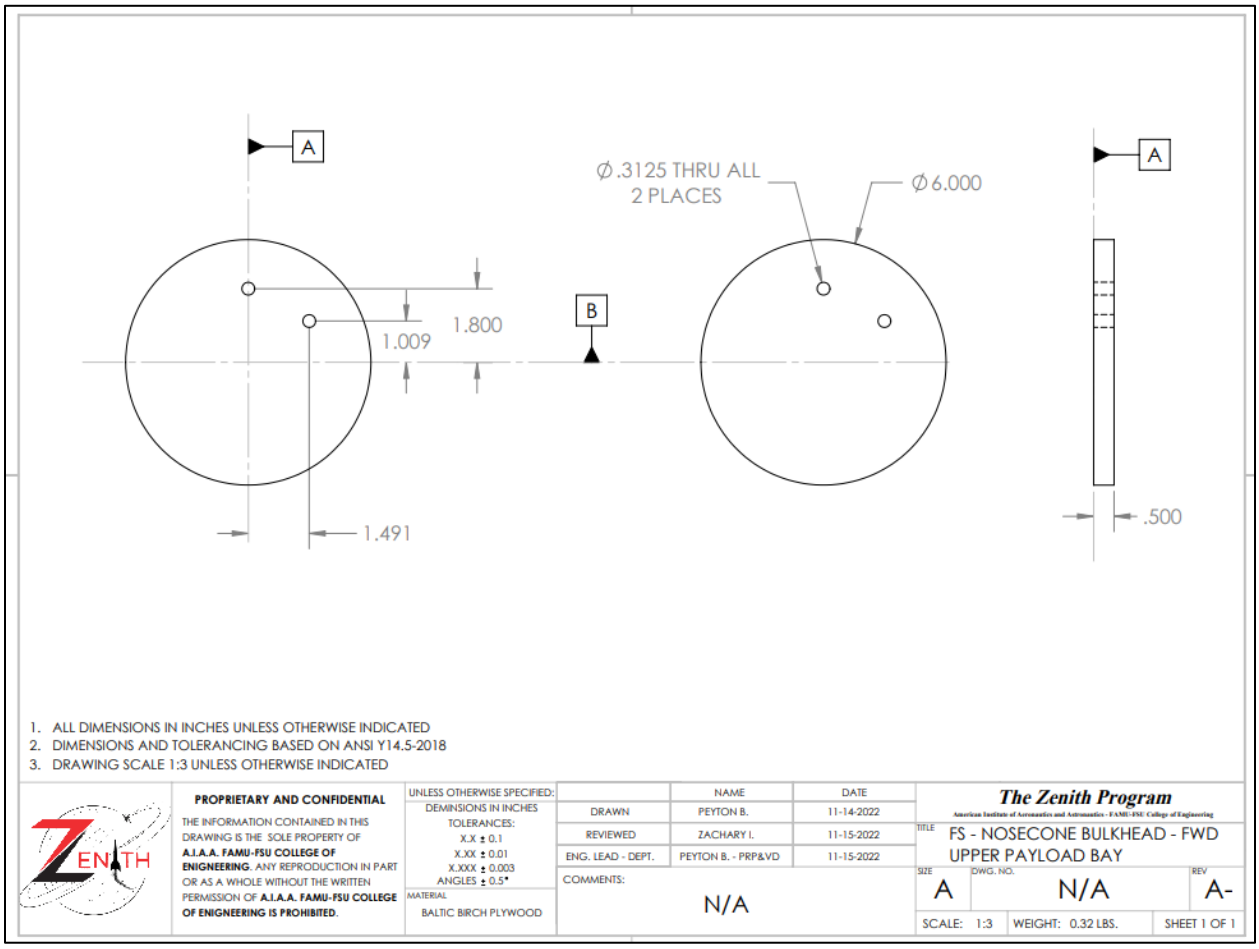



***Figure 3-13. Nosecone Bulkhead CAD Drawing***

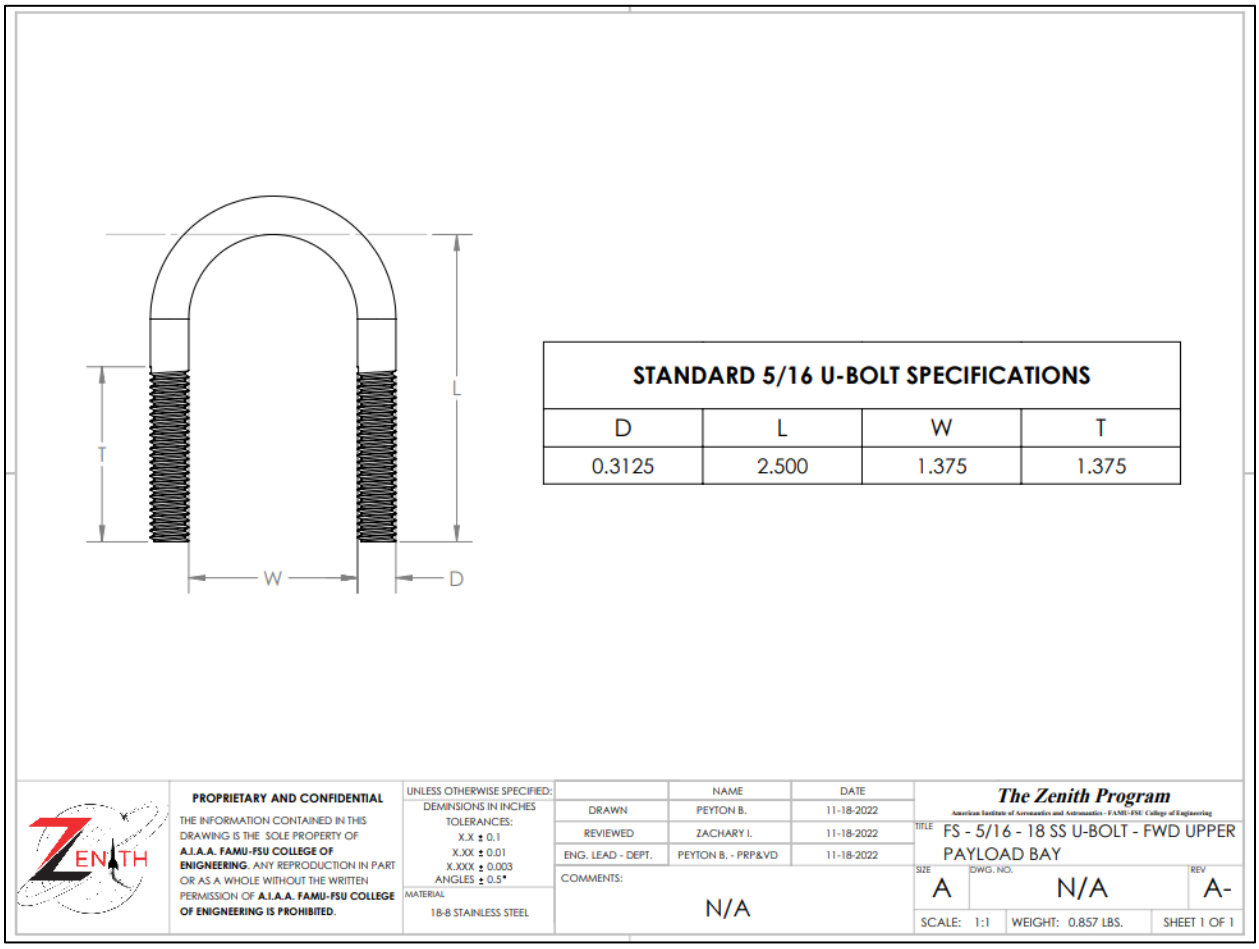



***Figure 3-14. U-Bolt CAD Drawing***

### 3.1.3.3 Avionics Bay

The avionics bay will be located between the upper and lower payload bays to not only act as a coupler connection point between the two airframe sections, but also house the avionics equipment. The avionics coupler is 12 inches in length and made from blue tube with a 1-inch-long outer airframe ring hugging the external surface of the coupler to provide a flush connection point between the coupler and the vehicle's airframe. The avionics bay as a whole is expected to weigh 3.71 lbs.

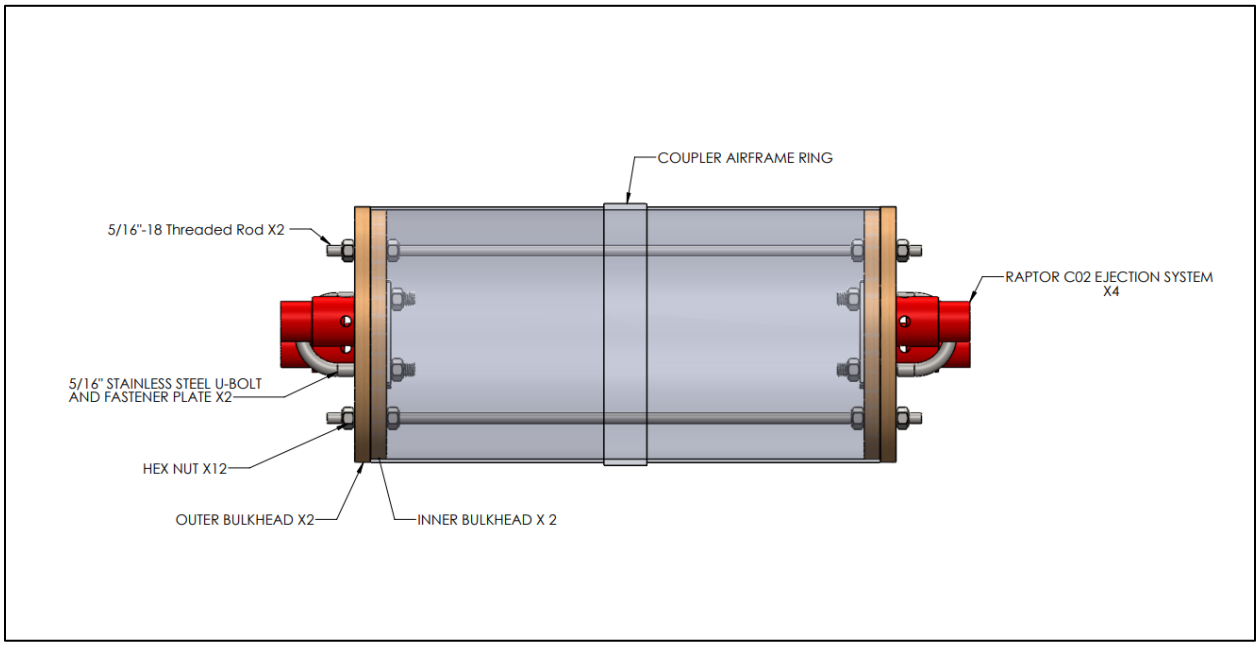



***Figure 3-15. AV Bay Transparent Assembly***

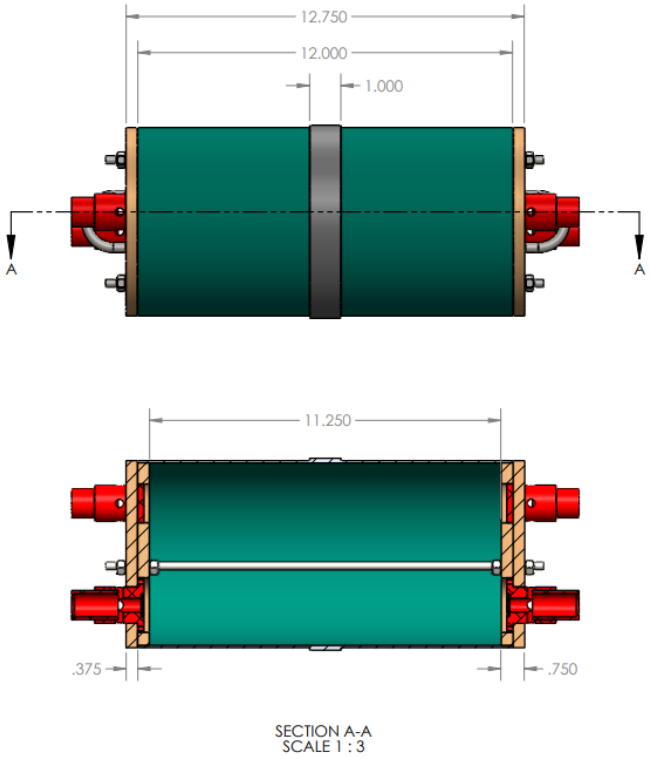



***Figure 3-16. AV Bay Solid CAD Drawing***

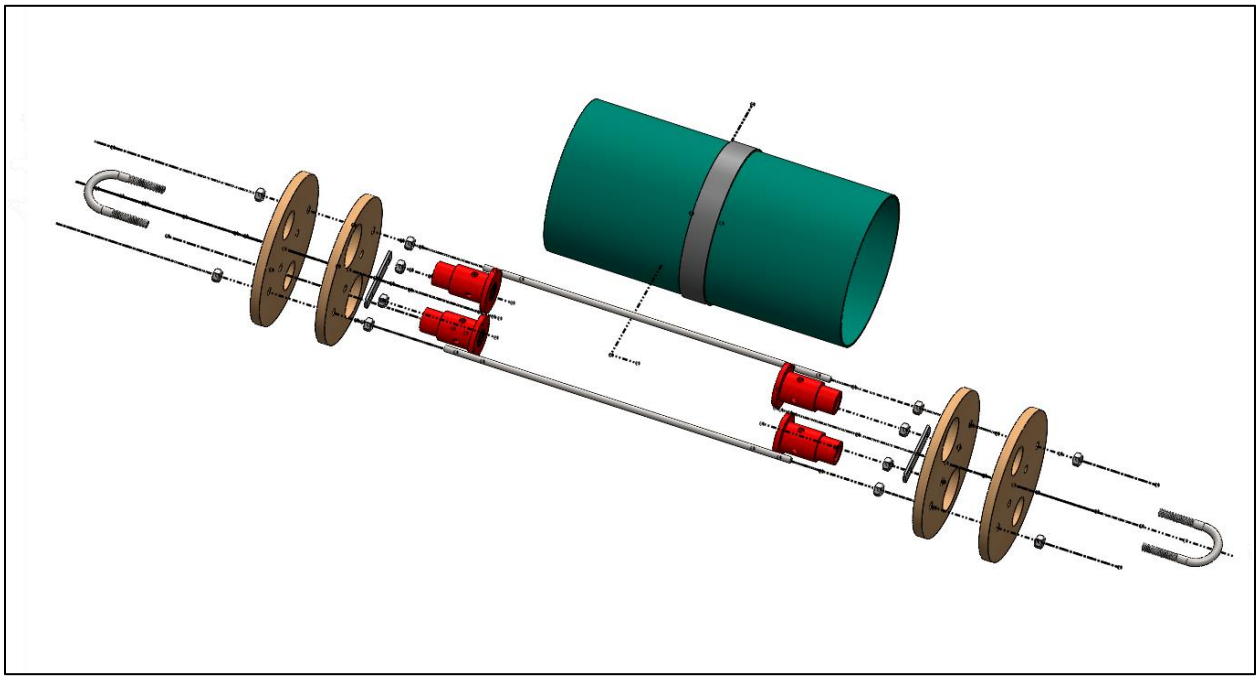


***Figure 3-17. AV Bay Exploded Assembly***

The coupler will have 4 bulkheads, 2 inner bulkhead and 2 outer bulkheads both 0.375” thick. The inner bulkheads, located inside the coupler, sit coincident against the outer flat face of the coupler and the outer bulkheads sit, located outside of the coupler, sit coincident against the outer flat face of the coupler. To account for modularity, the avionics bay has been designed to allow for a quick disassembly if any parts need to be modified or replaced. The RAPTOR CO2 Ejection Systems will be located at the inner and outer bulkheads of each side. The bulkheads will be modified to allow the ejection systems to be inserted through the two bulkheads and fixed in place via screws. Shown below are dimensioned CAD drawings of the avionics bay assembly and each of its components.

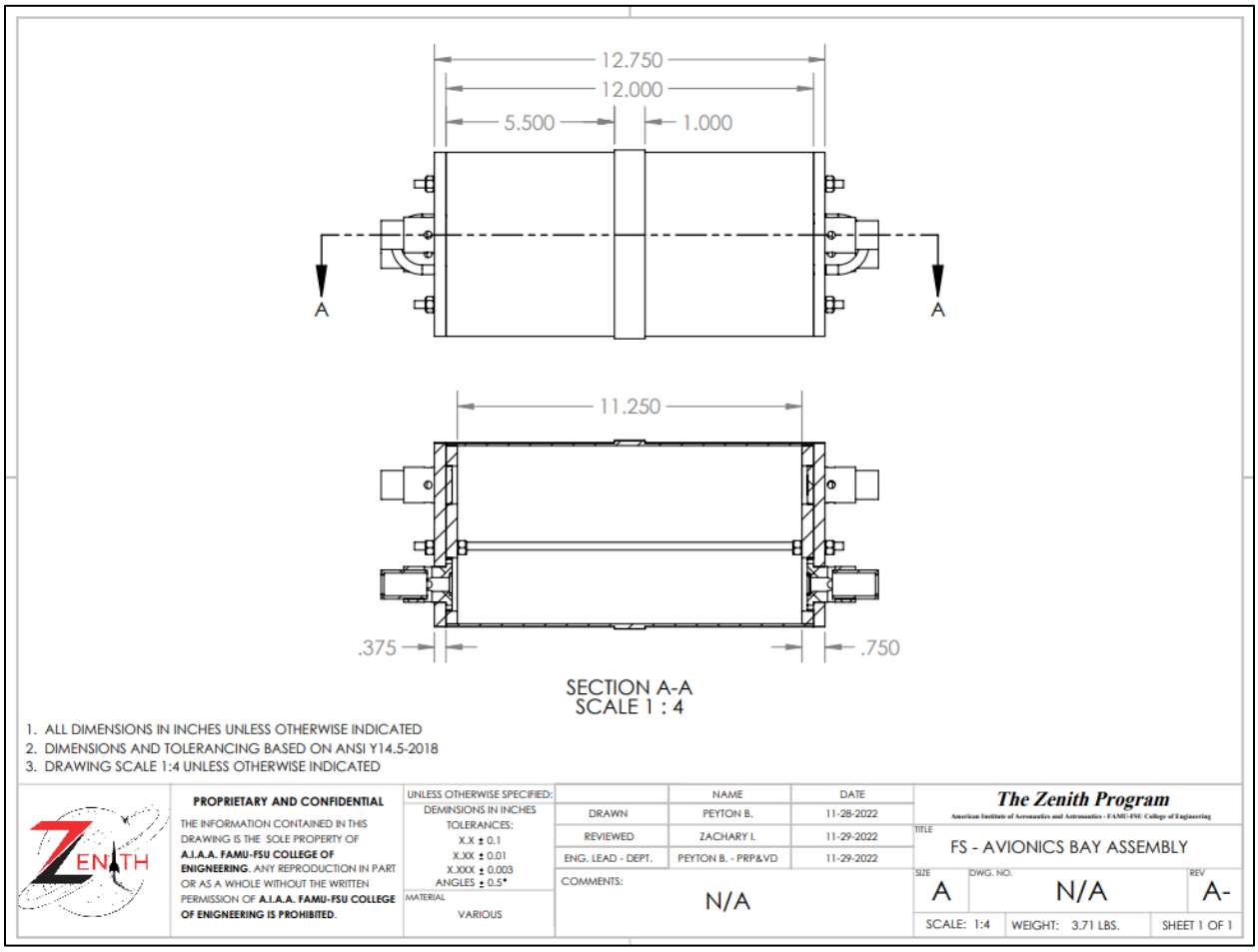



***Figure 3-18. AV Bay CAD Drawing***

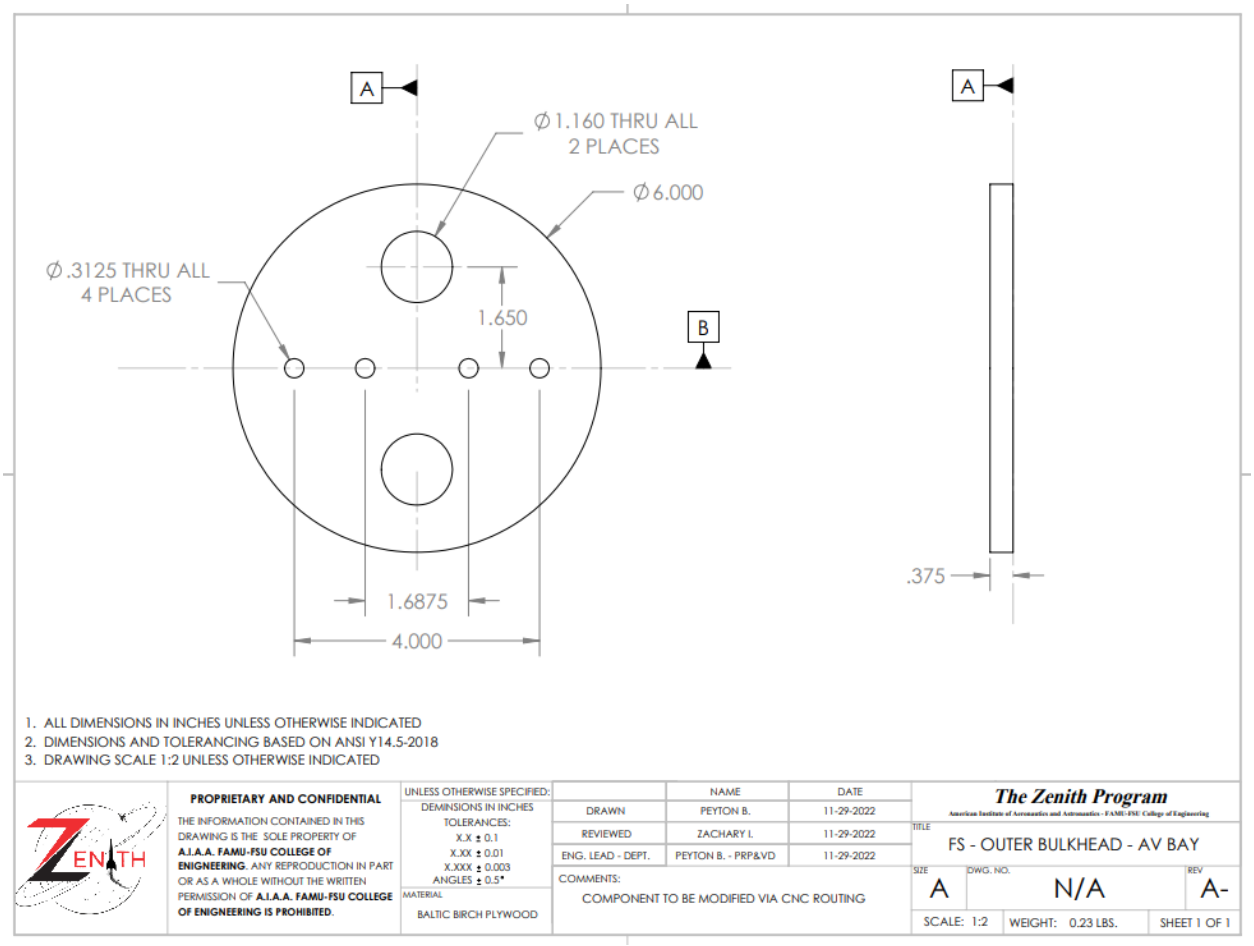



***Figure 3-19. AV Bay Outer Bulkhead CAD Drawing***

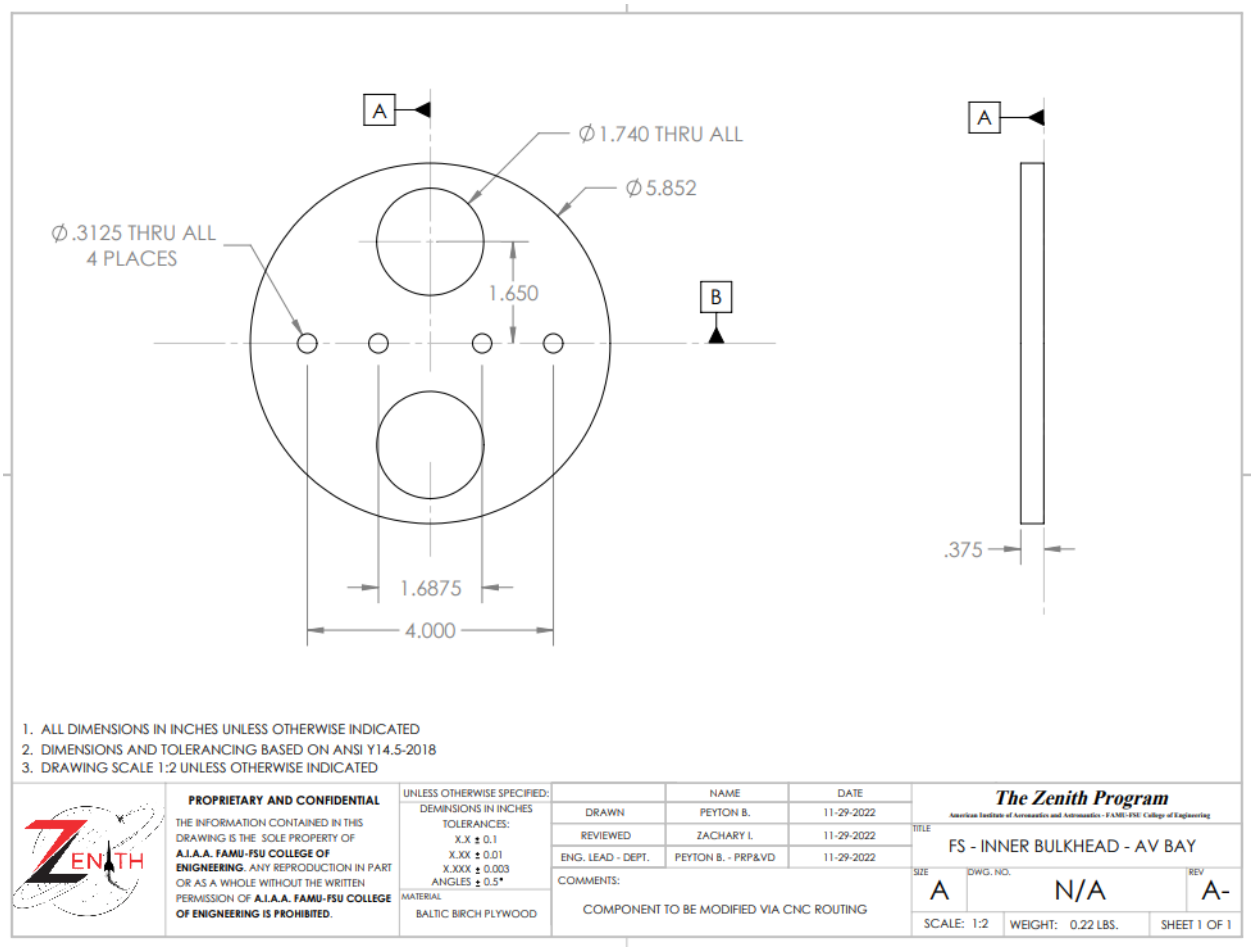



***Figure 3-20. AV Bay Inner Bulkhead CAD Drawing***

### 3.1.3.4 Lower Payload Bay and Thrust Structure

The lower payload bay as a whole is 43.50 inches in length.

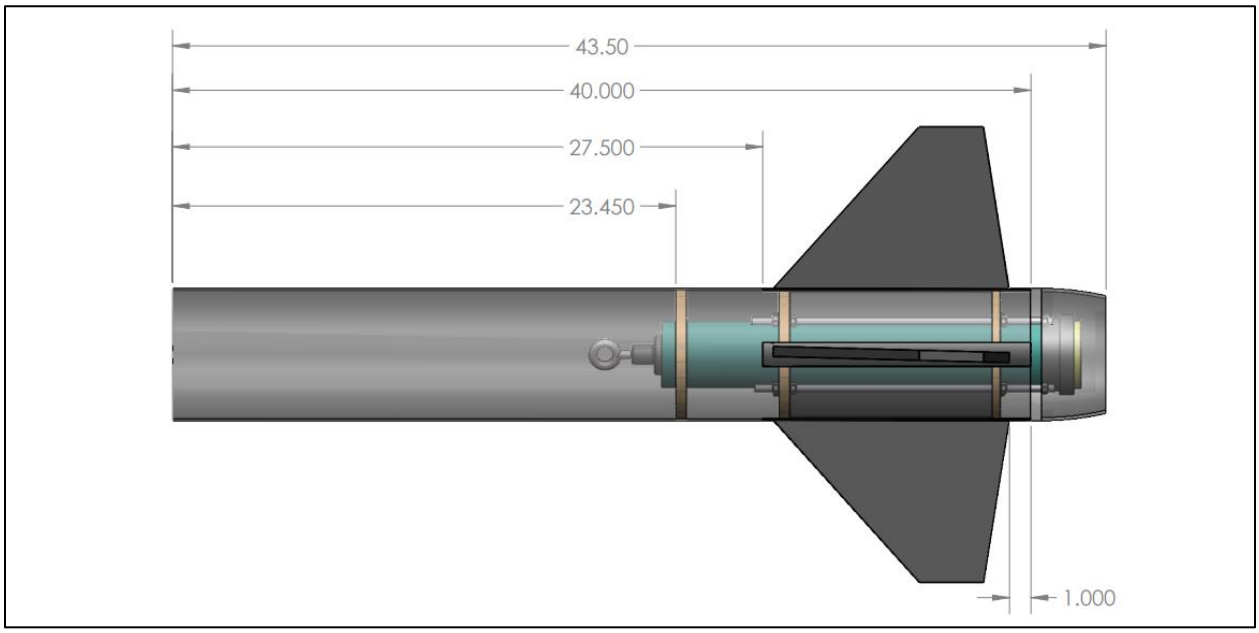



***Figure 3-21. Lower Payload Bay/Fin Can Transparent Assembly***

(a) Lower Payload Bay Airframe

The airframe of the lower payload bay will be 40 inches in length and made of blue tube material. The fin slots in the airframe will be CNC machined at our in-house manufacturing shop by certified personnel. The fins are designed to slide into the fin slots, with the fin base having the same curvature as the airframe for a flush and tangent surface fit.

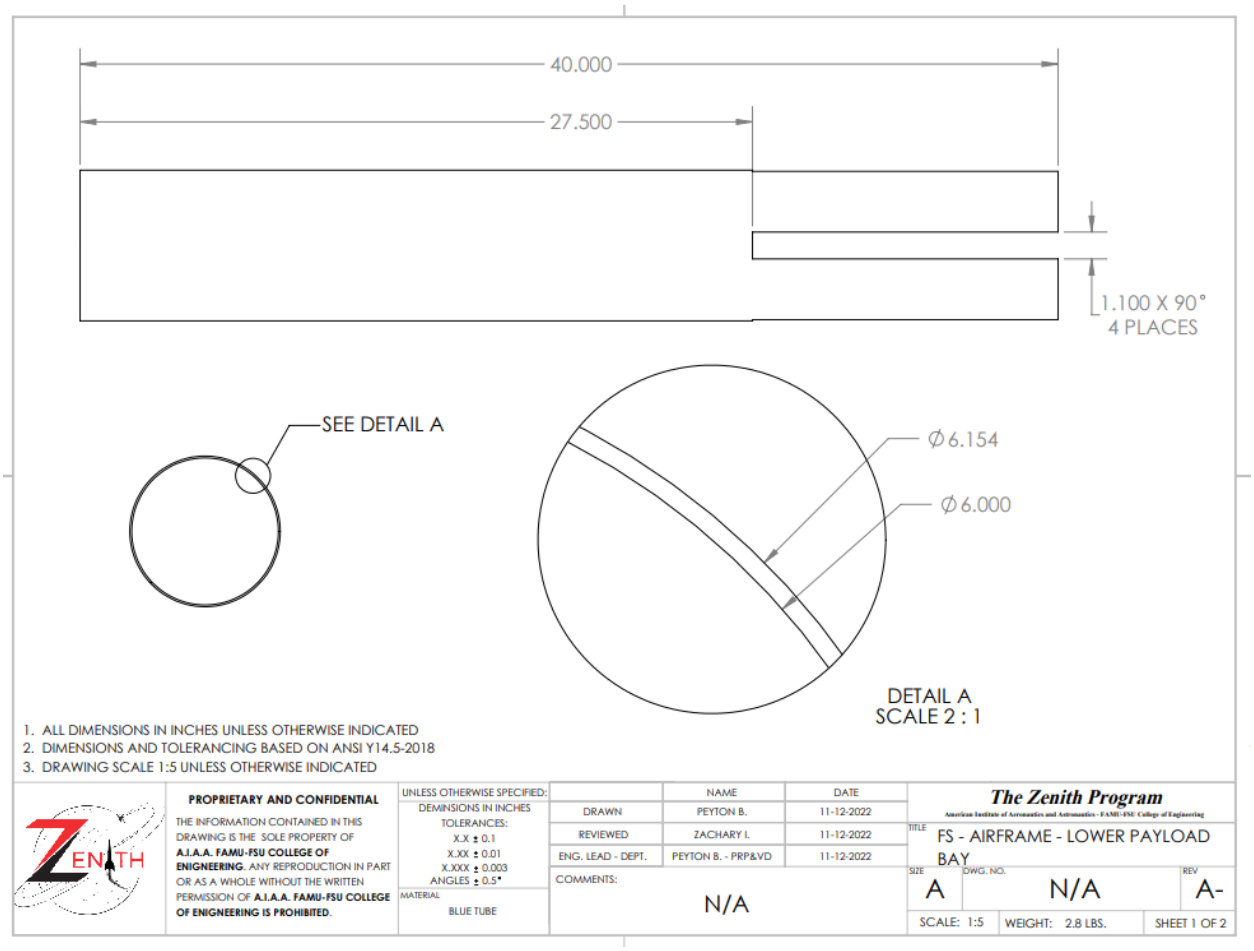



***Figure 3-22. Lower Payload Bay Airframe CAD Drawing***

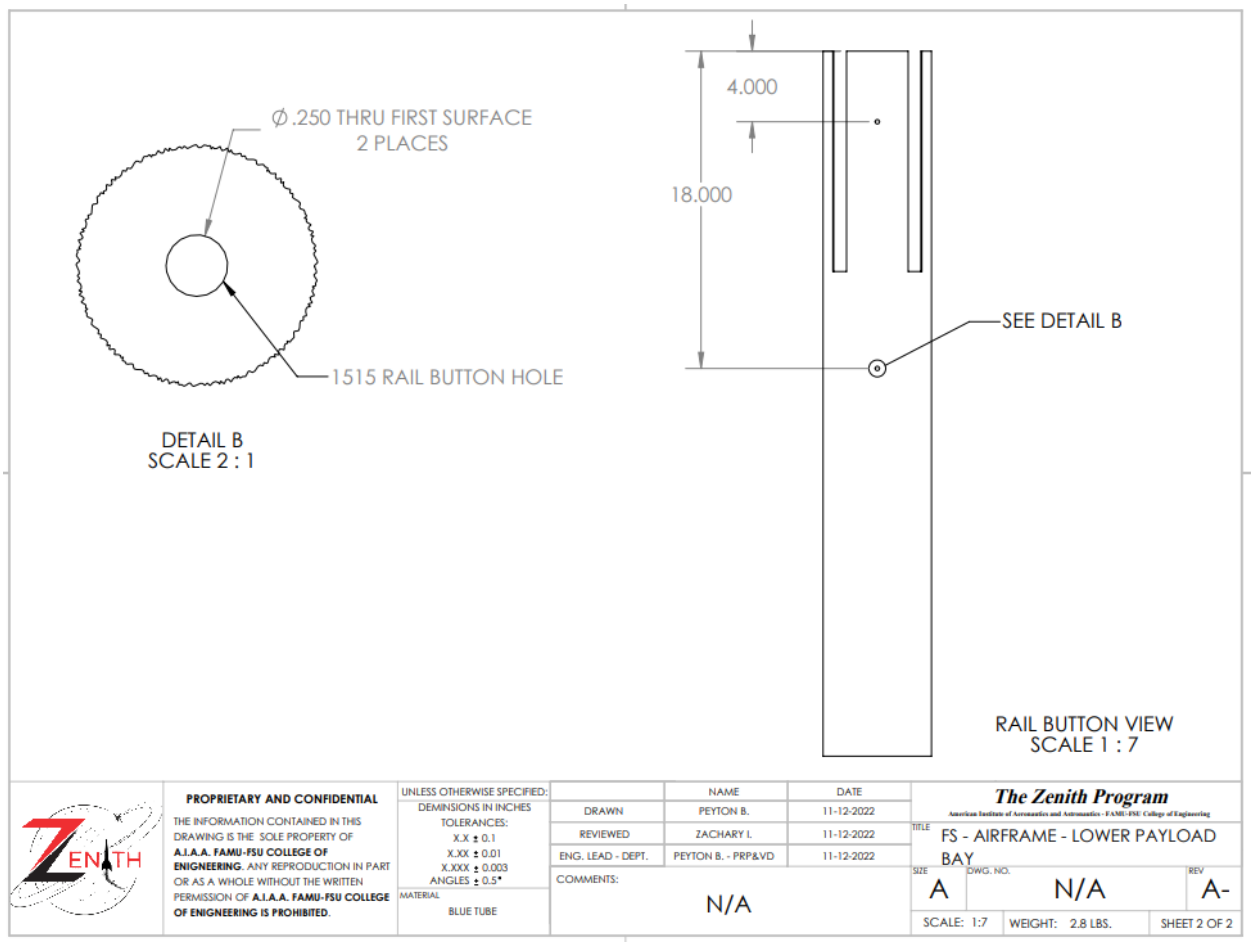



***Figure 3-23. Lower Payload Bay Airframe w/ 1515 Rail Buttonhole***

(b) Updated Thrust Structure

The thrust structure presented in PDR is relatively similar to the updated design, but with a few small changes.

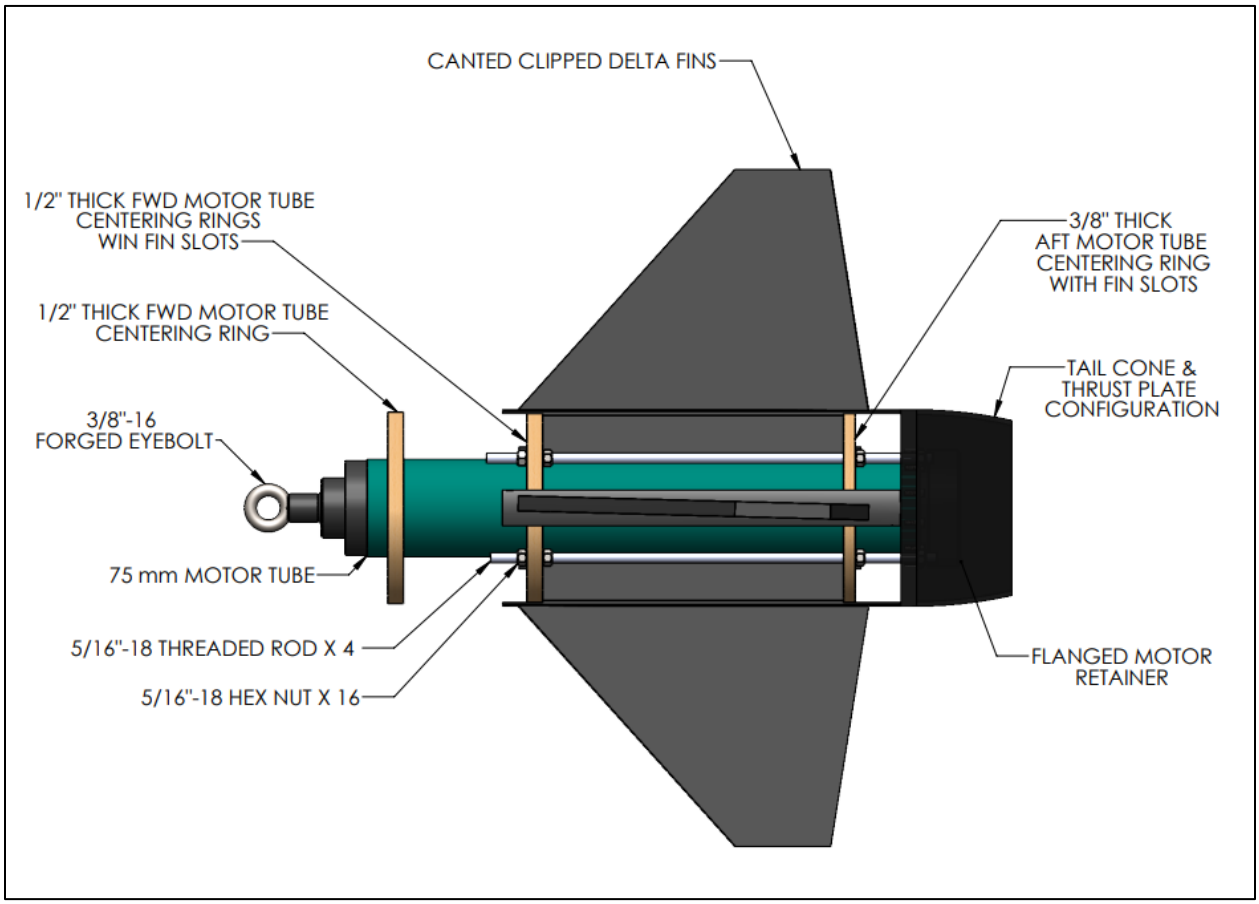



***Figure 3-24. Labeled Fin Can Assembly***

The fin tabs have been designed differently to fit into slots that were cut in the centering rings. Originally, the threaded rods ran through the fin tabs up to the forward bulkhead above the motor case (as shown in Figure 3-12 of PDR). However, the leading concerns with the design was the amount of compression acting on the threaded rods. The original design used 22-inch long 3/8”-24 threaded rods whereas the new design uses 14.5-inch long 1/4”-20 threaded rods. The threaded rods now only serve to hold the fins and the thrust plate/tail cone configuration in place. This modification decreases the amount of compression acting on the threaded rods and drastically lowered the vehicle’s weight, increasing the stability margin. The final fin design chosen for the vehicle will be the clipped delta fin shape. The large surface area of the clipped delta fin decreases wing loads and increases the stability of the fins. The fins will be canted 1.5 degrees clockwise off vertical to introduce spinning stabilization to the vehicle during flight. The

base plate of the fin has the same thickness and radial curvature as the airframe for a flush surface fit.

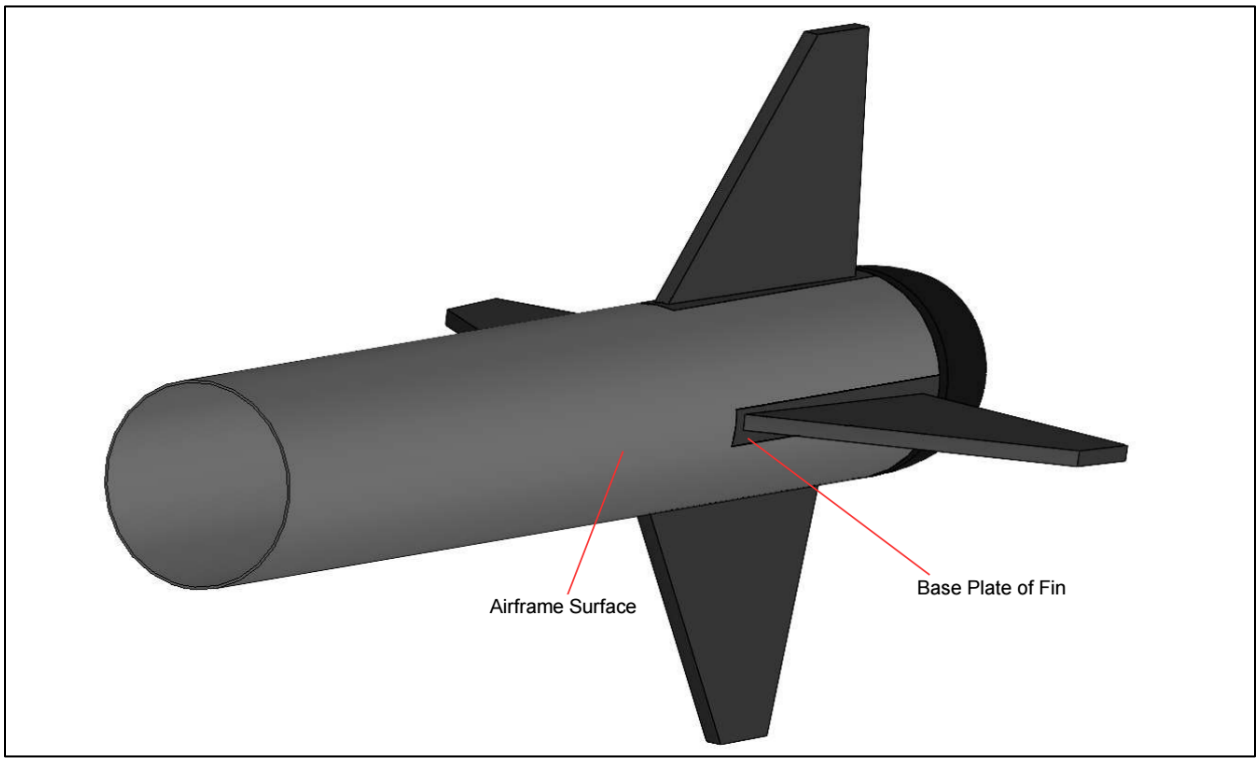



***Figure 3-25. Lower Payload Bay/Fin Can Solid Assembly***

The fins slide into the slots in the centering rings and the threaded rods sandwich the fin tabs between the two centering rings to keep the fins fixed in place. The fin tabs extend to the motor tube for extra structural stabilization and to transfer thrust loads to the centering rings.

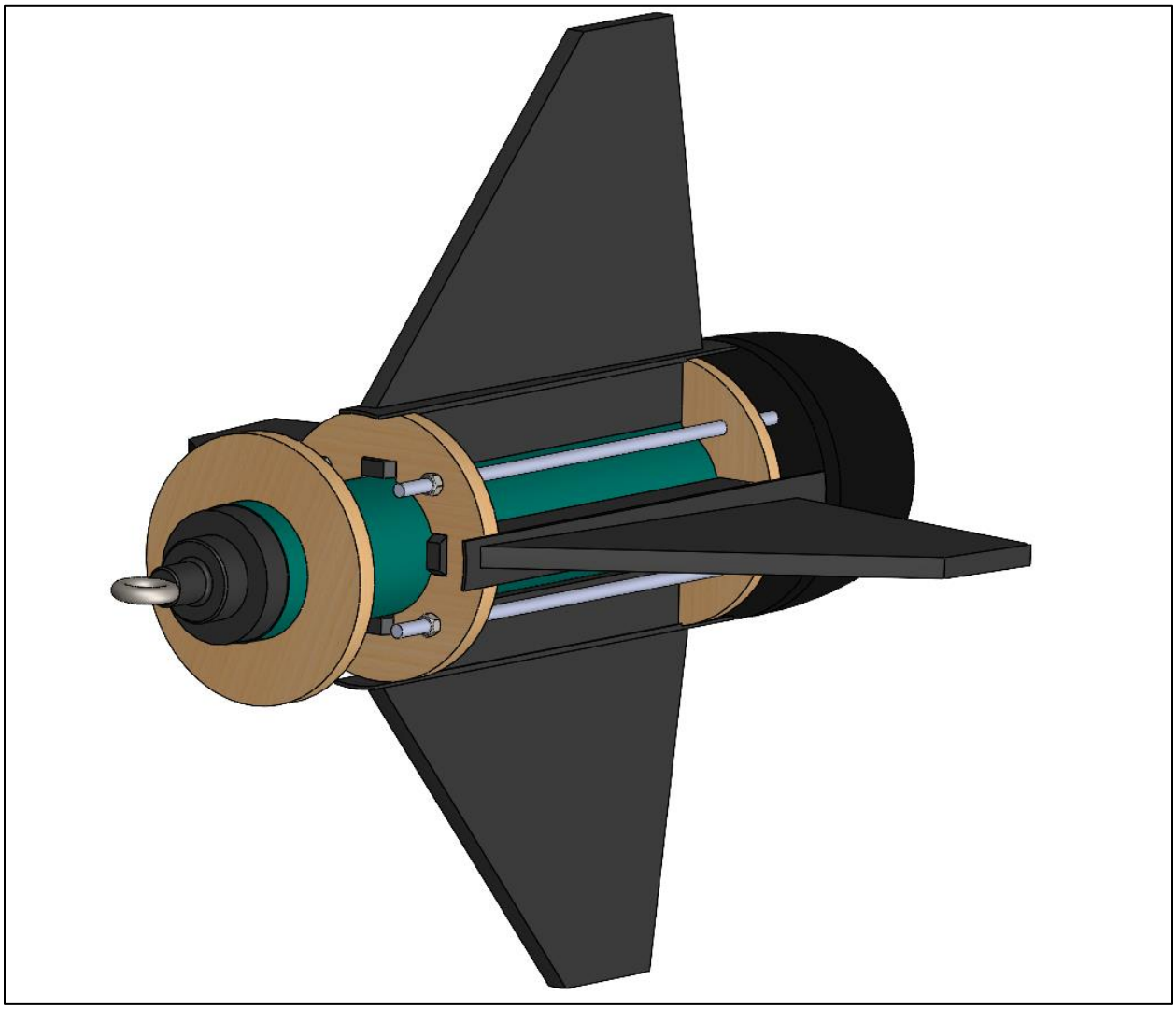


***Figure 3-26. Fin Can Assembly***

The fin assembly shown above was replicated in the subscale vehicle and had great success. The slots in the centering rings prevent the fins from rotating and each end of the fin tabs the slide into the centering rings are chamfered for ease of fitment. The fins will be 3D printed using ABS filament and have an estimated weight of 1.3 pounds each (608 grams). Shown below are dimensioned CAD drawings of the clipped delta fins.

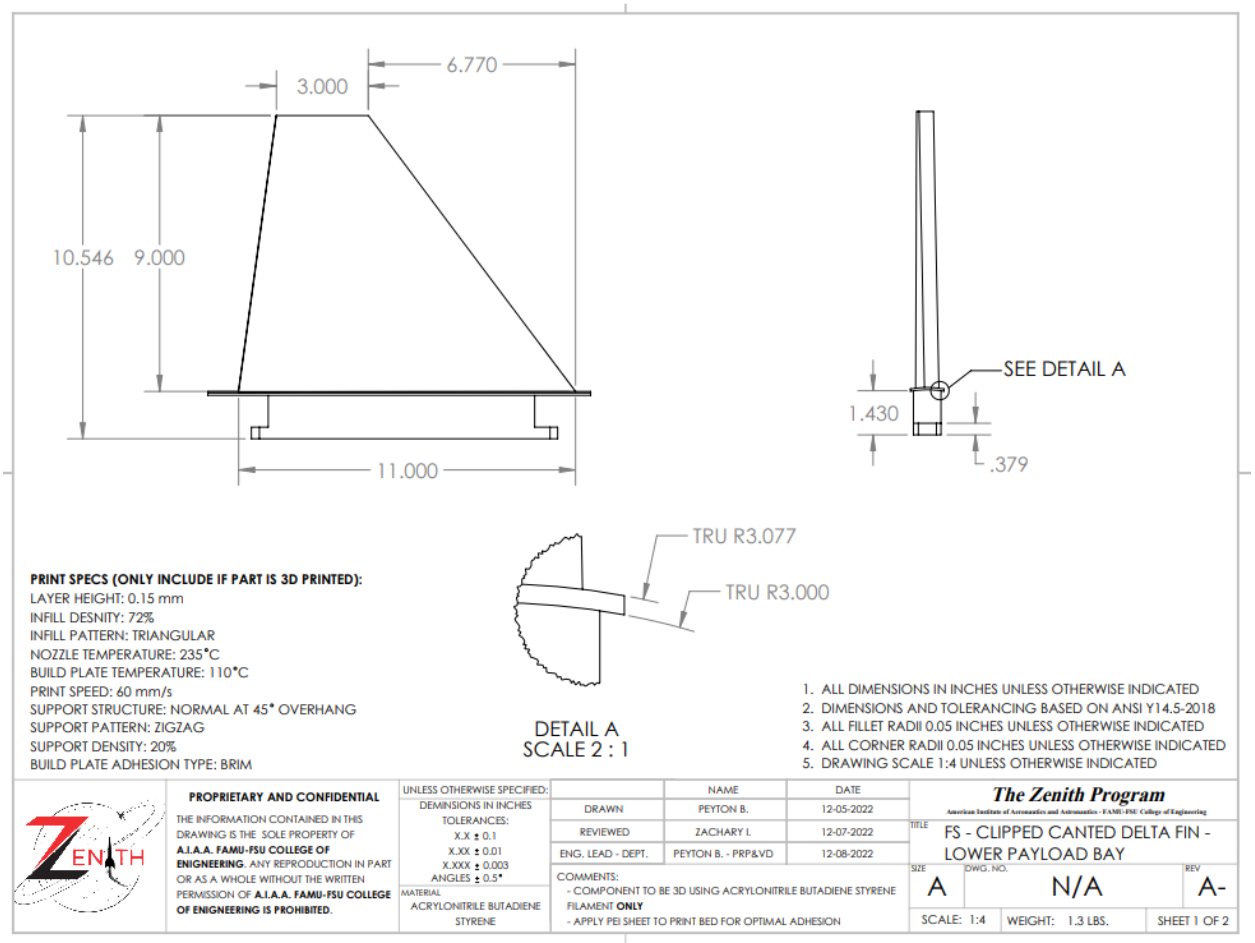



***Figure 3-27. Canted Clipped Delta Fin CAD Drawing Sheet 1 of 2***

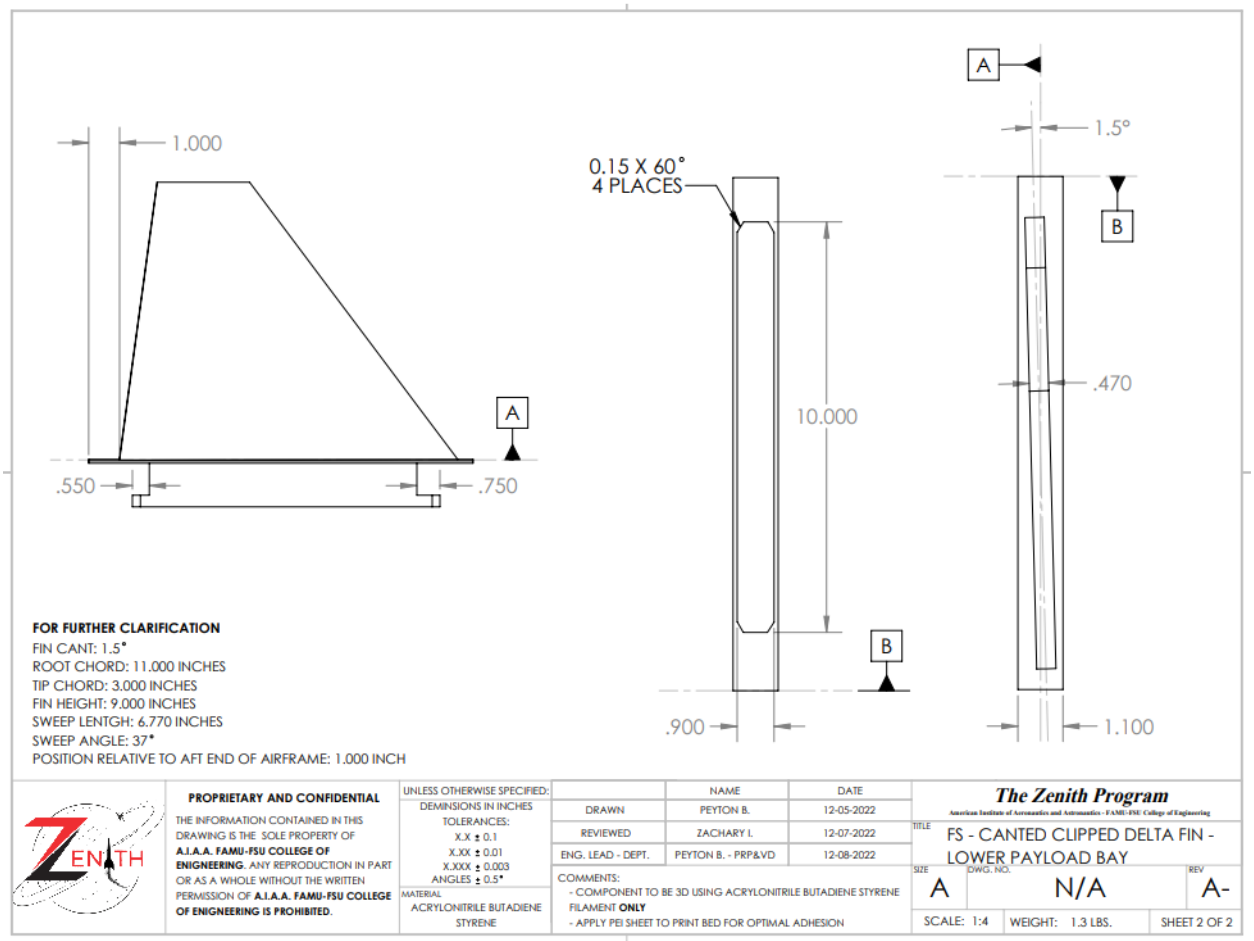



***Figure 3-28. Canted Clipped Delta Fin CAD Drawing Sheet 2 of 2***

Previously mentioned in PDR, a rising concern with using ABS as the material of choice was the fin flutter speed. To triple check our fin design for the final vehicle design, the fin flutter speed was calculated again. Shown below is the equation used to find the fin flutter speed, along with the variables and their calculated values.

$$V_f = a\sqrt{\frac{G}{\frac{1.337AR^3P(l+1)}{2(AR+2)\left(\frac{t}{c}\right)^3}}}$$

The variables in the equation are defined below along with their calculated values. The MATLAB code used to calculate these values and the flutter speed is attached as Appendix C.

***Table 3-1. Fin Flutter Speed Parameters***

| Fin Flutter Speed | | | |
|---|---|---|---|
| **Parameter** | **Symbol** | **Value** | **Unit** |
| Speed of Sound | $a$ | 1098.9 | ft/s |
| Shear Modulus | $G$ | 151920 | lb/in^2 |
| Aspect Ratio | $AR$ | 1.0714 | |
| Pressure | $P$ | 12.44 | lb/in^2 |
| Taper Ratio | $l$ | 0.2727 | |
| Fin Thickness | $t$ | 0.47 | inches |
| Root Chord | $c$ | 11 | inches |
| Fin Flutter Speed | $V_f$ | 1446.3 | ft/s |

***Table 3-2. Fin Flutter Speed Results***

| | |
|---|---|
| **Max Vehicle Speed:** | 545 ft/s |
| **Fin Flutter Speed:** | 1446.3 ft/s |
| **Percent Flutter Speed Achieved:** | 38% |
| **Factor of Safety:** | 2.65 |

The centering rings used for the thrust structure will be fabricated from Baltic Birch plywood. The two forwards are 0.5 inches thick and the aft centering rings is 0.375 inches thick. Both forward centering rings are epoxied to the motor tube and the inner airframe while the aft centering ring is held in place by the threaded rods. Shown below is a labeled image of the thrust structure showing which centering rings are epoxied for further clarification.

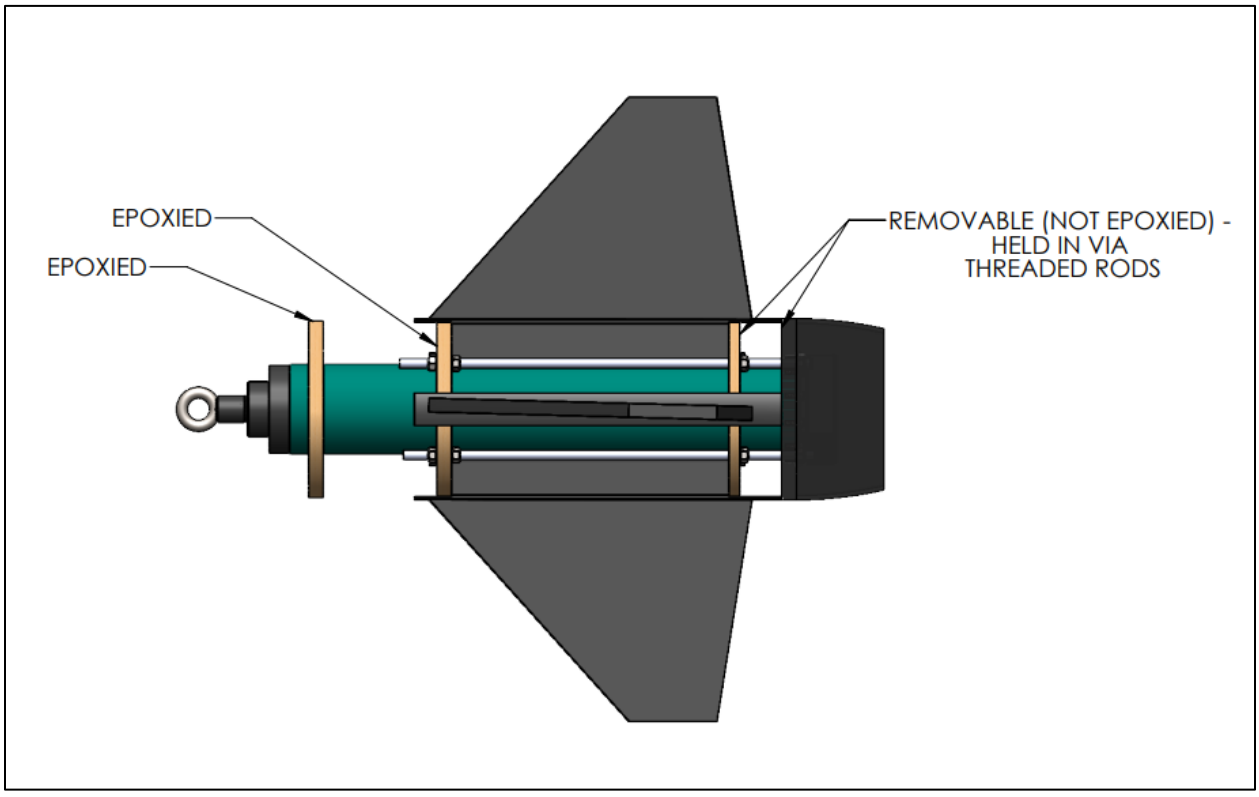



***Figure 3-29. Fin Can Assembly CAD Drawing 2***

The aft centering ring and the thrust plate/tail cone configuration were designed to be removable to allow the fins to slide out of the vehicle for modularity purposes. Simply remove the threaded rods from vehicle and the thrust plate will no longer be attached to the vehicle, allowing the aft centering ring to slide out of the vehicle. This will enable the fins to be removed from the vehicle and quickly replaced in the case of fin failure during assembly or testing.

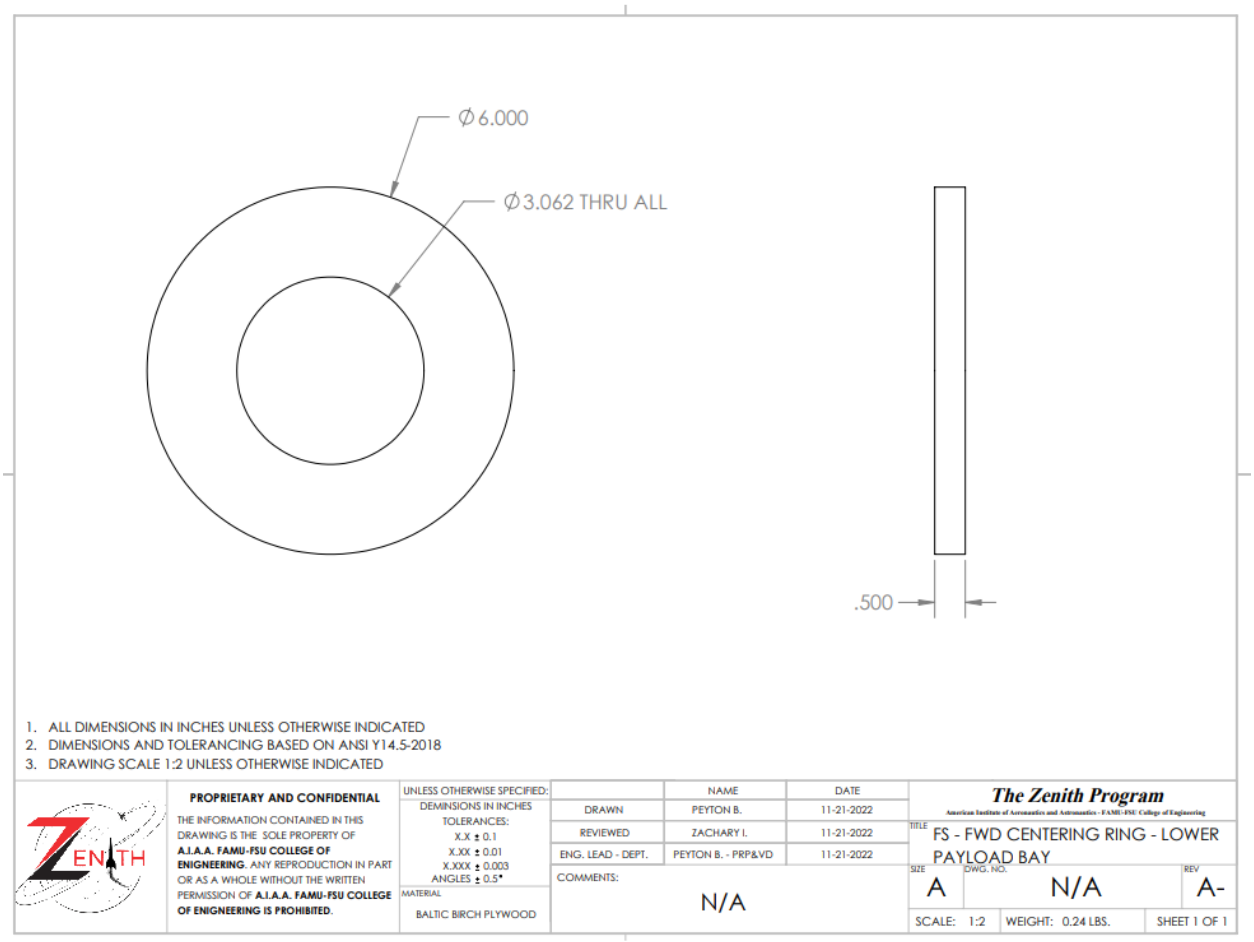



***Figure 3-30. Forward Centering Ring CAD Drawing***

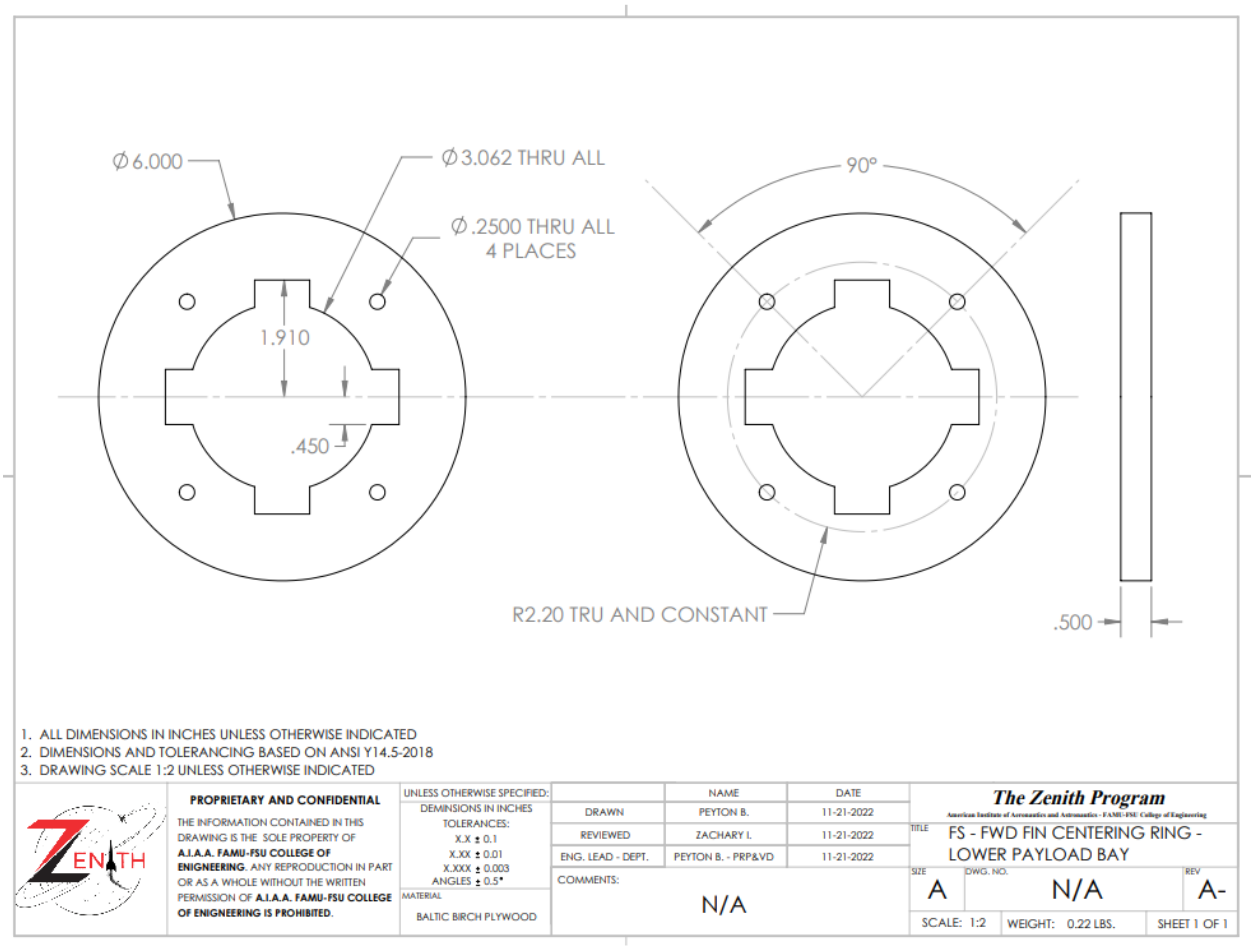



***Figure 3-31. Forward Fin Centering Ring CAD Drawing***

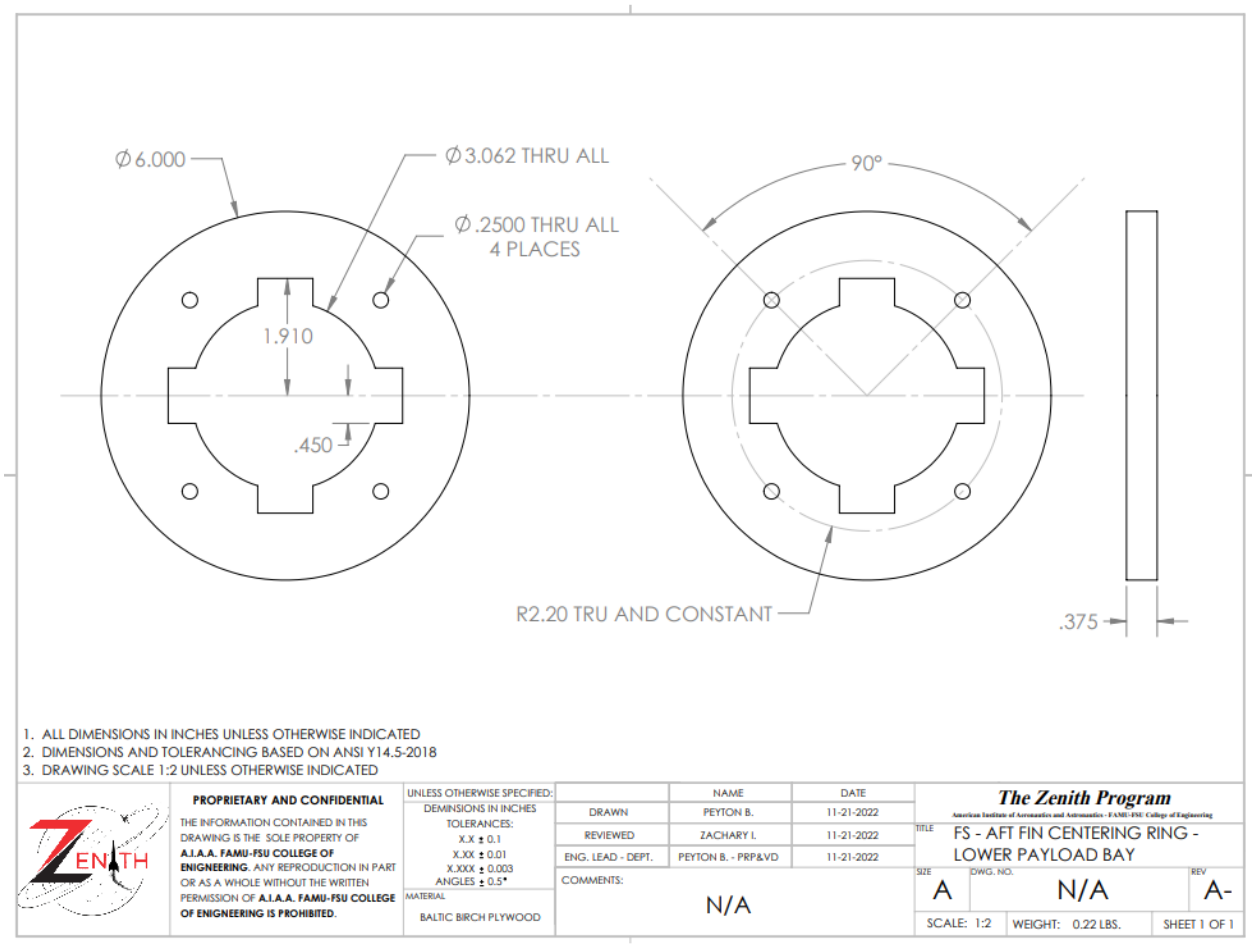



***Figure 3-32. Aft Fin Centering Ring CAD Drawing***

As previously mentioned, the thrust plate and tail cone configuration will be removable. The thrust plate and tail cone will be 3D printed as a whole component using ABS and will be held to the vehicle by the threaded rods. The flanged motor retainer body will be screwed to the 3D printed thrust plate using twelve 6# - 32 x ½" socket head cap screws.

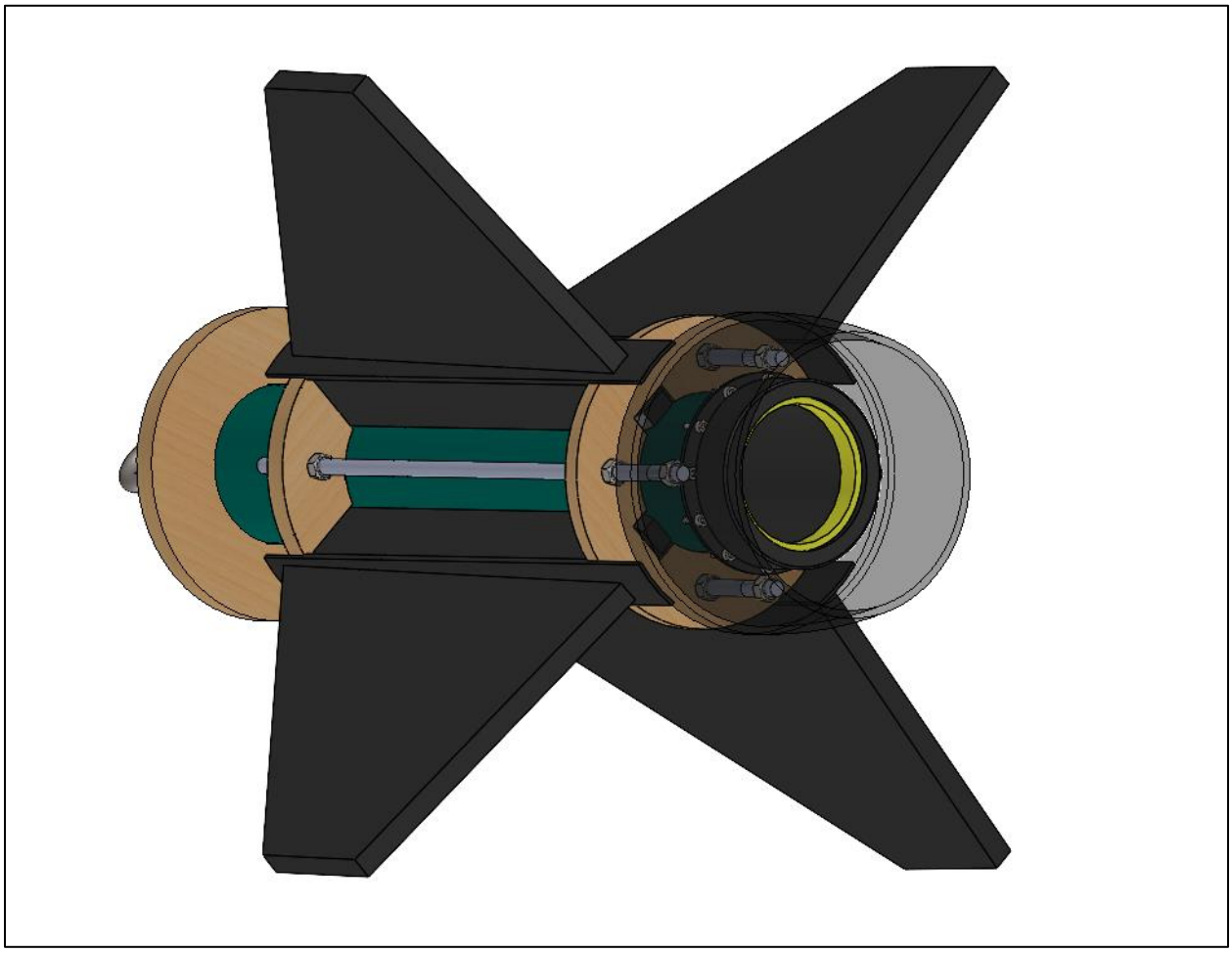


***Figure 3-33. Fin Can Assembly w/ Transparent Tail Cone***

The original leading design alterative discussed in PDR used an aluminum thrust plate and the team was considering using a tail cone to reduce the wake drag at the aft end of the vehicle. However, the weight of using an aluminum thrust plate is much heavier than a thrust plate printed from ABS. The aluminum thrust plate weighed 0.83 lb (380 g) at a thickness of 0.375 inches versus the ABS thrust plate weighing 0.43 lb (197 g) at a thickness of 0.5 inches. The decrease in weight raised the vehicle's stability margin and ultimately saved our team money on material and manufacturing costs. The newest and final design for the thrust plate and tail cone configuration shown below (not including the flanged motor retainer) and 3D printed at a 90% infill density weighs 0.73 lb (330 g). The thickness of the thrust plate is 0.5 inches, and the length of the tail cone is 3 inches.

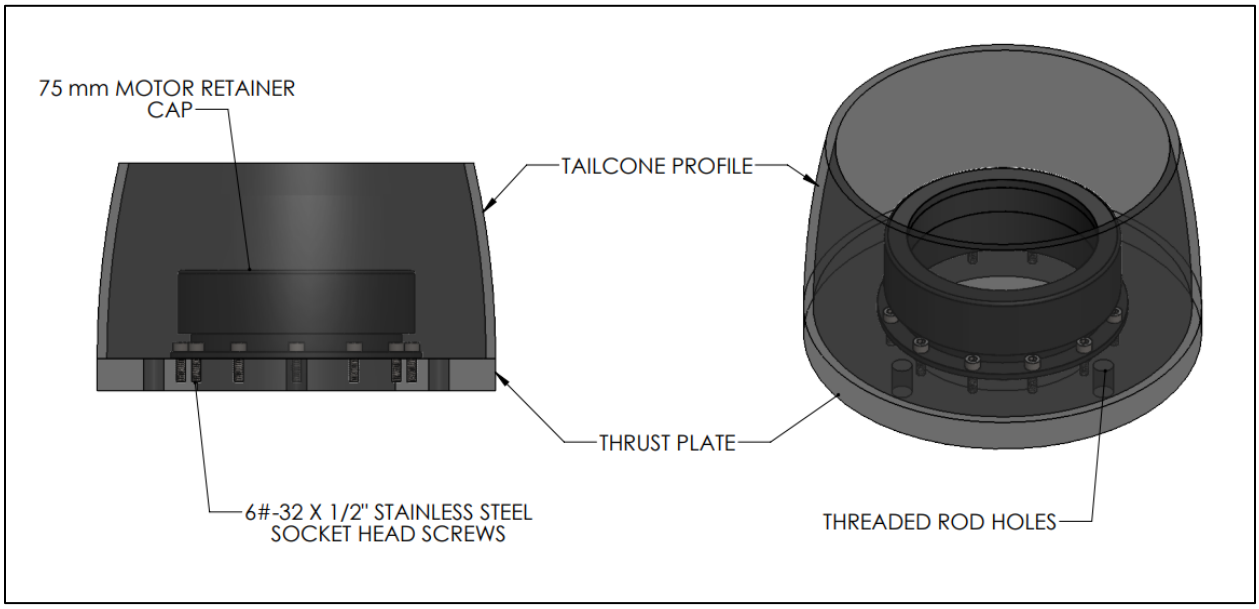



***Figure 3-34. Tail Cone CAD Model***

In traditional tail cone designs, the tail cone profile is much longer in order to act as a motor retainer. The length of the tail cone for our final design has been shortened and will not act as a motor retainer. The tail cone was implemented into the vehicle's designed to prevent the aft end wake of the vehicle and enhance the overall aesthetic. The length was shortened to prevent any direct contact to the exhaust flame during flight that could cause the ABS to melt. To take extra precaution, fiberglass sheets will be formed around the inner surface of the tail cone to reduce the amount of heat transfer to the ABS. The diameter of the thrust plate is the same diameter as the outer diameter of the vehicle's airframe and the tail cone's curvature is tangent to the vehicle's outer airframe surface. As the vehicle is launched, the thrust load will be transferred to the airframe as the thrust plate pushes against the aft end of the airframe.

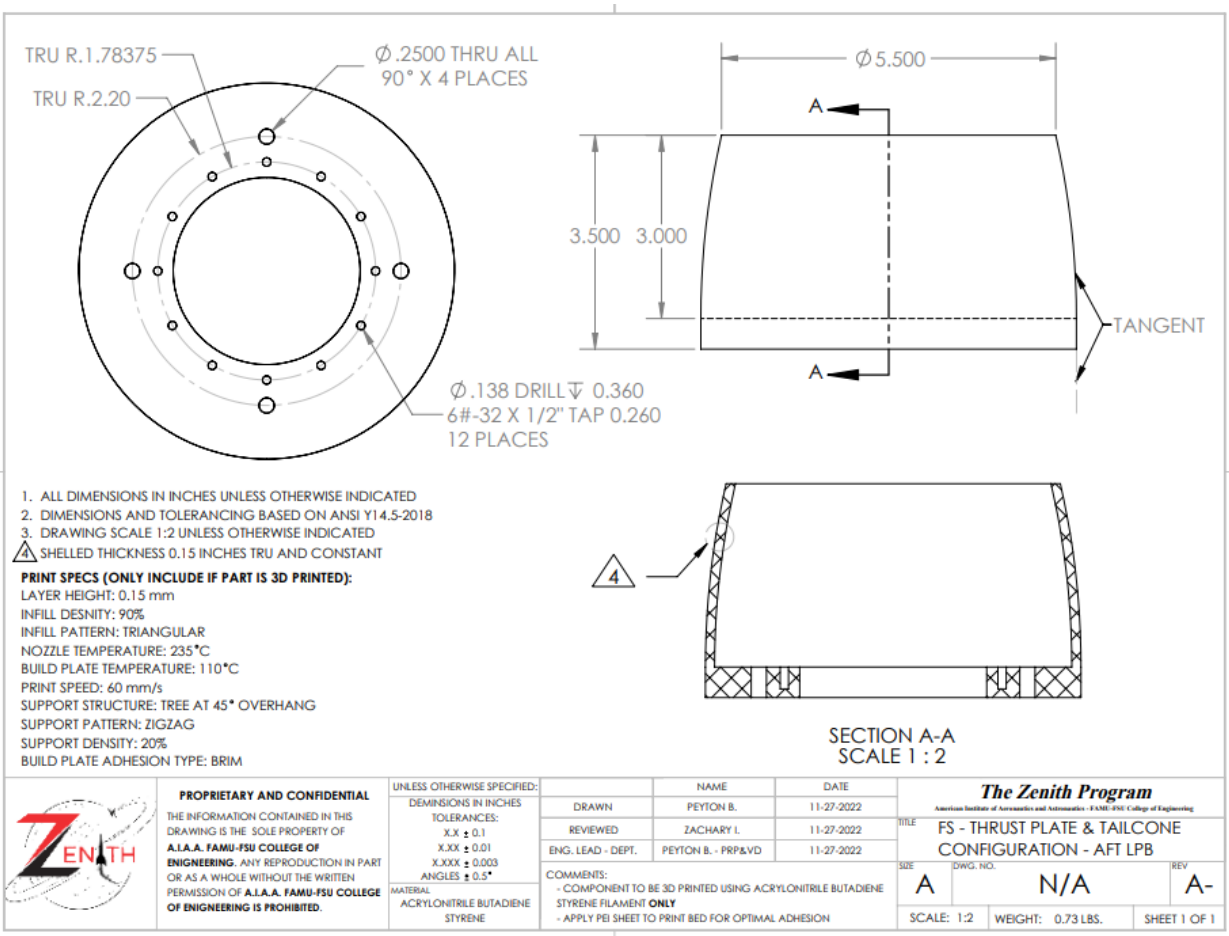



***Figure 3-35. Tail Cone CAD Drawing***

### 3.1.4 Manufacturing and Assembly

#### 3.1.4.1 3D Printed Components

One of the considerations that must be made when creating a part with additive manufacturing (especially FDM 3D printing) is the orientation in which the part is printed. The print orientation is important because it will determine which plane the layers of a part are built up in. A majority of printed parts on this vehicle will be made of ABS plastic. When ABS is 3D printed, the bonds that hold layers to each other are weaker in tension than the material itself, therefore 3D printed ABS components will be the strongest when force is applied parallel to the print planes.

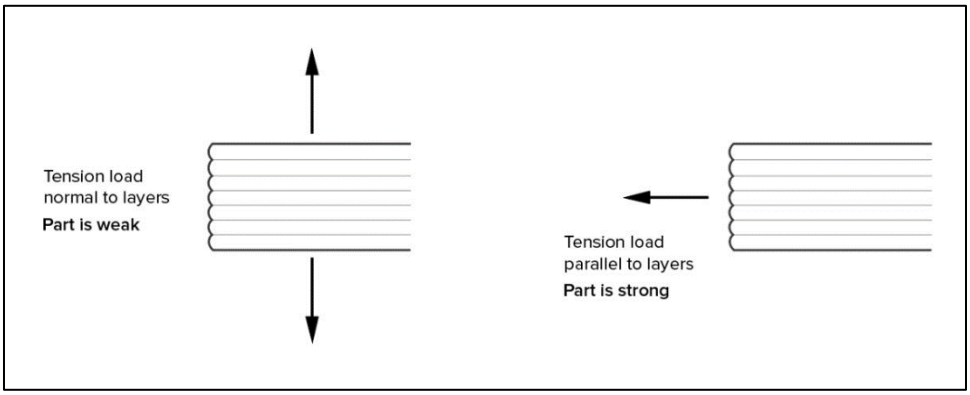



***Figure 3-36. ABS Strength Characteristics***

Printed ABS parts are strong and will maintain all desired dimensions if printed correctly, but some components will require post-processing to function properly. Because the prints are weakest perpendicular to the layer planes, post-processing can strengthen the connection between layers, normalizing the strength of the part. ABS melts when exposed to acetone, so immersing parts in an acetone vapor bath can fuse the outermost layers together. In addition to acetone smoothing, printed components can be coated with a thin layer of epoxy resin to build a hard outer shell to parts.

In order to quantify the effects that layer orientation and post-processing hardening methods have on the strength of the parts, a number of tests will be run. These tests will include a Short Beam Shear (SBS) test, an Izod hardness test, and applying measured forces on full scale parts. The SBS test will involve a small sample cuboid (8mm x 24mm x 4mm) being held between 2 notches, then applying a measured shear load to the sample. The SBS test is expected to provide helpful results as to how print orientation affects shear strength, but the small size of the samples limits the ability to test how different infill patterns and density will affect the parts. In order to learn about the factors not accounted for in the SBS test, an Izod hardness test will be conducted. The Izod hardness test involves impacting a notched specimen to observe fracture. Results from the SBS test will be considered when interpreting Izod data, to verify if results are due to layer orientation or infill qualities.

Testing of full-scale parts will be done by adding hanging weights to a part, and hopefully with a wind tunnel. Applying weight to a print allows for the part to be mounted in a similar fashion to how it will be on the vehicle, and the limits of each component will be accurately assessed. The wind tunnel (if tests are able to be completed) will allow for a better understanding of flow properties than could be secured with CFD. The use of a wind tunnel will also allow for testing of components to see if uncoated prints will “peel” layers away at high velocities, as well as if coated prints will flake off surface ABS or any epoxy resin coat. The nosecone, fins, and thrust plate/tail cone will be printed on a BIQU BE SE Plus 3D printer using ABS filament. To account for ABS deformation during the print, polyetherimide (PEI) adhesive sheets will be placed on

the printing bed for optimal adhesion. PEI sheets were used for the subscale components and will be replicated in printing the full-scale components.

(a) Nosecone

The subscale nosecone was printed as two parts: the nosecone profile, and the shoulder. The shoulder piece is 2.25 inches in length and had a threaded coupling end to screw into the receiving end of the nosecone component. The nosecone profile was 10 inches in length and is shown below.

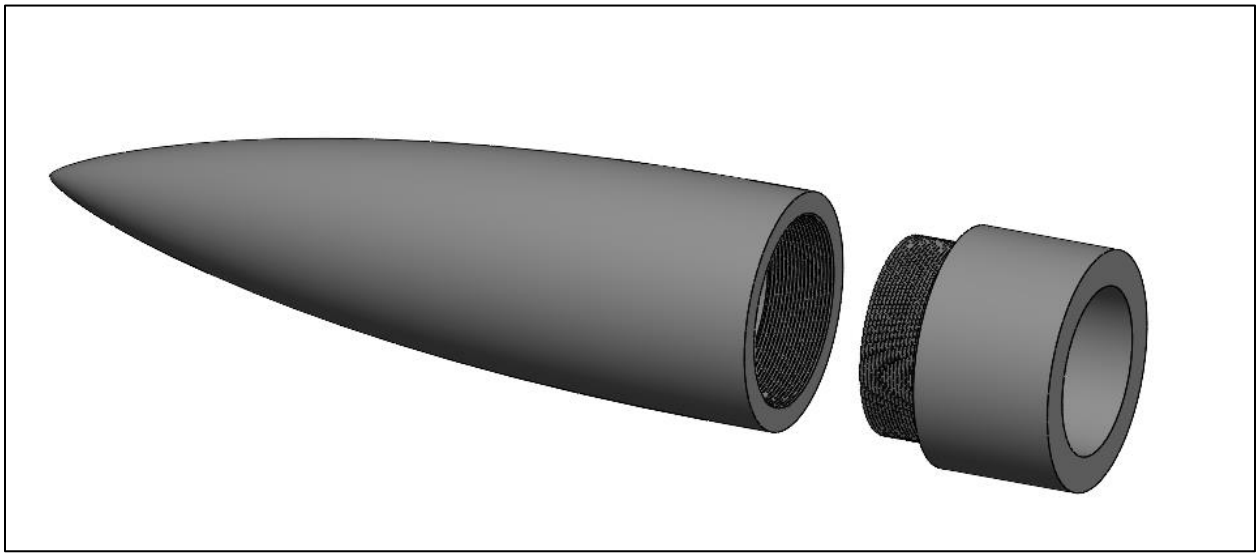


***Figure 3-37. Subscale Launch Vehicle Nosecone***

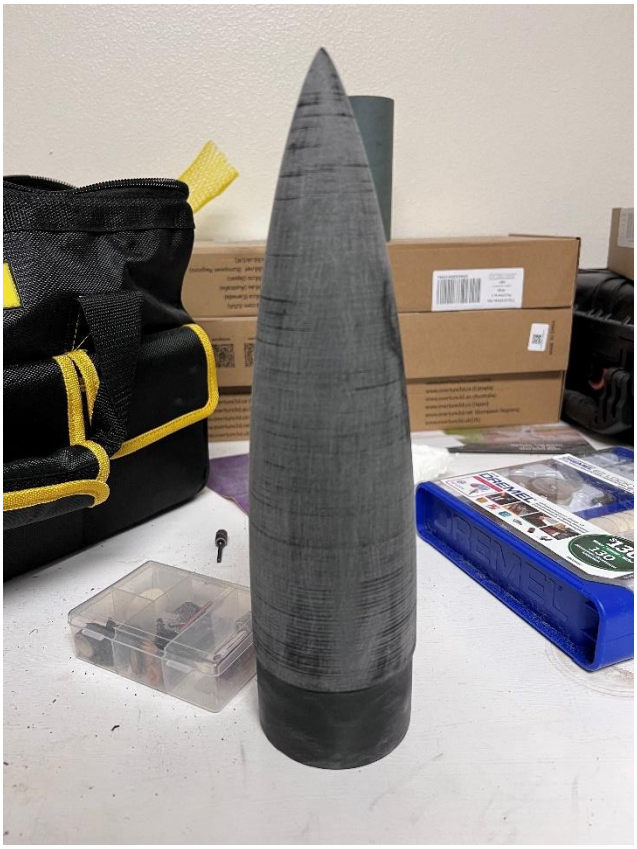



***Figure 3-38. Subscale Launch Vehicle 3-D Printed LD-Haack Nosecone***

The printing orientation plays a big role in the performance of the print, the nose cone for both the subscale and the full-scale vehicle are printed vertically. With printing ABS, there will more than likely be some deformation regardless of how insulted the machine is or how much adhesion is provided to the part. To account for this, the base of the nosecone shoulder and the profile was printed 3/8” longer than the actual model so that the team could sand down the base to ensure a smooth and flat base at the exact length simulated in OpenRocket and modeled in SolidWorks. Shown below is the orientation and print specifications for the subscale and full-scale nosecone using Ultimaker Cura software.

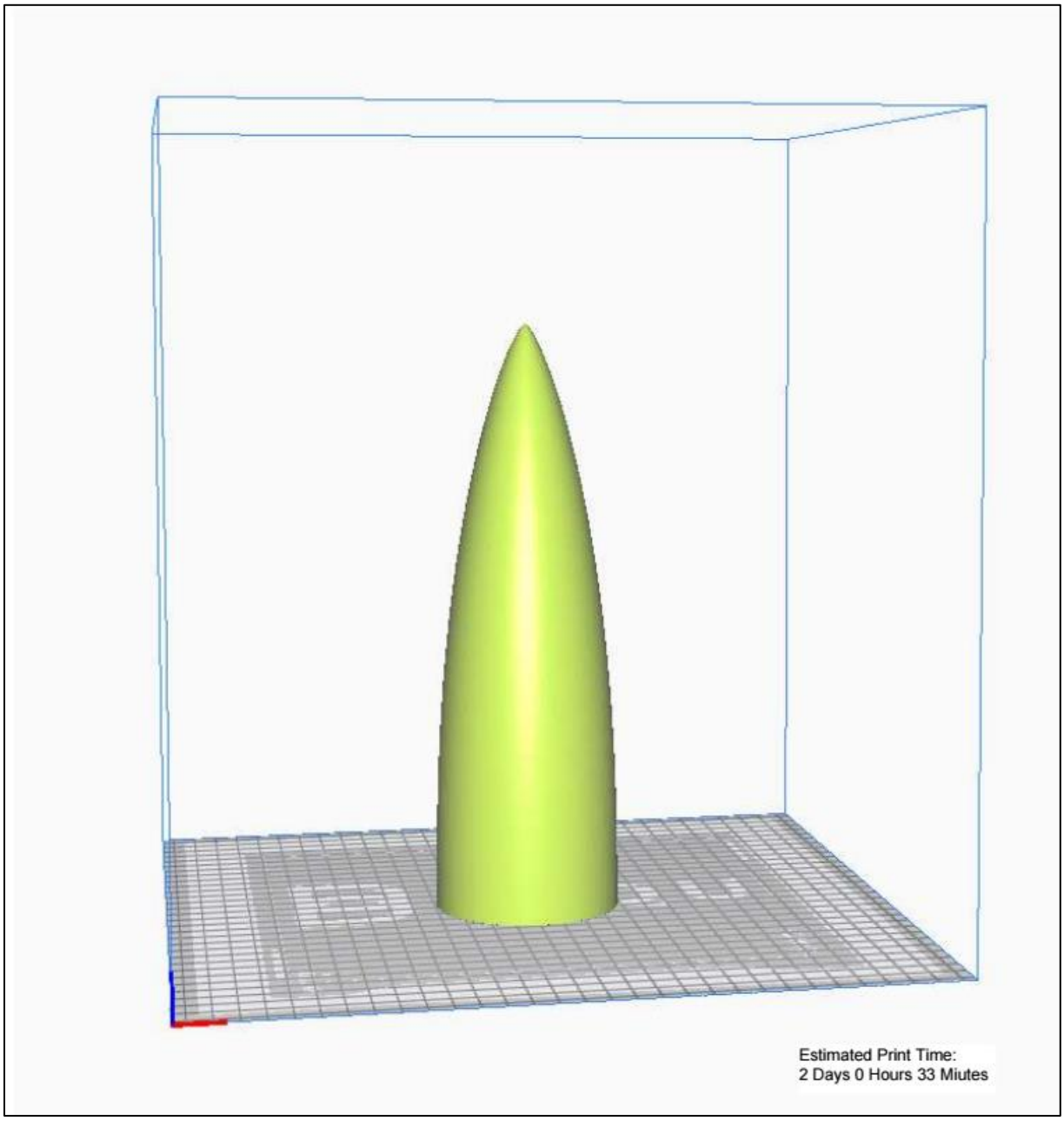



***Figure 3-39. Subscale Nosecone Assembly***

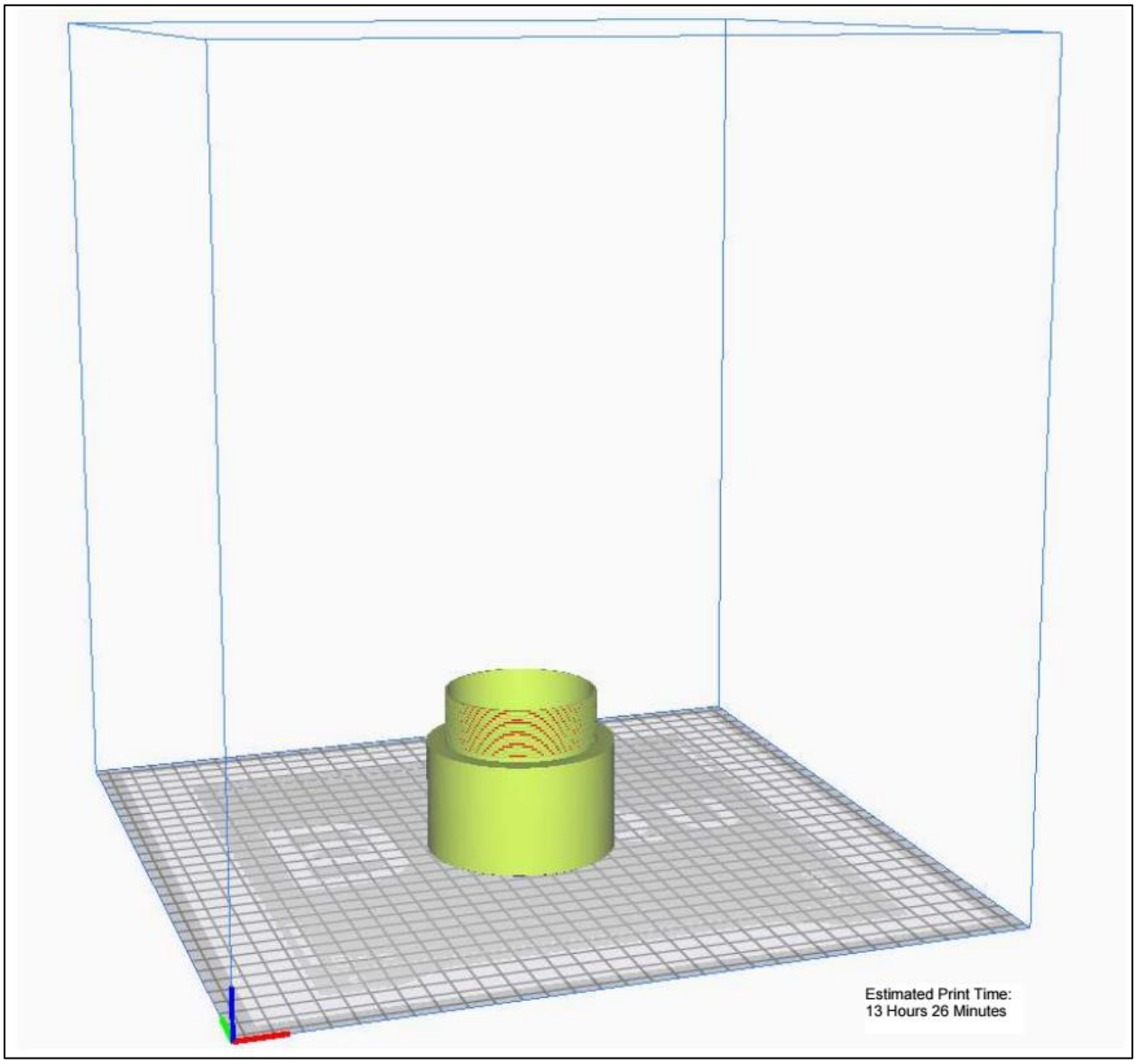



***Figure 3-40. Subscale Nosecone Shoulder***

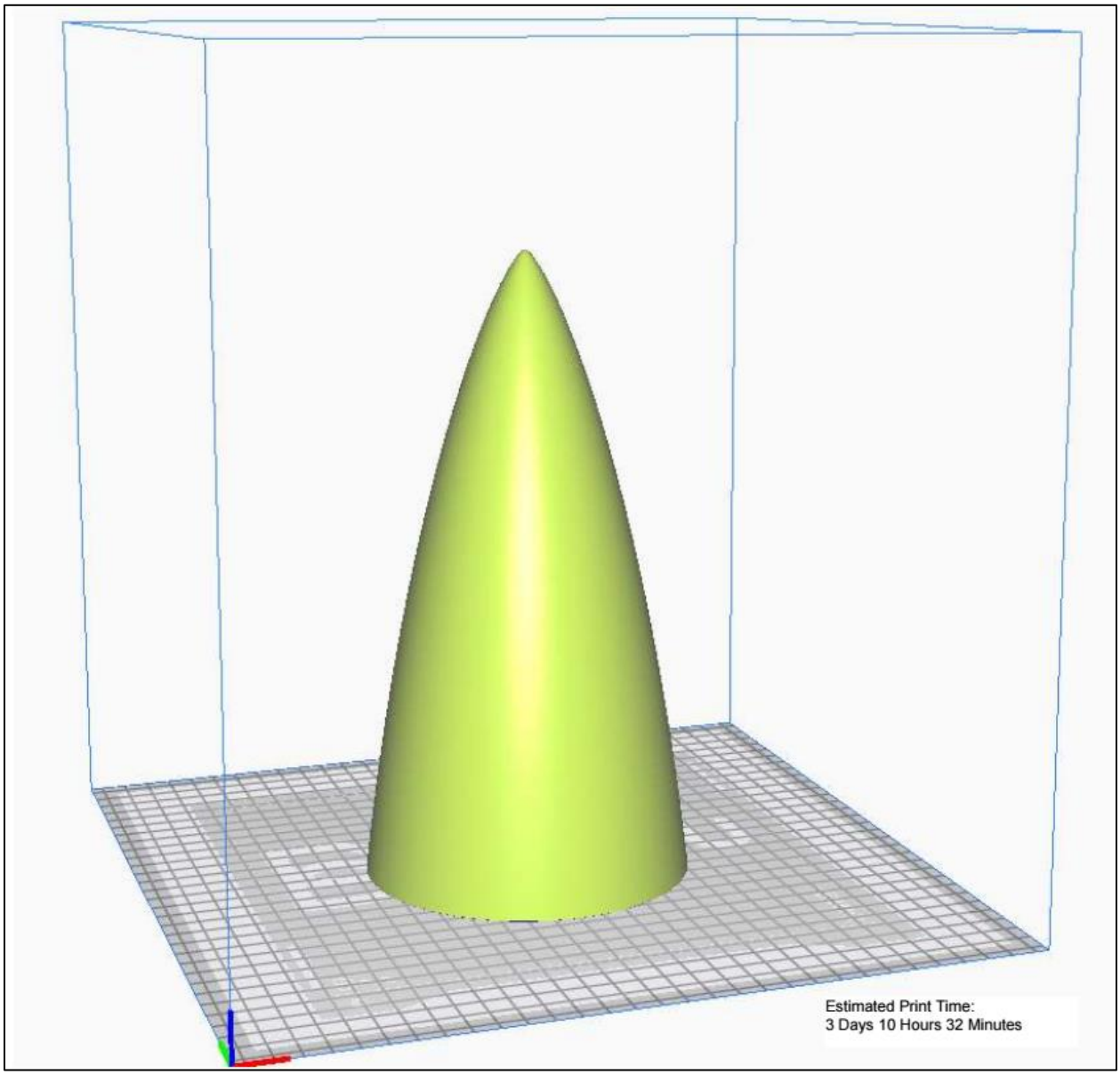



***Figure 3-41. Full Scale Nosecone Cap***

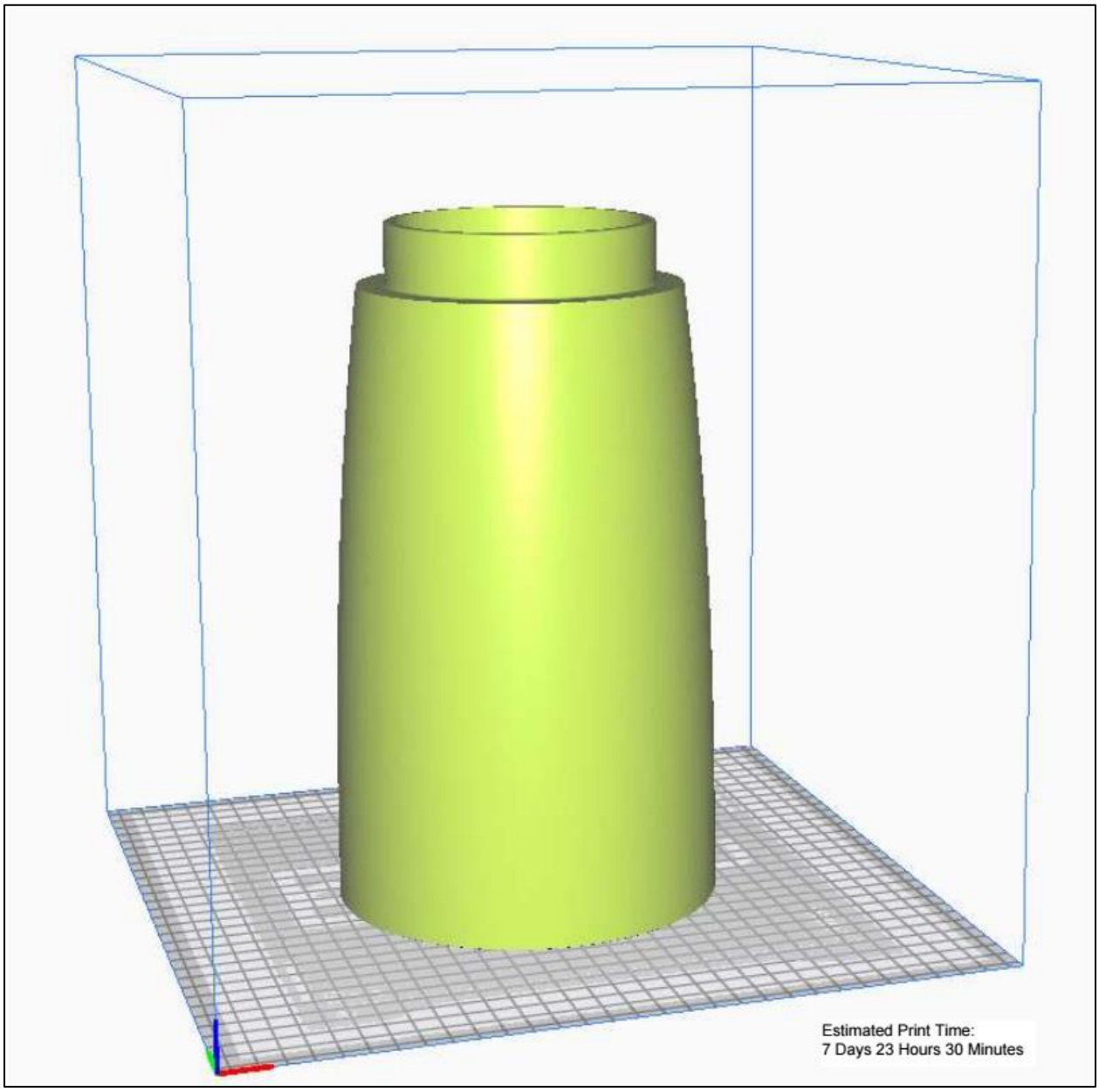



***Figure 3-42. Full Scale Nosecone Midsection***

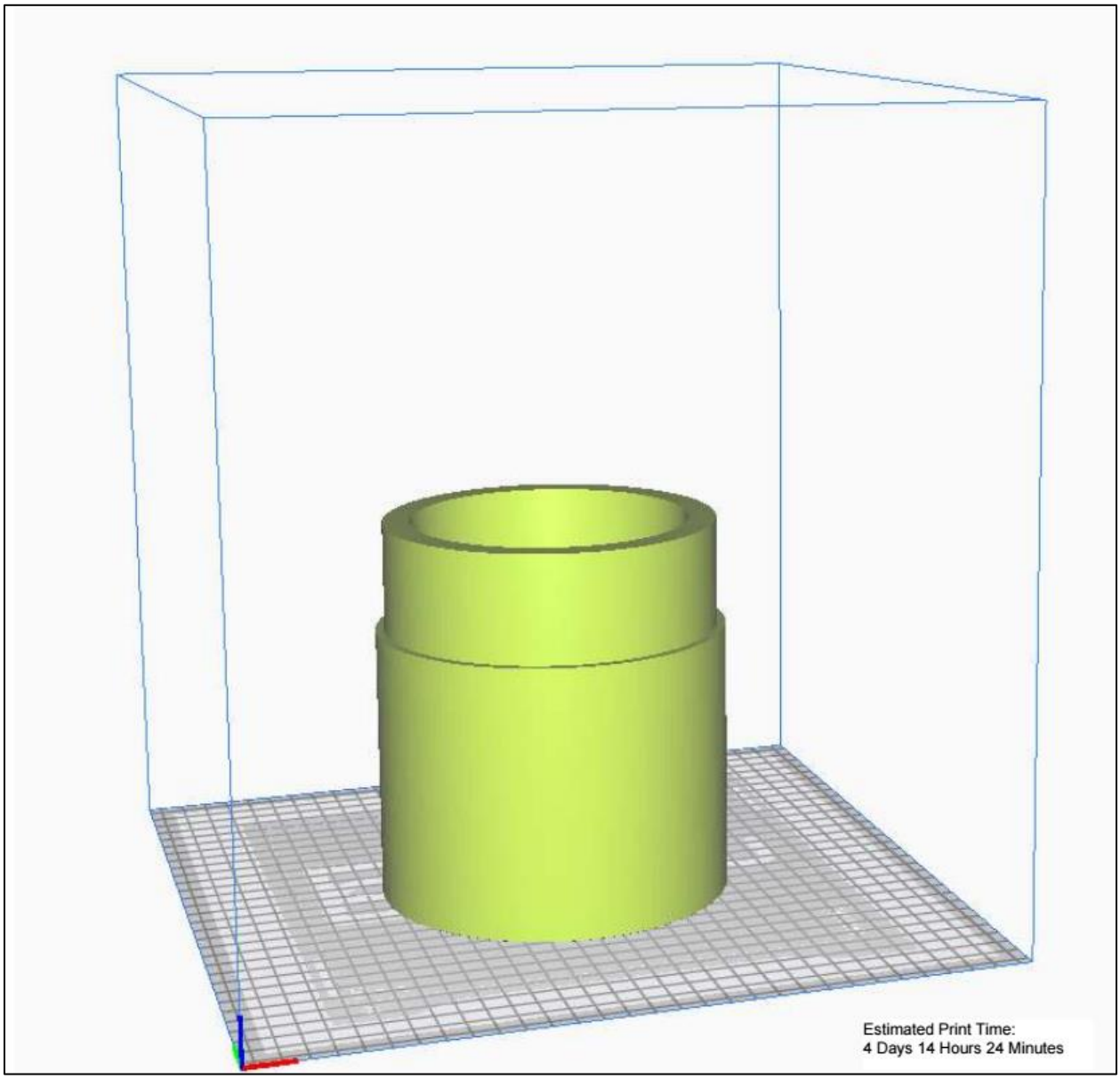



***Figure 3-43. Full Scale Nosecone Shoulder***

**NOTE: The printing specifications shown below will be used for the full-scale vehicle nose cone due to successful subscale print.**

| Ultimaker Cura Printing Specifications | |
|---|---|
| Layer Height | 0.15 mm |
| Infill Density | 85% |
| Infill Pattern | Triangular |
| Nozzle Temperature | 235°C |
| Build Plate Temperature | 110°C |
| Print Speed | 60 mm/s |
| Support Structure | Tree Structure at 45° Overhang |
| Support Pattern | Zigzag |
| Support Density | 10% |
| Build Plate Adhesion Type | 10 mm thick Brim |

(b) Fins

The subscale fin shown below represents a ½ scale of the full-scale fin.

***Figure 3-44. 3-D Printed Subscale Fin***

Looking at the image above, the subscale fin experienced a small amount of deformation at the fin tab base and the fin root chord base. Many different printing methods were used to try and counteract the deformation such as PEI adhesion printing sheets, different printing structural supports, and different print speeds. Figure 3-44 shows the best print of the many attempts. So, the printing specifications used for the 3D printed fin show in figure 3-44 were the print specifications used for the rest of the fins. PETG will be ordered and printed to compare fin prints between ABS and PETG to further our 3D printing study. Shown below is the fin assembly used for the subscale flight.

***Figure 3-45. Subscale Fins Installed***

Looking at the image above, electrical tape was put in the base of the fins and the airframe to form a flush surface between the fin base and the outer surface of the airframe. The electrical tape provided successful results in terms of fin performance; however, the full-scale 3D printed fins will guarantee a non-deformed, flush fit with the fins into the fin slots. Shown below is the orientation and print specifications for the subscale and full-scale fins using Ultimaker Cura software.

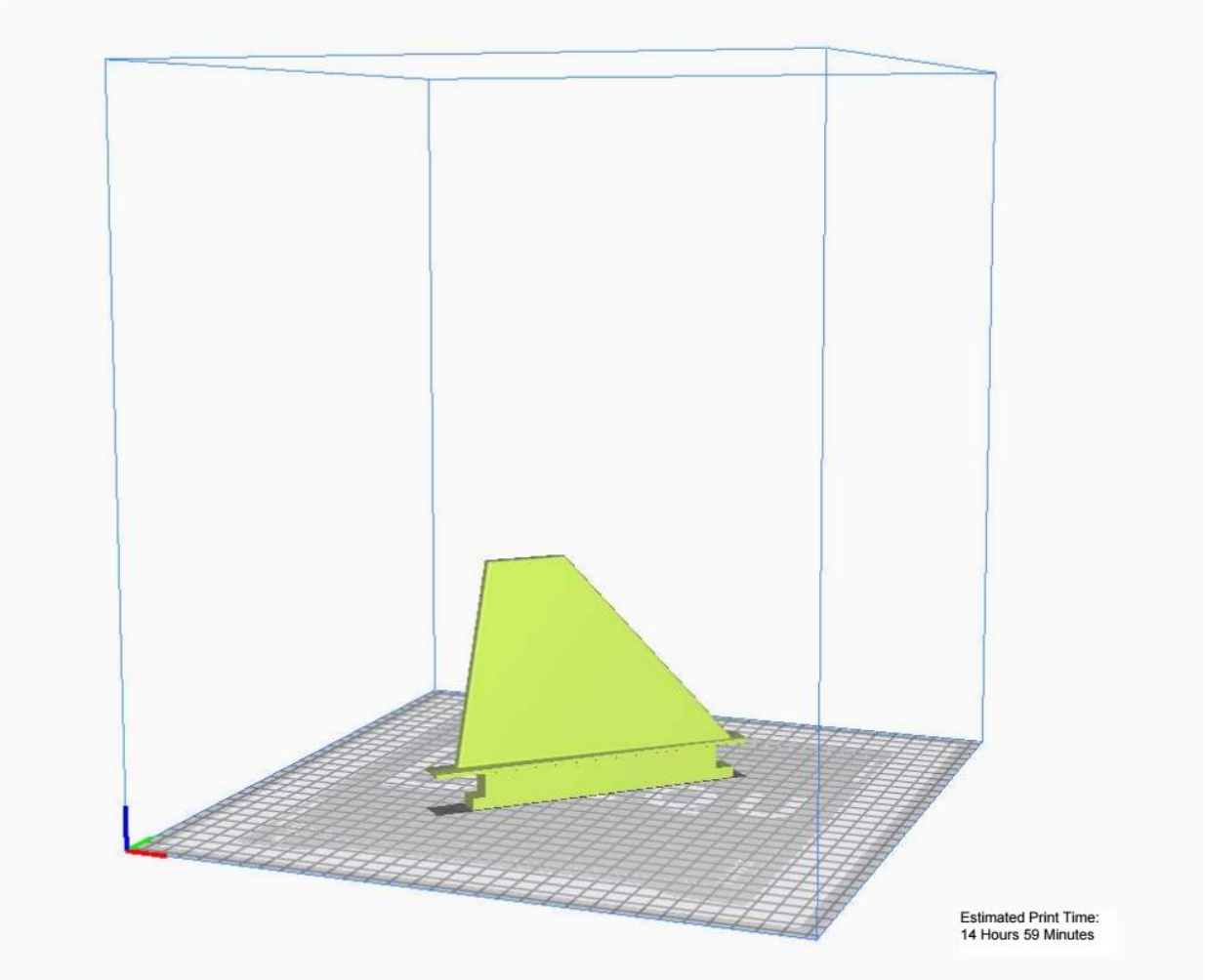



***Figure 3-46. Subscale Fin***

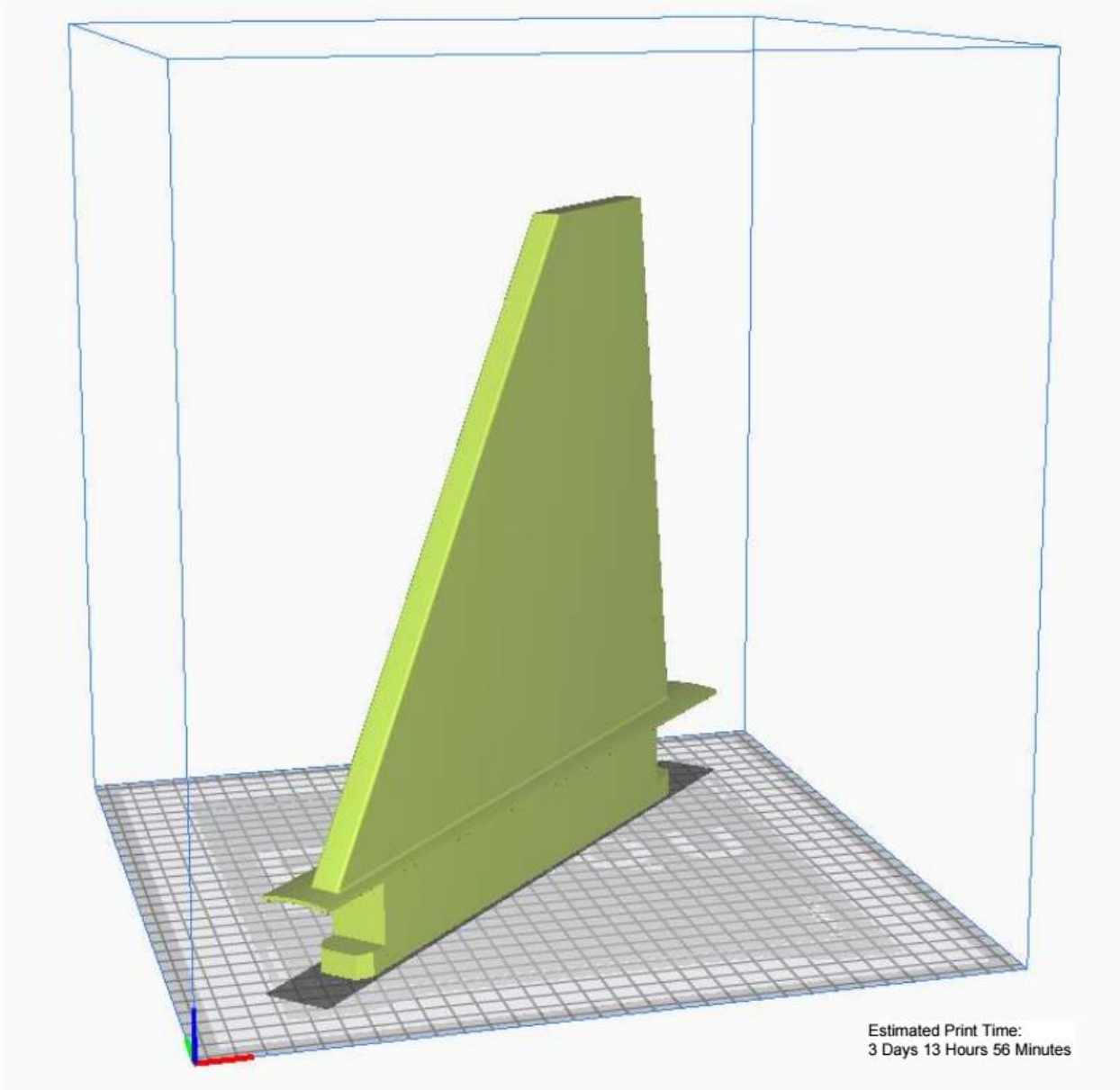



***Figure 3-47. Full Scale Fin***

| Ultimaker Cura Printing Specifications – SUBSCALE VEHICLE | |
|---|---|
| Layer Height | 0.15 mm |
| Infill Density | 85% |
| Infill Pattern | Triangular |
| Nozzle Temperature | 235°C |
| Build Plate Temperature | 110°C |
| Print Speed | 60 mm/s |
| Support Structure | Normal Structure at 45° Overhang |
| Support Pattern | Zigzag |
| Support Density | 10% |
| Build Plate Adhesion Type | 10 mm thick Brim |

The infill density for the full-scale fins will be less than the subscale. The infill density was lowered to improve the stability margin during the OpenRocket simulation phase of the final full-scale design.

| Ultimaker Cura Printing Specifications – FULL-SCALE VEHICLE | |
|---|---|
| Layer Height | 0.15 mm |
| Infill Density | 72% |
| Infill Pattern | Triangular |
| Nozzle Temperature | 235°C |
| Build Plate Temperature | 110°C |
| Print Speed | 60 mm/s |
| Support Structure | Normal Structure at 45° Overhang |
| Support Pattern | Zigzag |
| Support Density | 20% |
| Build Plate Adhesion Type | 10 mm thick Brim |

(c) Tail Cone and Thrust Plate Configuration

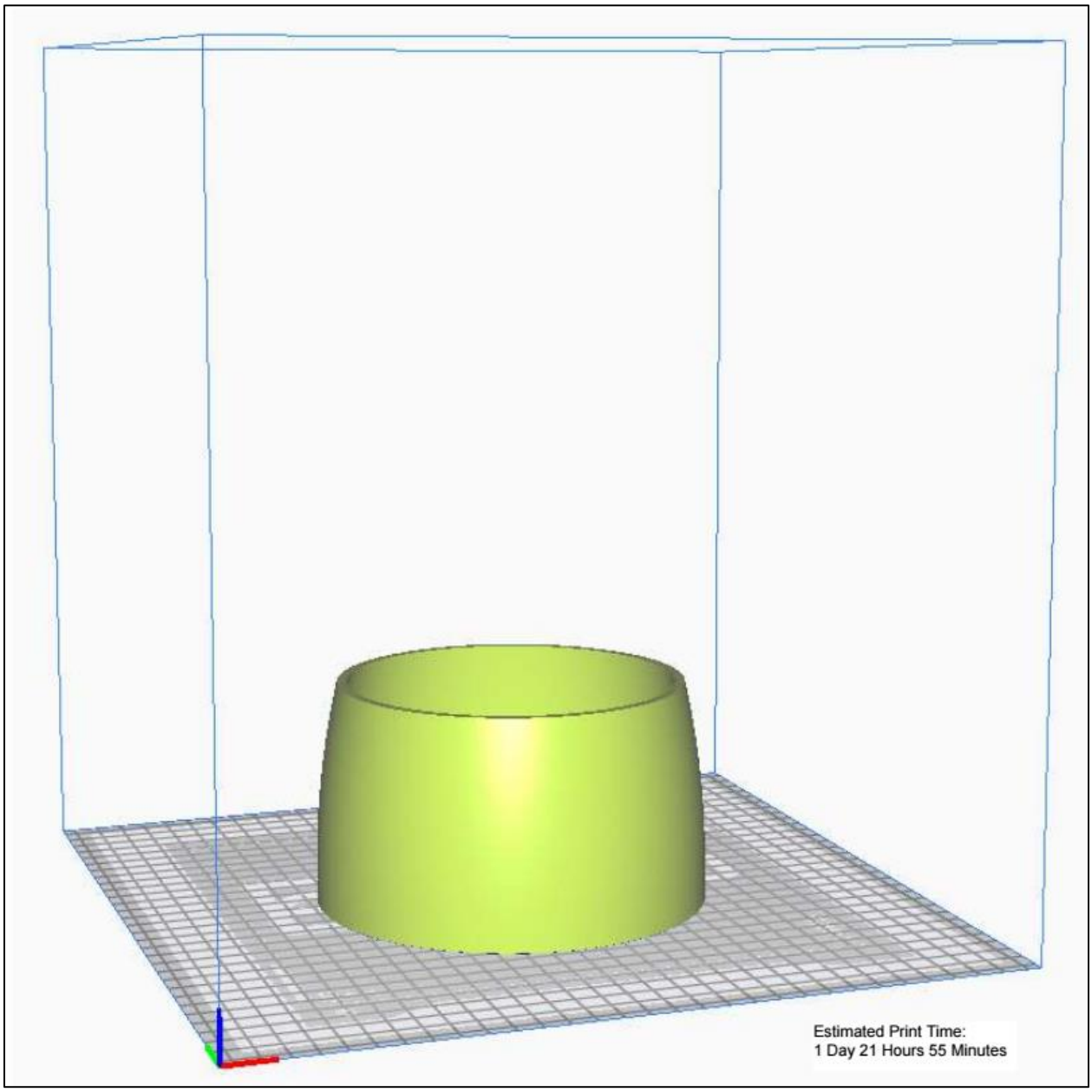



***Figure 3-48. Integrated Thrust Plate and Tail Cone***

| Ultimaker Cura Printing Specifications – FULL-SCALE VEHICLE | |
|---|---|
| Layer Height | 0.15 mm |
| Infill Density | 90% |
| Infill Pattern | Triangular |
| Nozzle Temperature | 235°C |
| Build Plate Temperature | 110°C |
| Print Speed | 60 mm/s |
| Support Structure | Tree Structure at 45° Overhang |
| Support Pattern | Zigzag |
| Support Density | 20% |
| Build Plate Adhesion Type | 10 mm thick Brim |

#### 3.1.4.2 Airframe Cutting

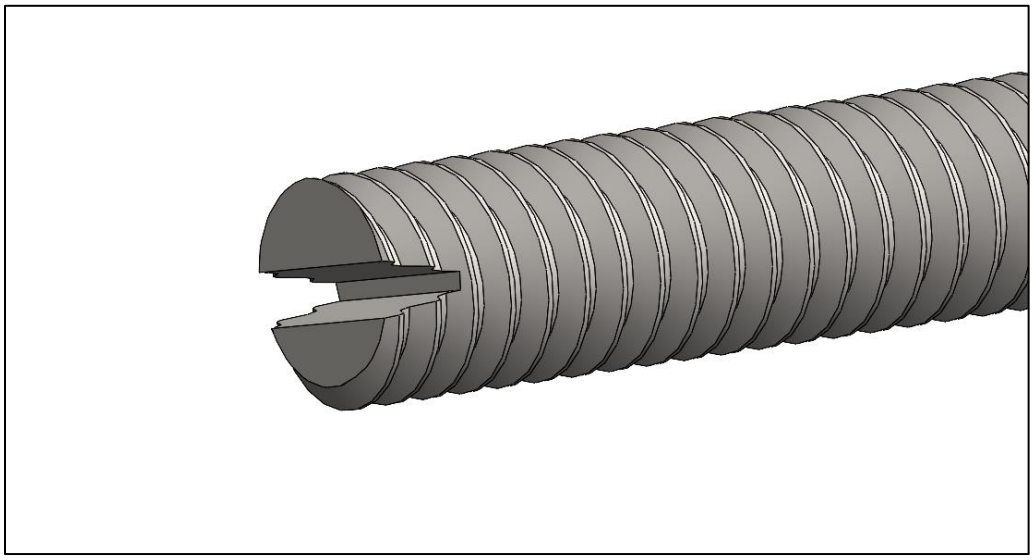
The airframe will be cut to size using a Dremel and Metal Wood cutting wheel attachment. After The airframe sections have been cut to size, the lower payload bay airframe will be sent to the FAMU-FSU COE's in housing manufacturing facility for professional personnel to cut the fin base slots. All other small holes and construction add-ons will be manufactured by the student team under faculty supervision.

#### 3.1.4.3 Bulkhead and Centering Ring Fabrication

The bulkheads and centering rings will be cut using an in-house CNC wood router. After the bulkheads/centering rings have been CNC'd, sandpaper will be used to sand down any rough surfaces or edges.

#### 3.1.4.4 Threaded Rods

The threaded rods for the avionics bay will be delivered in the correct length to accommodate the avionics bay. However, the threaded rods for the thrust structure will be cut to the appropriate size using a Dremel and disk cutting bit. The face at the end of each rod will be cut to replicate a flat head screwdriver. This allows the rods to be taken much quicker using a flat head screwdriver opposed to twisting the rods by hand until free.



### 3.1.5 Finite Element Analysis

Finite Element Analysis (FEA) simulations were ran on the nose cone bulkhead and the upper payload bay avionics bay bulkhead to ensure that the stress experienced on the bulkhead and U-bolt under recovery system loads will not cause any component failures. The FEA simulations were run in SolidWorks. Shown below are the material properties for each component. The properties found for Baltic Birch plywood were found online and the properties for the U-bolt were already in the SolidWorks database.

| AISI 304 Stainless Steel | | |
|---|---|---|
| Material Property | Value | Unit |
| Elastic Modulus | 27557170.16 | psi |
| Poisson's Ratio | 0.29 | N/A |
| Shear Modulus | 10877830.32 | psi |
| Mass Density | 0.28902 | lb/in^3 |
| Tensile Strength | 74986.976 | psi |
| Yield Strength | 29994.819 | psi |

| Baltic Birch Plywood | | |
|---|---|---|
| Material Property | Value | Unit |
| Elastic Modulus | 435113.1016 | psi |
| Poisson's Ratio | 0.35 | N/A |
| Shear Modulus | 101526 | psi |
| Mass Density | 0.026 | lb/in^3 |
| Tensile Strength | 14503.8 | psi |
| Compressive Strength | 3727.47 | psi |

### 3.1.5.1 Nose Cone Forward Bulkhead U-Bolt

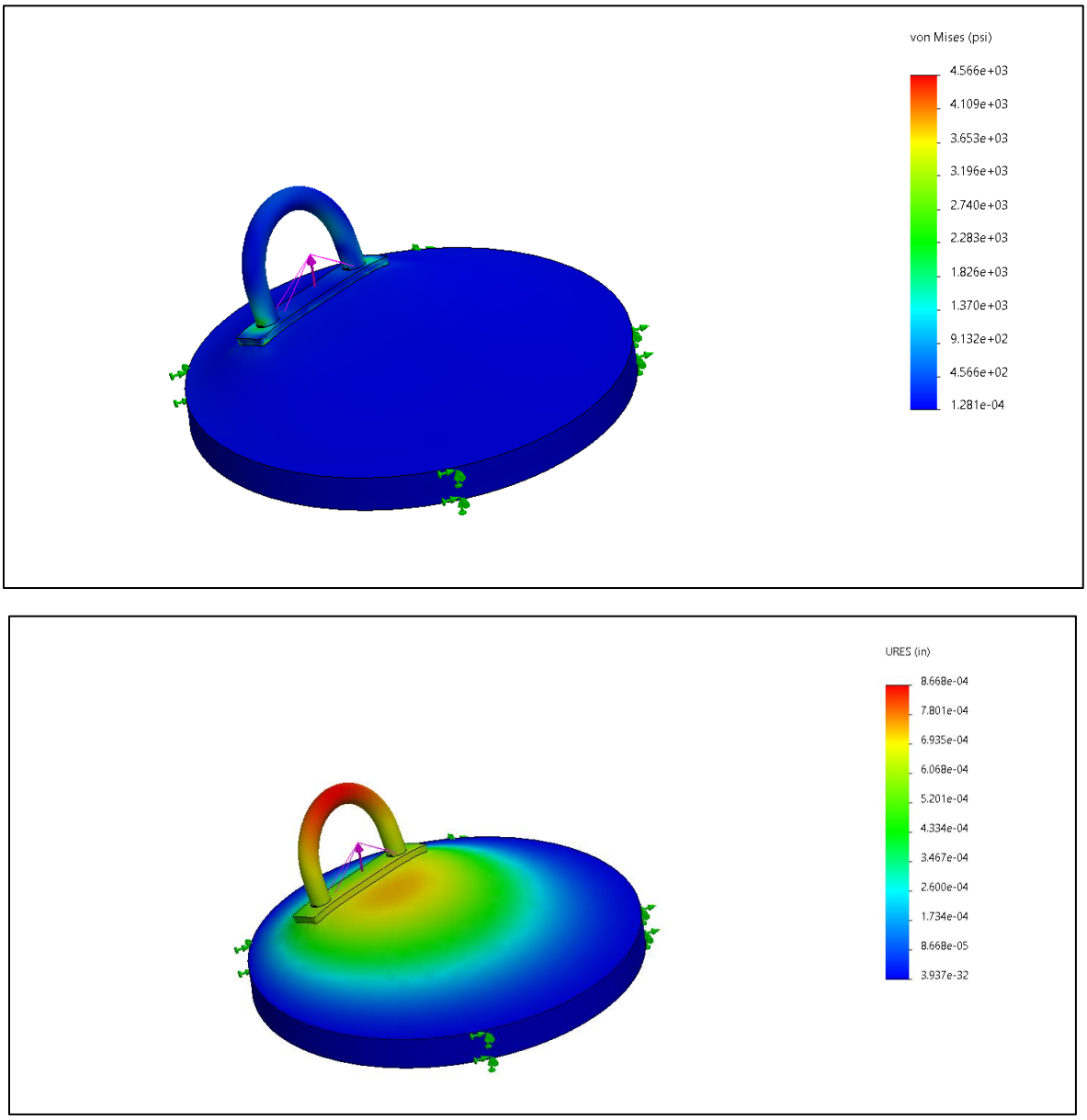



***Figure 3-49. Forward Bulkhead FEA***

The nose cone bulkhead is 0.5 inch thick Baltic Birch plywood with a 5/16” U-bolt/fastener plate configuration. The FEA was conducted with a force of 71.95 lbf pulling on the U-bolt to simulate the main parachute deploying. The bulkhead is a fixed structure in the simulation to mock the epoxied state of the real-time assembly. Deformations seen in the lower simulation are on the order of thousandths of an inch, therefore we can conclude that this configuration will hold under the load of chute deployment.

### 3.1.5.2 Avionics Bay Bulkhead U-bolt

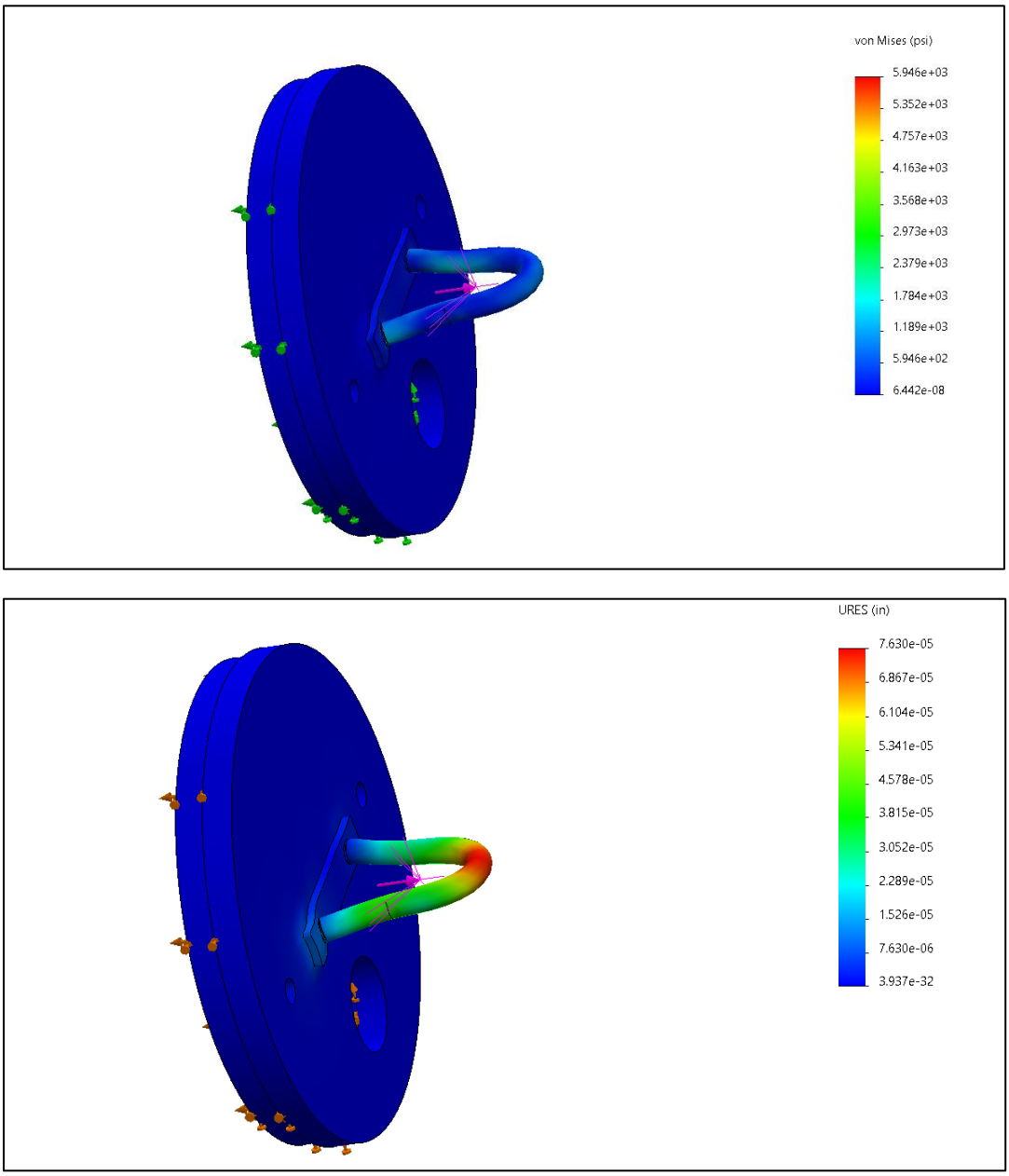



***Figure 3-50. Avionics Bulkhead FEA***

Similar to the foreword assembly, the avionics bay U-bolt and bulkheads were simulated under the maximum force during parachute deployment of 71.95 lbf. Deformations seen in the lower simulation are on the order of hundreds of thousandths of an inch, even smaller than the forward bulkhead given the U-bolts are centrally located to better distribute the load in this case.

### 3.1.5.3 Thrust Plate/Tail Cone Configuration

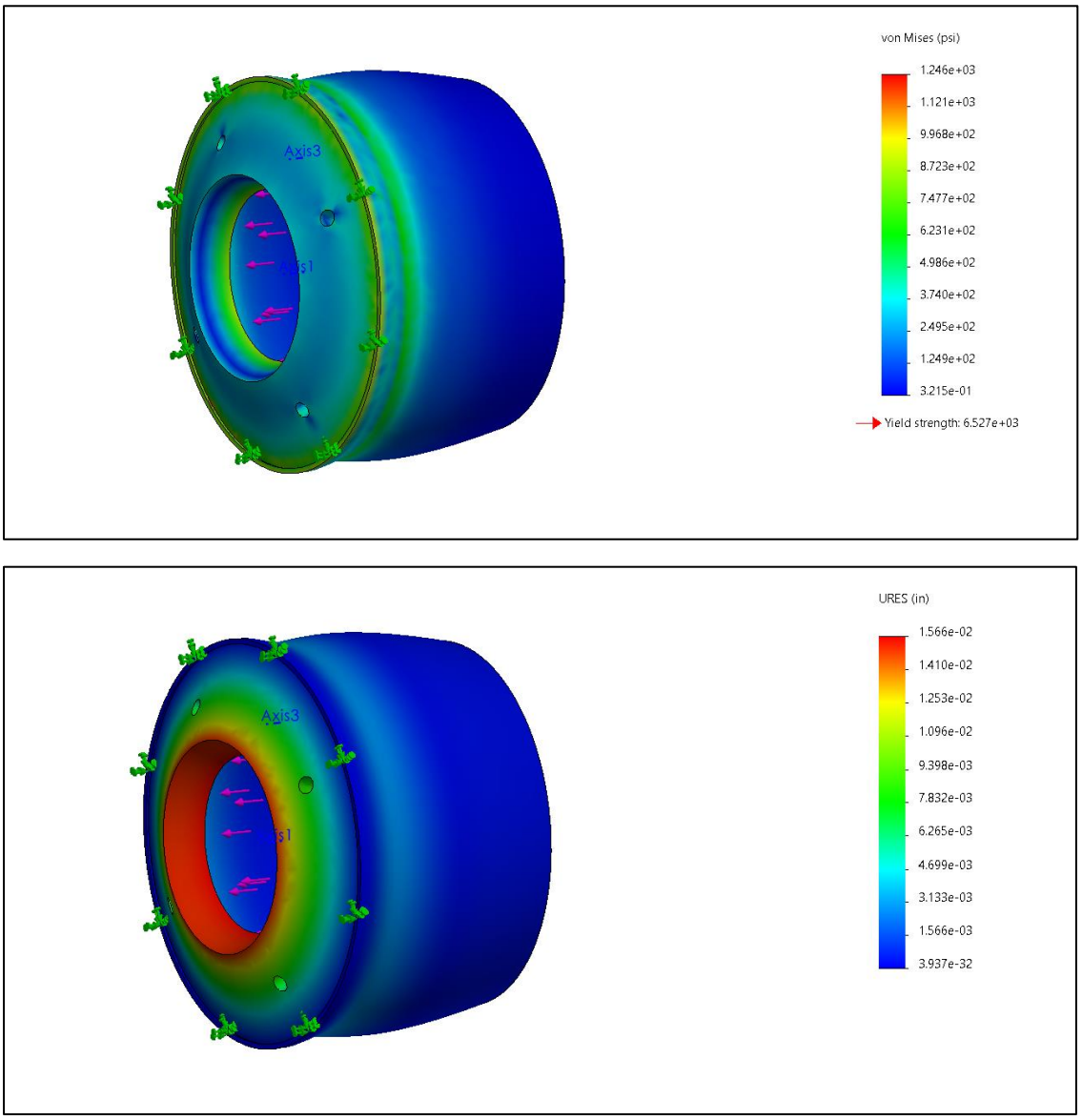



***Figure 3-51. Integrated Thrust Plate & Tail Cone FEA***

The tail cone and thrust plate were subjected to a simulated force of 420 lbf, the maximum thrust the motor will produce. The force was applied at the point where the retaining ring will contact the thrust plate, pushing up on the plate and transmitting force to the airframe. The largest deformations in this case were on the order of hundredths of an inch, which is acceptable considering that the motor only produces max thrust for ~0.8 seconds. The maximum deformation, which is still very small, occurs effectively instantaneously before the load begins to decrease rapidly.

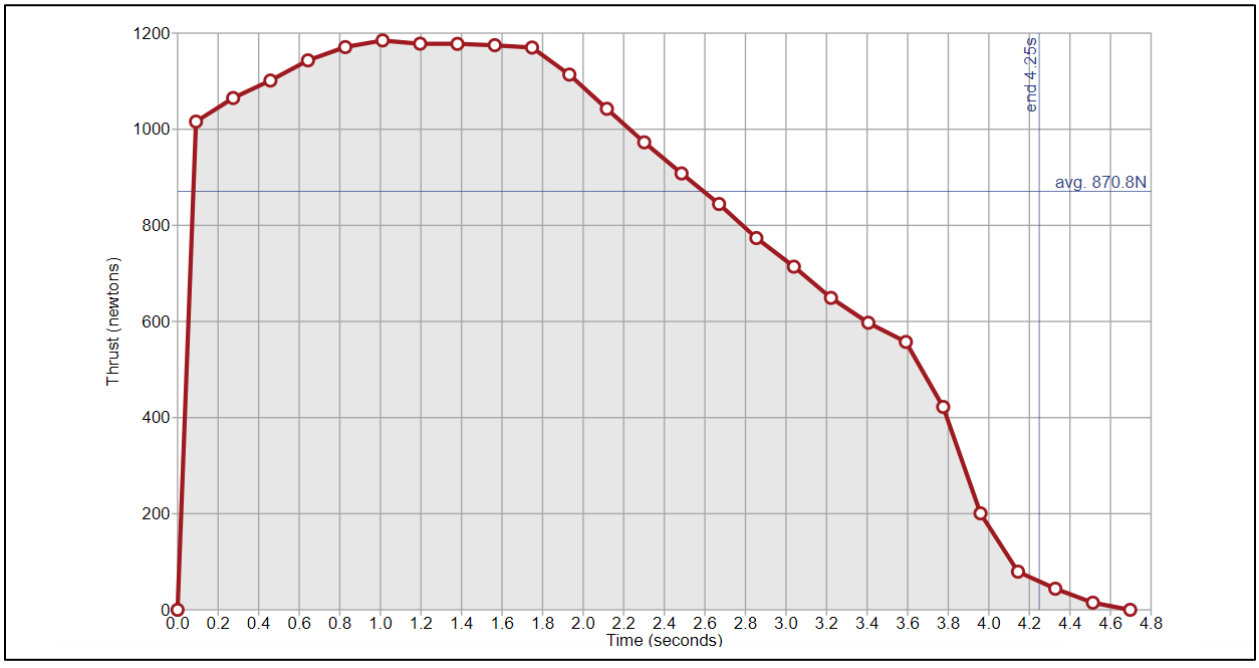
### 3.1.6 Vehicle Weight Breakdown

***Table 3-3. Vehicle Section Weights***

| Vehicle Section | Mass (lb) |
|---|---|
| Nosecone | 7.28 |
| Upper Payload Bay | 3.86 |
| Payload | 3.00 |
| Avionics Bay | 4.53 |
| Lower Payload Bay + Fin Can | 10.40 |

### 3.1.7 Final Motor Choice

The final motor selection to power the flight vehicle will be the Aerotech L850W. Originally the leading motor selection mentioned in PDR was the Cesaroni L3200. However, after further analysis of the vehicle's stability margin, the Aerotech L850W has a longer burn time than the L3200. The longer burn time allows the stability margin to continuously stay well above 2.0 calibers longer and increases apogee by a few hundred feet than if the vehicle was powered by the L3200. The L850W also reaches a lower maximum thrust value and ultimately decreases the amount of thrust forces acting on the thrust structure for better structural integrity. Lastly, in terms of availability in purchasing, the Aerotech L850W was available for early purchase opposed to the L3200. Shown below is an image of the thrust curve of the L850W.



## 3.2 Subscale Construction Methods

***Figure 3-52. Fin Slots***

Cuts to the airframe to create the upper and lower payload bay, as well as the fin slots, were made with a bandsaw in the machine shop. Bulkheads and centering rings, after modification and hardware installation, were epoxied inside the airframe or fixed in place by threaded rods running the length of the section.

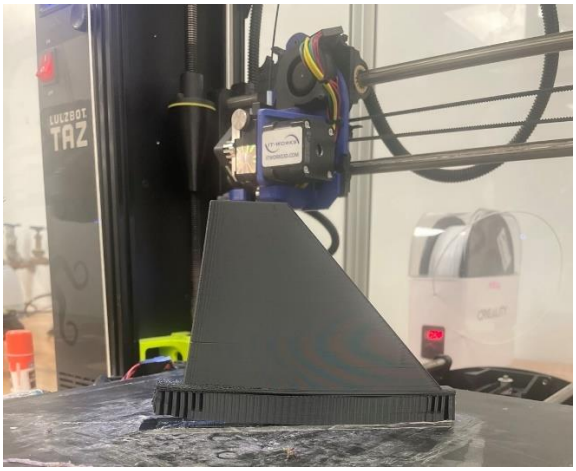



***Figure 3-53. Fin on 3D Print Bed***

Vehicle fins and nosecone were 3D printed using ABS filament in the Senior Design Lab, as well as on some of the Zenith Program team members' personal printers.

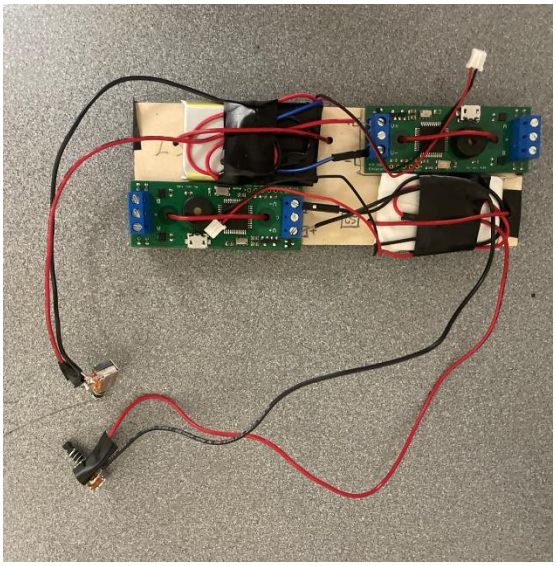


***Figure 3-54. Avionics Sled***

The avionics sled was constructed from a piece of plywood. Holes were drilled to allow cable to be passed through, holding components down to the sled. Electrical connections were made with standard jumper wires, with some connections, such as the switches, being spliced, soldered, and wrapped in electrical tape to hold firm. Extra length of wire was held down to the battery with electrical tape wraps, and the batteries were oriented with the charging cables pointing away from the sled for ease of access.

***Figure 3-55. Avionics Bulkheads, Rods, and Ejection Charges***

All holes for hardware such as threaded rods or eyebolts were drilled into bulkheads using a standard power drill. Odd-shaped holes, such as those for the CO2 ejection charges to pass through, or the + shaped cutouts in the centering rings to slide the fin tabs into, were cut with a combination of chisels and dremel.

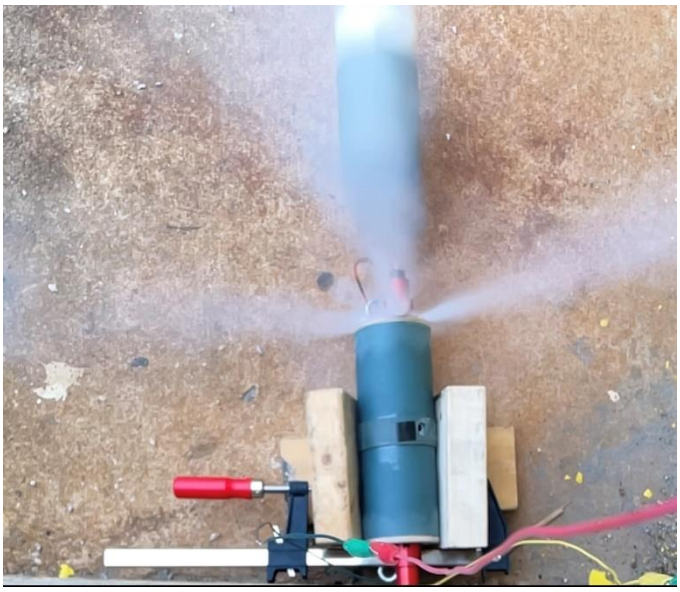


***Figure 3-56. Ejection Test***

The ejection system was tested in the block and clamp rig shown above, with a small closed-end section of airframe shear pinned to the avionics bay. Ejection was successful validating, that the ejection force was sufficient to snap the shear pins.


***Figure 3-57. Vehicle in Paint Process***

The vehicle exterior was decorated using matte black and gloss red spray paint, and letter stencils to apply the ZENITH nametape to the upper payload bay. The upper payload bay was first painted all red, then stencils applied, then an overcoat of matte black. Removal of the stencils left a black upper payload bay with the red ZENITH lettering. The nosecone was then sprayed with black paint from a distance to create the black haze over red background effect seen on the final vehicle.


***Figure 3-58. The Zenith 0.5***

The connection points between nosecone and payload bay, as well as the entirety of the base of each fin, were wrapped or covered in layers of electrical tape to smooth out minor protrusions and cover minor gaps. Battery charge cables were fed through a vent hole in the avionics bay to allow charging prior to flight without any disassembly.


***Figure 3-59. Team Prepping Ejection Charges on Sub-scale Launch Day***

Final assembly occurred at the launch site, where ejection charges were loaded, the avionics bay sealed, and surface switches tested. The recovery harnesses were then connected to the top and bottom sections of the vehicle and joined at the ends of the avionics bay. Parachutes were quick linked to the recovery harnesses, packed, and stowed in their respectively payload bay, before the avionics bay was mated and shear pinned to the upper and lower sections.

## 3.3 Subscale Flight Results

### 3.3.1 Flight Simulations and Prediction

OpenRocket Simulation software was used to calculate the subscale vehicle's performance parameters. Each of the component's weights were input into the simulation after completion of manufacturing and assembly, with a small deviation in accuracy before updating.

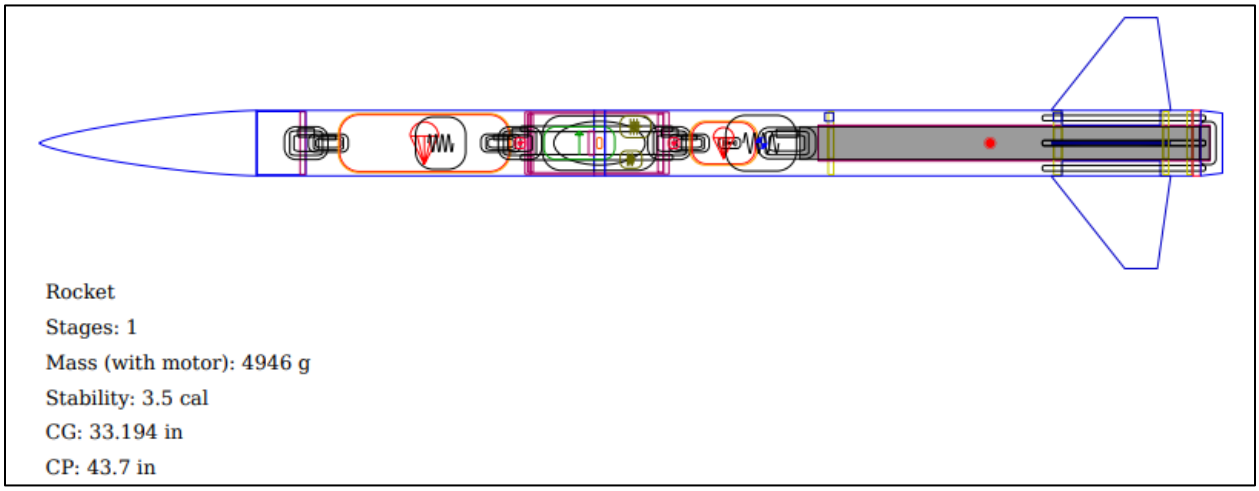



***Figure 3-60. Sub-scale OpenRocket Design***

Looking at the figure above, the vehicle weighs 4946 grams (11 pounds), which is roughly 1/3 of the full-scale vehicle's weight. The predicted apogee of the subscale vehicle was 3,189 feet at 0 mph winds and a launch angle of 5 degrees using a 96-inch launch rail.

### 3.3.2 Recovered Configuration

***Figure 3-61. Sub-Scale Recovered Configuration***

The vehicle was recovered intact on an asphalt road in a community adjacent to the launch site.

***Figure 3-62. Detailed Section Views - Recovered Configuration***

The only damage sustained during recovery can be seen in the upper left photo, where the paint was stripped from the tip of the upper right fin at the point it impacted the pavement.

### 3.3.3 Flight Data and Timeline

#### 3.3.3.1 Major Flight Metrics

A MATLAB program was used to process the flight data recovered from both altimeters. Plots were produced using a spline interpolation scheme with a resolution 100x that of the raw data to convert the initial step-plot output to a smooth curve. The program also sought maximums in the data, providing the following outputs for metrics of interest:

**Table 3-4. Sub-scale Flight Metrics**

| | Simulation | Altimeter 1 | Altimeter 2 |
|---|---|---|---|
| Altitude (ft) | 3182 | 3322 | 3279 |
| Max Velocity (ft/s) | 502 | 531 | 543 |
| Max Mach Number | 0.45 | 0.476 | 0.486 |

With the data above, a table of deviation and percent error could be generated to evaluate the accuracy of the simulation.

**Table 3-5. Sub-scale Flight Error Analysis**

| | Altimeter 1 | | Altimeter 2 | |
|---|---|---|---|---|
| | Delta | % Error | Delta | % Error |
| Altitude (ft) | 140 | 4.40 | 97 | 3.04 |
| Max Velocity (ft/s) | 29 | 5.77 | 41 | 8.16 |
| Max Mach Number | .026 | 5.77 | .036 | 8.16 |

With an error averaged across both altimeters of 3.72% and 6.97% in the altitude and velocity/Mach, respectively, we can conclude that the OpenRocket model very accurately represented the real vehicle in terms of component masses, mass distribution, aerodynamics, and impulse delivered.

The deviation in expected altitude and velocity can be explained by several factors, such as minor errors in component weights and placement in OpenRocket, although the most likely are those pertaining to the motor. Since we exceeded the expected velocity, we can assume that the motor delivered slightly more impulse than expected, either by burning slightly longer than simulated or having denser (more) propellant than advertised. Since the propellant is mixed and cast into grains to solidify, there is some expected deviation in performance between each motor, and the data used for simulation was the average performance as stated by the manufacturer.

#### 3.3.3.2 Flight Timeline

Categorization for each flight event is as follows:

**Table 3-6. Event Outcomes**

| Result | Description |
|---|---|
| Nominal | As expected |
| Failure (Class 1) | Deviation from expected performance. Insignificant impact on flight profile and vehicle performance. No vehicle damages. |
| Failure (Class 2) | Major deviation from expected performance. Significant impact on flight profile and vehicle performance. No vehicle damages. |
| Failure (Class 3) | Catastrophic failure. Major damages or loss of vehicle. |

The sub-scale flight saw a successful launch and recovery of the vehicle with no damage, although two Class 2 and two Class 1 failures were experienced. The order of events for the flight are as follows:

**Table 3-7. Sub-scale Flight Timeline**

| Event | Time (s) | Result | Notes |
|---|---|---|---|
| Ignition/liftoff | 0 | Nominal | - |
| Burnout | 4 | Nominal | - |
| FC read apogee | 15 | Nominal | - |
| Fire ejection charge 1 | 16 | Nominal | - |
| Separation 1 | 16 | Nominal | - |
| Drogue deployment | 17 | Nominal | - |
| Separation 2 | 17 | Failure (Class 2) | Undersized shear pins broke under load from drogue deployment causing premature separation of the lower half of the vehicle |
| Main Deployment | 18 | Failure (Class 2) | Premature main deployment (3175 ft) because of first failure |
| FC read 550ft AGL | 150 | Failure (Class 1) | FC was set to read MSL not AGL |
| Fire ejection charge 2 | 155.5 | Failure (Class 1) | Charge was fired low (500 ft). FC executed default ejection (150m) rather than 550ft programmed by avionics team |
| Ground Impact | 184 | Nominal | - |

The primary failure on this test flight was the deployment of the main parachute immediately following drogue deployment. Undersized shear pins for the bottom half of the vehicle caused a premature separation due to jerk from the drogue parachute catching the air. The team was able to visually confirm the chute deployment was successive and not simultaneous, and this also shows in the plots discussed later. The team also confirmed that the second ejection charge fired once the avionics bay was recovered and opened, and the flight computer data shows the command to fire was sent at the default altitude of 150m, rather than the programmed 550ft or 168m. The cause of this off-nominal command has yet to be discovered, although the team will continue extensive testing of the new primary flight computer, the TeleMega, as well as the AIM3's used in this flight to ensure that the main parachute deploys above the 550ft hard deck set by NASA requirements.

Post flight discussion with the team mentor regarding the shear pin failure gives us confidence that if the pins were sized correctly, the flight would have been entirely nominal. The first ejection charge fired at apogee as expected and the top half separated without issue. The drogue parachute was able to deploy without entanglement or damage to the vehicle. The second separation, although premature, also occurred without issue, as did the deployment and inflation of the main parachute. This leads us to believe that the design of the recovery system is sound, but there must be extensive drop testing of joined full-scale vehicle sections to ensure the shear pins will not fail under flight loads again. Further separation tests will also be conducted to ensure that pins which do not shear in drop tests will shear as desired when ejection charges are fired.

High altitude winds on launch day caused significant deviation from the expected recovery area. The vehicle was recovered over a mile from the launch pad, where it landed on a paved road. Despite landing on asphalt, the vehicle sustained no damage from the ground impact. The team is confident that correction of the premature main deployment will place the vehicle well within the 2500 ft recovery area as simulations suggest. We also find the lack of damage from impacting pavement at 17 ft/s to be proof that the construction methods, materials, and overall design are sound, and will surely survive impact with soil.

### 3.3.3.3 Altitude Plots

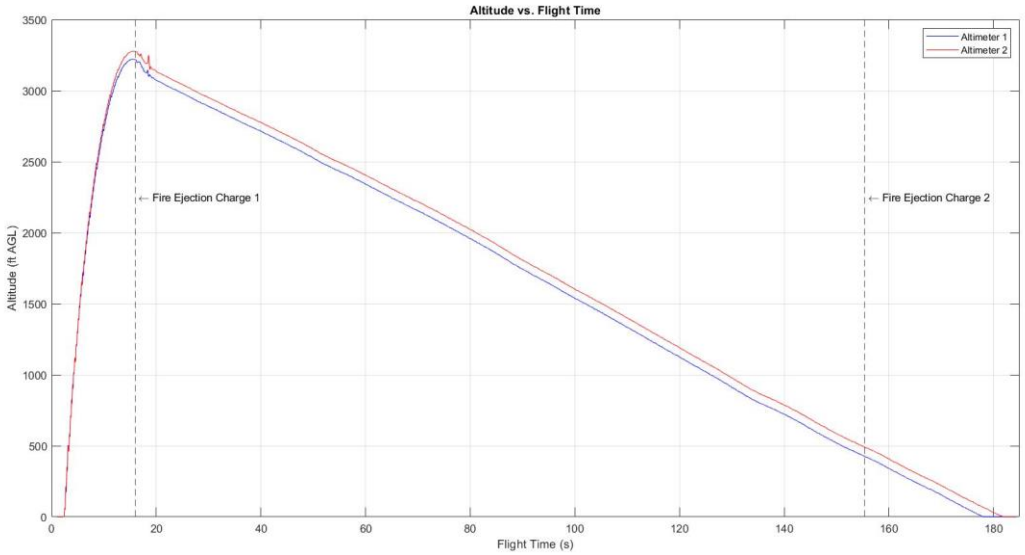



**Figure 3-63. Altitude vs. Flight Time Plot**

The linear portion of the ascent represents the time during which the motor was burning, followed by a parabolic shaped ascent curve as the vehicle coasted to apogee. The plot shows apogee and the firing of the first ejection charge immediately after. Since this is the flight portion where the two parachutes successively deployed, the plot shows a constant linear descent rate to ground impact. The second ejection charge fired when altimeter 1 read 500ft, as altimeter 2 was in a partial failure mode on launch which prevented it from activating its second pyro channel.

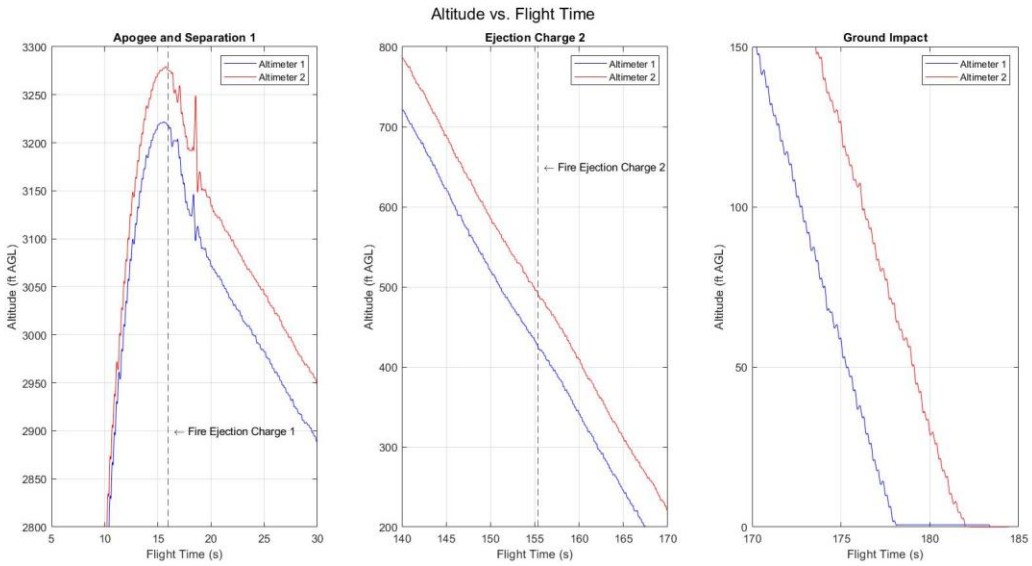



**Figure 3-64. Event View, Altitude Plot**

From the figure on the left, we can see two peaks after the firing of the ejection charge where the altitude suddenly increases for a short moment. The first peak is far less pronounced than the second, with the first occurring at around 16s and the second at 18s. These peaks represent the successive parachute deployments, as the avionics bay was jerked vertically upwards by the parachute, or swung laterally along a curved path, thereby increasing its altitude. The first jerk/swing is less pronounced because the drogue chute has less area than the main, thereby creating less force on deployment.

The center plot demonstrates that the second ejection charge fired right as the first altimeter read 500ft, or the preset 150m deployment from the manufacturer. The ejection would have occurred sooner, as altimeter 2 detected 500ft prior to altimeter 1, but as previously mentioned altimeter 2 had a known failure of its second pyro channel before launch.

The right plot shows the time at which the altimeters read ground impact. We can surmise from this plot that altimeter 1 (red) is the more accurate of the two, as it did not experience the same partial failure mode in the pyro channels and continued to sense deltas in pressure after altimeter 2 registered no deltas and determined zero altitude. The velocity plots bear out this result as well.

### 3.3.3.4 Velocity Plots

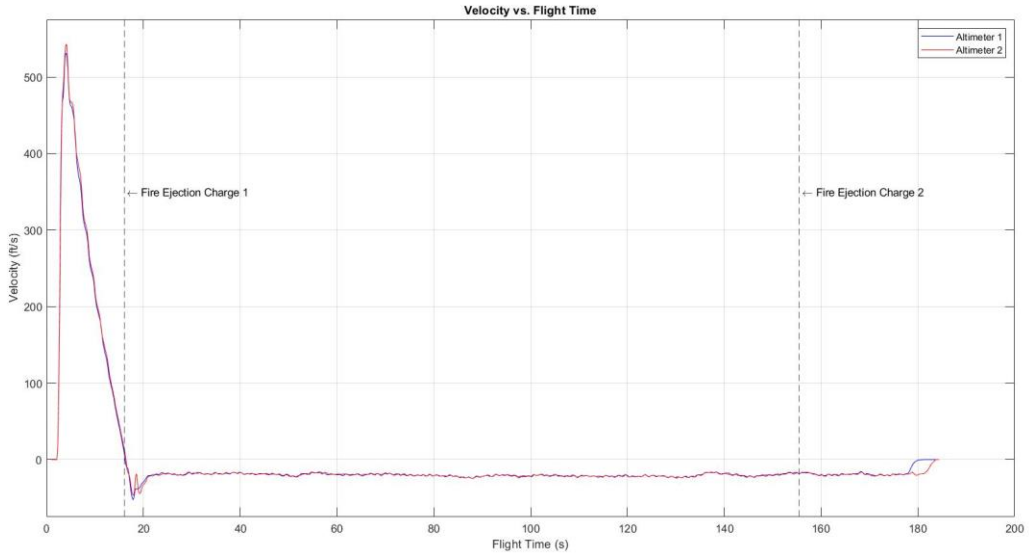



**Figure 3-65. Velocity vs. Flight Time**

The velocity plot demonstrates a linear increase in airspeed as the motor burned. Small fluctuations are seen as burnout occurred, followed by a constant decrease in velocity until zero is crossed at apogee and the velocity turns negative as the descent begins. Fluctuations are seen as the parachutes successively deploy and the vehicle stabilizes, after which a constant negative velocity is seen until impact.

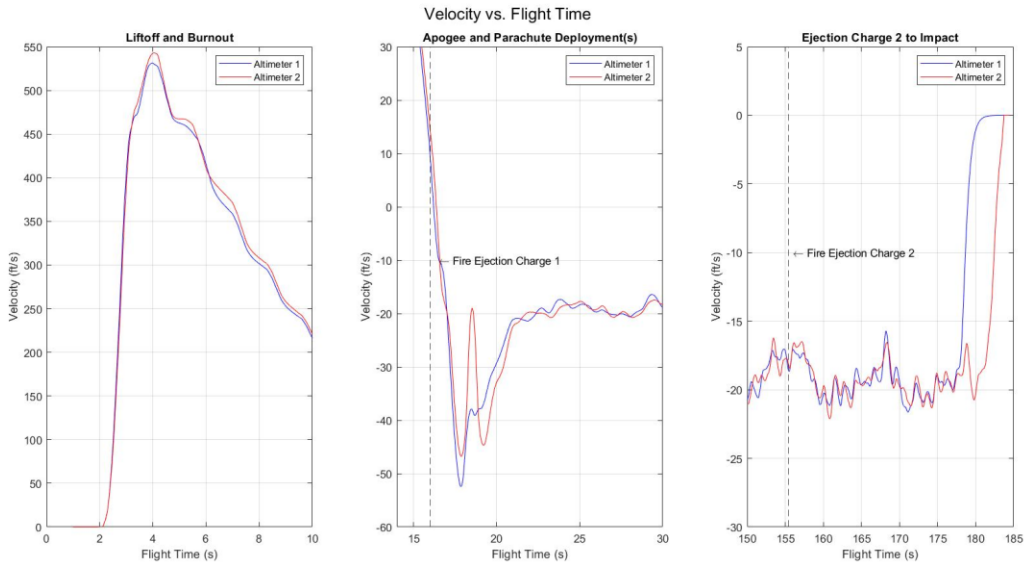



**Figure 3-66. Event View, Velocity Plot**

The left plot shows liftoff and motor burnout. Around 3 seconds the slope of the velocity decreases slightly, suggesting this is the point where the thrust curve began to fall off. At exactly 4 seconds the direction of the curve reverses as the motor burns out. Burnout is immediately followed by a steep drop in velocity. The slope of the velocity drop becomes shallower as the vehicle's airspeed and stability decrease during the coasting portion of the ascent. Sinusoidal fluctuations can also be seen in the unpowered ascent, which are result from spin stabilization of the vehicle.

The center plot shows the velocity fluctuations following the first ejection charge firing. There are two distinct and rapid drops in the velocity corresponding to the successive deployment of the parachutes. The plot begins with the descent under gravity, with the velocity increasing negative until the drogue deployment where the velocity rapidly decreases. The velocity then rapidly increases due to the phenomena discussed in the altitude section where the avionics bay is jerked or swung upwards rapidly. The main chute then deploys prematurely, causing another rapid velocity decrease which then settles out to a constant approximately -20 ft/s for the duration of the descent. Minor random fluctuations are seen in the velocity across the entire descent which are a result of high-altitude winds and the avionics bay swinging and spinning underneath the main parachute.

The right plot shows a continuation of the random fluctuations about -20 ft/s until ground impact, where the velocity goes to 0 ft/s near instantaneously. The discrepancy between impact time for altimeters 1 and 2 shows again, as altimeter 2 reads zero velocity well before altimeter 1. For reasons previously explained, altimeter 1 will be taken as the more accurate case.

### 3.3.4 Scaling Factors and Influence on Full-Scale Design

***Table 3-8. Sub-scale Vehicle Scaling Factors***

| Vehicle Parameter | Scaling Factor |
|---|---|
| Max Thrust | 0.45 |
| Impulse | 0.22 |
| *Dimensions | 0.5 |
| Mass | 0.285 |

**NOTE: Airframe diameter, nosecone, and fins scaled down 50%. Hardware and fittings not scaled. Body tube length not exactly 0.5 scale to maintain stability margin.**

The intention of the team was for the sub-scale vehicle to be manufactured at 50% size scale and 33% thrust/impulse scale. In reality, motor options available meant that the final scaling was nearer to 20% impulse and 50% thrust. The vehicle was scaled in almost every way possible to 50% size, although the motor being longer and skinnier than the full-scale counterpart forced the scale of the airframe length to be larger than this target. The mass was expected to fall at around 33% of full scale, and the 29% actual value very nearly approaches that goal.

Given that the scaling factors differ radically from one vehicle parameter to another, we cannot estimate full-scale performance by scaling or extrapolating sub-scale data. We can, however, confirm through our post-flight data analysis that the OpenRocket simulation for the vehicle matched reality to within a 5% margin of error, which suggests that the simulation can be relied upon to produce highly accurate performance estimates for the full-scale vehicle as well. The performance of the recovery system in subscale was also validated, and although the forces and loads will be increased for full-scale, the operating concept for the dual-deployment recovery system was successfully demonstrated.

## 3.4 Recovery System

### 3.4.1 Recovery System Summary

The entirety of the recovery system will ensure the launch vehicle and all its components safety upon descent. There are two recovery events, drogue parachute deployment and main parachute deployment. The two recovery events will be controlled by an Altus Metrum TeleMega flight computer, the primary altimeter, and an Entacore AIM 4, the secondary altimeter. Each altimeter draws power from separate 3.7 V rechargeable Lithium Polymer batteries and are both armed with simple push-button switches. The ejection charges will both be CO2 gas charges that are manufactured by Tinder Rocketry. These ejection charges were chosen to limit the amount of pyro events that will occur, which also lowers the many points of failure for the recovery event if black powder was used. The CO2 charge still requires the use of black powder, but only a small amount of it. Approximately 0.15 grams of 4F black powder is used to propel a piston with a pointed tip that punctures the CO2 cartridge and releases gas into the payload bays. The black powder is loaded into a charge cup that sits at the end of the charge in the payload bay and is connected to an e-match wire from each altimeter. Both charges are designed to have the CO2 placed cartridge in the avionics bay attached to the puncture piston mechanism that is threaded through the bulkhead. The figure below shows the interface between the CO2 charge mechanism (in red) and the AV bay bulkheads. For the full-scale launch vehicle there will be two separate charges for both the drogue and main parachutes, totaling to 4 charges.

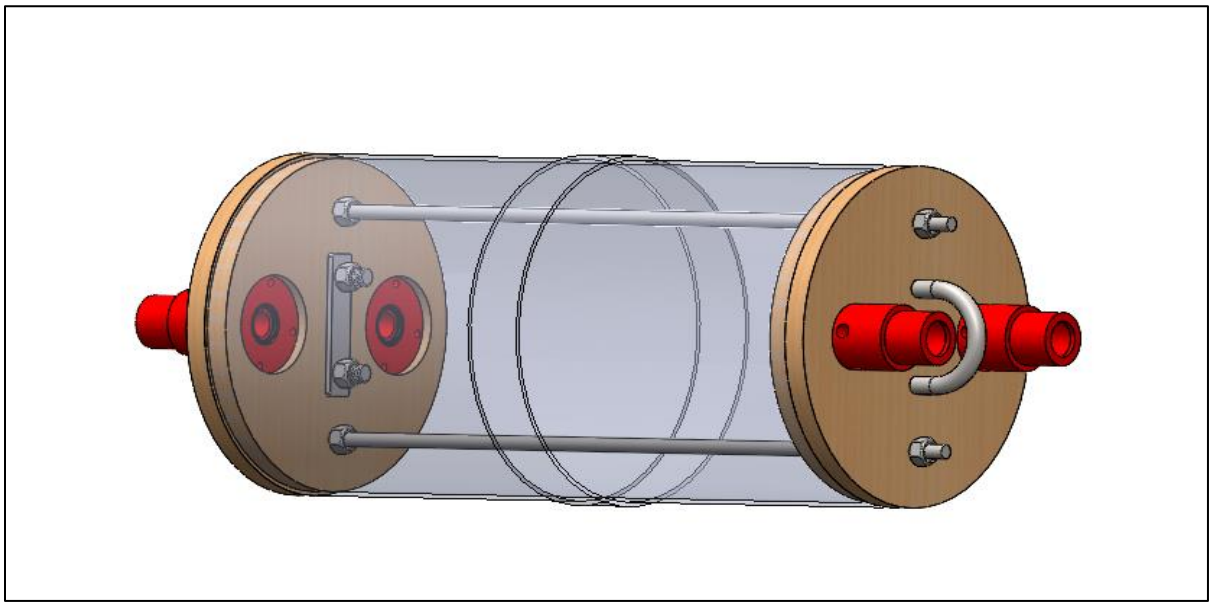


***Figure 3-67. CO2 Ejection Charge (Red) to Bulkhead Interface***

At apogee, the TeleMega altimeter will send a current through the e-match that will fire the first ejection charge. The CO2 gas will rapidly pressurize the lower payload bay and shear the #4-40 nylon pins that connects it to the AV bay, deploying the drogue parachute. A secondary ejection charge on a two-second time delay controlled by the AIM 4 altimeter will fire to ensure proper separation of the vehicle sections. Deployment of the main parachute is similar; the only difference is that the payload will also be tethered to the recovery harness. The primary ejection charge for the main parachute is set to deploy at 550 ft AGL, and the redundant secondary charge will deploy two seconds afterwards. A 24” compact elliptical parachute will be the drogue parachute and an 84” iris ultra-standard will be the main parachute, both of which are manufactured by Fruity Chutes. Both parachutes are tethered to 9/16-inch Nylon webbed shock cord, rated at 3000 lb, with the use of ¼-inch quick links.

## 3.5 Mission Performance Predictions

### 3.5.1 Target Altitude

The target altitude for the Zenith 1 is 4600 ft AGL.

### 3.5.2 Updated Flight Profile

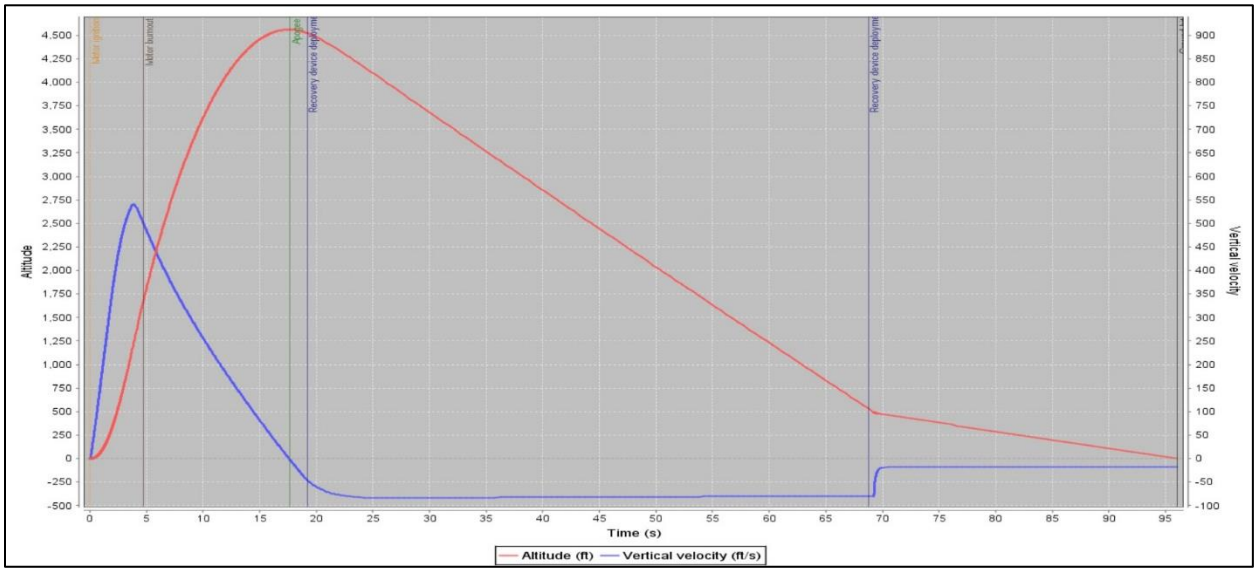



***Figure 3-68. Updated Flight Profile – 0 mph Winds***

***Table 3-9. Nominal Flight Profile (No Wind, 5° Launch Angle)***

| Event | Flight Time (s) | Notes |
|---|---|---|
| Liftoff | 0 | Rail Exit: 64.5 ft/s |
| Max Velocity | 4 | 545 ft/s (subsonic) |
| Motor Burnout | 4.5 | - |
| Apogee | 17.5 | 4561 ft AGL |
| Separation Charge 1 Fire | 19 | 1.5s delay |
| Separation Charge 2 Fire | 68 | Deploy Vel: 74.5 ft/s |
| Ground Impact | 96 | Impact Vel: 18 ft/s<br>Descent Time: 78.5 s |

### 3.5.3 Apogee Calculations

The theoretical apogee of the rocket can be calculated by first calculating the altitude that the rocket achieves under powered ascent (the solid motor is producing thrust) and then by calculating the altitude that the rocket achieves after powered ascent while in the "coasting phase." The powered ascent altitude formula can be derived from Newtons 2nd law.

$$F = m * a \qquad (1)$$

Where F is Force, m is mass, and a is acceleration. Using definition of acceleration:

$$F = m \frac{dv}{dt} \qquad (2)$$

The entire force on the rocket can be written as:

$$F = T - W_{avg} - F_{drag} \qquad (3)$$

Where T is the trust force. $F_{drag}$ is the drag force acting on the rocket. $W_{avg}$ is the average weight force during powered ascent, we take the average because as the propellant burns the vehicle will lose weight, decreasing the load. For a more accurate calculation the weight force can be integrated over the duration of the burn, however because the mass of the vehicle (17.368 kg) is large compared to the propellant mass (2.095 kg) and the burn time is relatively low (4.4 s), the method for determining the average mass in equation (4) is sufficient.

$$m_{avg} = m_{takeoff} - 0.5 * m_{propellant} \qquad (4)$$

and

$$W_{avg} = g * m_{avg} \qquad (5)$$

Where $m_{takeoff}$ is the mass of the vehicle at takeoff, $m_{propellant}$ is the mass of the propellant, and g is the gravitational constant of Earth. Because the rocket's target altitude is not greater than 5,000 ft, we will assume g to be constant. The drag force model we will use is listed in equation (6):

$$F_{drag} = k * v^2 \qquad (6)$$

Where v is the velocity of the vehicle and

$$k = 0.5 * \rho * C_d * A \qquad (7)$$

Where A is the greatest cross-sectional area of the vehicle. $C_d$ is the coefficient of drag of the vehicle, for this calculation a standard value was chosen for a vehicle of the same size. $\rho$ is the density of the air. Again, because the rocket will only travel 5,000 ft, we will assume this value to be constant. We can now plug equations 2, 5, and 6 into equation 3.

$$m\,\frac{dv}{dt} = T - \ g * m_{avg} - \ k * v^2 \qquad (8)$$

Equation 8 can be rearranged, and integrated to eventually obtain:

$$v = \sqrt{\frac{T - g * m_{avg}}{k}} * \frac{1 - e^{\frac{-2 * t * k * \sqrt{\frac{T - g * m_{avg}}{k}}}{m_{avg}}}}{1 + e^{\frac{-2 * t * k * \sqrt{\frac{T - g * m_{avg}}{k}}}{m_{avg}}}} \qquad (9)$$

Where t is the burn time and v is the velocity of the vehicle after the burn is complete. We can now begin to formulate the equation for the height of the vehicle after the burn and we will use the velocity of the vehicle to determine the height. To find the equation for height of the vehicle, we begin by rewriting equation 2:

$$m * \frac{dv}{dt} = m * \frac{dv}{dh} * \frac{dh}{dt} = m * v * \frac{dv}{dh} \qquad (10)$$

By substituting equation 10 into equation 8, then rearranging and integrating, we obtain:

$$h_{burnout} = \frac{m_{avg}}{2*k} * \ln\left(\frac{T - m_{avg}*g}{T - m_{avg}*g - k*v^2}\right) \quad (11)$$

Where $h_{burnout}$ is the height of the vehicle after the powered ascent. Now, we will find the height of the vehicle after its coasting portion of flight. For these calculations we will use the mass of the vehicle without the propellant ($m_{vehicle} = m_{takeoff} - m_{propellant}$) because during this portion of the flight, it is already all burned off. Using similar reasoning as above, with the exception of removing the impulse from the equation of motion, we obtain:

$$h_{coasting} = \frac{m_{vehicle}}{2*k} * \ln\left(\frac{m_{avg}*g + k*v^2}{m_{avg}*g}\right) \quad (12)$$

Now that we have formulated equations for the altitude of both portions of the flight, we can now add them together to find the total altitude of the vehicle that accounts for drag and changing mass.

$$h_{apogee} = h_{burnout} + h_{coasting} \quad (13)$$

Using the above equations, the theoretical apogee of the rocket was found to be 4,431 feet.

The MATLAB program used to execute the above calculations is attached as Appendix D.

### 3.5.4 Stability Margin Calculations

The vehicle's stability margin is one of the most important parameters that vehicle must be designed around. The stability margin can negatively or positively optimize the vehicle's flight performance and ultimately determines whether the vehicle is successfully designed. Although OpenRocket simulations do not define the real-time launch vehicle's stability margin on launch day, it is a very accurate form of measurement. Shown below is the vehicle's stability margin profile at the maximum allowable launch day wind speed conditions.

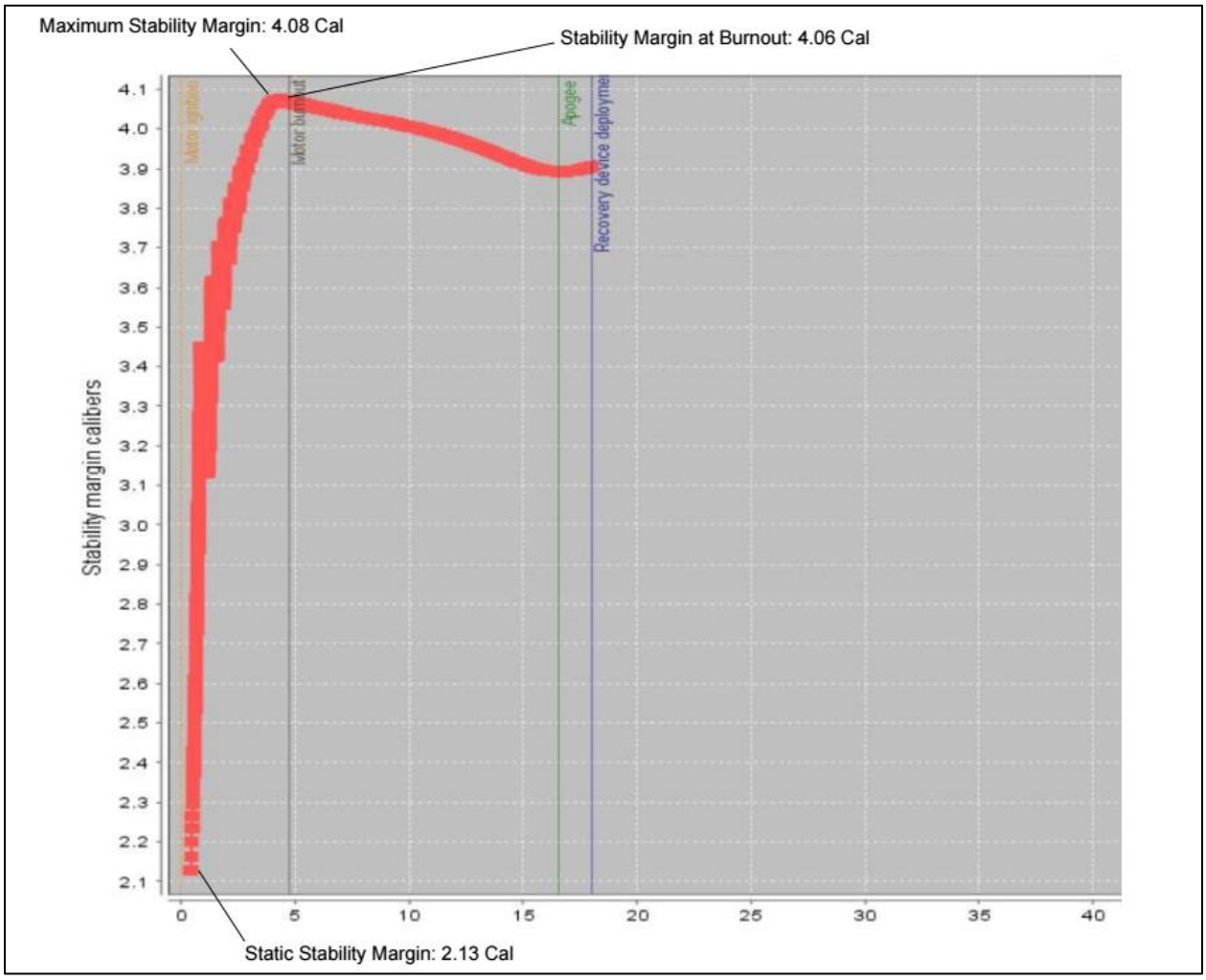



***Figure 3-69. Stability vs. Flight Time***

Looking at the figure above, the static stability margin of vehicle at rest is 2.13 calibers, the maximum stability margin is 4.08 calibers, and the stability margin at motor burnout is 4.06 calibers. The static stability margin shown above is above NASA's minimum requirement, ensuring that any other wind speed conditions lower than 20 MPH will also be above NASA's minimum requirement. For the sake of sanity checking, the table below shows the vehicle's stability margin at 0, 5, 10, 15, and 20 MPH wind speeds at the launch competition's geographical location/conditions.

***Table 3-10. Wind Speed vs. Stability for 5° Launch Angle***

| 5° Launch Angle | |
|---|---|
| Wind Speed (mph) | Static Stability Margin |
| 0 | 3.47 |
| 5 | 2.97 |
| 10 | 2.61 |
| 15 | 2.33 |
| 20 | 2.13 |

Another method of calculating the static stability margin is the Barrowman's method. The Barrowman's method was written into a MATLAB script and used to calculate the vehicle's static stability margin at 0 MPH wind speeds. The following equation was used to calculate the static stability margin:

$$Stability\ Margin_{\ Static} = \frac{X_{CP} - X_{CG}}{D}$$

Where $X_{CG}$ is the center of gravity and $X_{CP}$ is the center of pressure, both measured from the tip of the nosecone. The center of gravity is given as 58.578 inches and the center of pressure can be found by

$$X_{CP} = \frac{C_N X_N + C_F X_F}{C_N + C_F}$$

The arm length of the fins, $X_F$ can be found using the following equation

$$X_F = X_B + \frac{X_R C_R + 2C_T}{3(C_R + C_T)} + \frac{1}{6}\left(C_R + C_R - \frac{C_R C_T}{C_R + C_T}\right)$$

Where $X_B$ is the distance from the tip of the nosecone to the fin root chord leading edge, $C_R$ is the length of the fin root chord, and $C_T$ is the length of the fin tip chord.

The fin coefficient shown in equation, $C_F$, is represented as

$$C_F = \left(1 + \frac{R}{S+R}\right)\left(\frac{4N\left(\frac{S}{2R}\right)^2}{1+\sqrt{1+\left(\frac{2L_F}{C_R+C_T}\right)^2}}\right)$$

Where $N$ is the number of fins and $L_F$ is the length of the fin mid-chord line. $L_F$ can be calculated using the fin semispan, $S$, and the following equation

$$L_F = \sqrt{S^2 + \left(0.5C_T - 0.5C_R + \frac{S}{tan\theta}\right)}$$

The variables in the equations above and their calculated values are shown below in table. The MATLAB script written to calculate the above parameters is attached in Appendix C.

***Table 3-11. Stability Parameters***

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Fin Semispan | $S$ | 9.00 | Inches |
| Fin Tip Chord | $C_T$ | 3.00 | Inches |
| Fin Root Chord | $C_R$ | 11.00 | Inches |
| Fin Sweep Angle | $\theta$ | 37 | Degrees |
| Fin Mid-Chord Line | $L_F$ | 8.14 | Inches |
| Radius of Airframe | $R$ | 3.00 | Inches |
| Number of Fins | $N$ | 4 | N/A |
| Nose Tip to Fin Root Chord Leading Edge | $X_B$ | 83.50 | Inches |
| Fin Root Leading Edge to Fin Tip Leading Edge | $X_R$ | 6.77 | Inches |
| | $X_F$ | 88.18 | Inches |
| Arm Length of Nosecone | $X_N$ | 9.32 | Inches |
| Nose Cone Length | $L_N$ | 20.00 | Inches |
| Nose Cone Term | $C_N$ | 2.00 | N/A |
| Fin term | $C_F$ | 16.95 | N/A |
| Center of Pressure | $X_{CP}$ | 79.86 | Inches |
| Center of Gravity | $X_{CG}$ | 58.58 | Inches |
| Diameter of Airframe | $D$ | 6.154 | Inches |
| Static Stability Margin | $Stability\ Margin_{\ Static}$ | 3.46 | Calibers |

Comparing the stability margin values calculated from OpenRocket and the MATLAB Code

***Table 3-12. Stability Results***

| Method | Stability Margin (Calibers) |
|---|---|
| OpenRocket Simulation Software | 3.47 |
| Barrowman's Method | 3.46 |

Any deviation between the two values is more than likely due to rounding the pre-defined MATLAB values in the coded script.

### 3.5.5 Landing Kinetic Energy Calculations

The kinetic energy of each section of the vehicle during descent is governed by the mass and velocity of each. The equation used to determine the kinetic energy of each section is stated below:

$$KE = \frac{1}{2}mv^2$$

where m is the mass, and v is the velocity of the section. The maximum kinetic energy set by the requirement in the Student Launch Handbook is 75 ft-lb, which can be used to derive the maximum velocity for each descending section. The maximum velocity of each descending section is shown below.

***Table 3-13: Maximum Descent Velocity***

| Section | mass (g) | mass (slug) | Maximum Descent Velocity (ft/s) |
|---|---|---|---|
| Nosecone + UPB | 4720 | 0.3235 | 21.5329 |
| Payload | 1400 | 0.0960 | 39.5375 |
| AV bay | 2056 | 0.1409 | 32.6258 |
| LPB + Fin can | 6235 | 0.4273 | 18.7351 |

### 3.5.6 Descent Time and Drift Calculations

The descent time is determined by the descent velocity of each parachute and the altitudes at which they are deployed. The drift can be calculated, but a few assumptions must be made. The first assumption is that the launch vehicle reaches apogee directly above the launch pad. The second is that at apogee and main deployment altitude, the terminal velocities are reached instantaneously. Lastly, the wind speeds are applied uniformly on the vehicle and it all drifts in one direction. Although these assumptions make the calculations not entirely accurate, it still gives a good understanding of how severe wind conditions can affect the vehicle's descent. To determine the total descent time of the vehicle the equation below was used:

$$t = \frac{h_a - h_m}{v_d} + \frac{h_m}{v_m}$$

where $h_a$ is the apogee altitude, $h_m$ is the main parachute deployment altitude, $v_d$ is the descent velocity underneath the drogue parachute, and $v_m$ is the descent velocity underneath the main parachute. For the declared altitude of 4600 ft, the calculated descent time is 80.7 seconds.

***Table 3-14. Descent Time and Drift***

| Wind Speed (mph) | Apogee (ft) | Descent Time (s) | Wind Drift (ft) |
|---|---|---|---|
| 0 | 4600 | 80.7 | 0 |
| 5 | 4600 | 80.7 | 591.8 |
| 10 | 4600 | 80.7 | 1183.6 |
| 15 | 4600 | 80.7 | 1775.4 |
| 20 | 4600 | 80.7 | 2367.2 |

Once the maximum velocity is known, the descent velocity and subsequent kinetic energy of each section can be determined using the 84-inch Iris Ultra Standard main parachute.

***Table 3-15. Maximum Kinetic Energy***

| Section | mass (g) | mass (lbm) | mass (slug) | Descent Velocity (ft/s) | Kinetic Energy (ft-lb) |
|---|---|---|---|---|---|
| Nosecone + UPB | 4720 | 10.4058 | 0.3234 | 18.6 | 55.946 |
| Nosecone + UPB + payload | 6120 | 13.4923 | 0.4194 | 18.6 | 72.540 |
| Payload | 1400 | 3.0865 | 0.0959 | 18.6 | 16.594 |
| AV bay | 2056 | 4.5327 | 0.1409 | 18.6 | 24.370 |
| LPB + Fin can | 6235 | 13.7458 | 0.4272 | 18.6 | 73.903 |

The table above shows the maximum kinetic energy for each section of the vehicle. The heaviest section of the launch vehicle will be its lower payload bay and fin can section. The maximum kinetic energy calculated for that section is 73.9 ft-lb, which is under the requirement of 75 ft-lb stated in the Student Launch Handbook. The second row of the column highlights a failure mode if the payload does not exit the upper payload bay when the main parachute deploys. In this scenario the second maximum kinetic energy is 72.54 ft-lb, which also satisfies the maximum requirement.

### 3.5.7 Parachute Opening Shock Calculations

The parachute opening shock calculations is done by finding the rate at which the launch vehicle's sections decelerate once the main parachute is fully open. To get the time it takes for the parachute to unravel the following equation was used from a technical report written by William P. Ludtke:

$$t = \frac{8 \cdot r}{v}$$

where r is the radius of the parachute, and v is the terminal velocity of the launch vehicle before the parachute is deployed. The time calculated for the 84" iris ultra-standard parachute to open was 0.35 seconds. The deceleration rate can then be determined by the following kinematic equation:

$$a = \frac{v_d - v_m}{t}$$

where $v_d$ is the terminal velocity of the launch vehicle under the drogue parachute, $v_m$ is the terminal velocity under the main parachute, and t is the time it takes for the main parachute to open. The deceleration rate calculated was 171.52 ft/s^2 and used in Newton's 2nd law to get the opening shock force that the recovery harness experiences for each section of the launch vehicle upon main parachute deployment. The shock force values is shown in the table below.

***Table 3-16. Main Parachute Opening Shock***

| Section | Mass (slug) | Opening Shock (lbf) |
|---|---|---|
| Nosecone + UPB (slug) | 0.3235 | 55.4881 |
| Payload (slug) | 0.0960 | 16.4583 |
| AV Bay (slug) | 0.1409 | 24.1703 |
| LPB + Fin Can (slug) | 0.4286 | 73.5100 |

# 4 Payload Criteria

## 4.1 Payload Mission Statement

The mission of the Zenith Program Payload Prototype is to employ a sturdy majority 3D printed design to survive ground impact and come to rest camera side up as flat as the terrain allows to execute a RAFCO sequence involving rotation of a camera turret, image capture, and application of filters or effects to the images autonomously through effective Arduino programming.

## 4.2 Payload Success Criteria

1) The payload Deploys with the main parachute.
2) The payload body section lands intact.
3) The payload electrical connections stay connected during flight and landing.
4) The payload receives the entire RAFCO sequence.
5) The payload executes the entire RAFCO sequence.
6) The payload stores all the images successfully with timestamps and proper filters.

## 4.3 Payload System Summary

The updated payload design stemmed from a philosophy of including only what is necessary to execute the baseline requirements for the RAFCO mission. The static housing was designed to hold a camera turret and the antenna securely, shield them from ground impact, and come to a stop without tipping or rolling after touchdown.

This section of the report will focus on the redesign and integration of the payload.

Preliminary code to operate the stepper motor, continuously check the antenna for receipt of the RAFCO command string, decode the command string, and execute the requested commands has been attached for review as Appendix E.

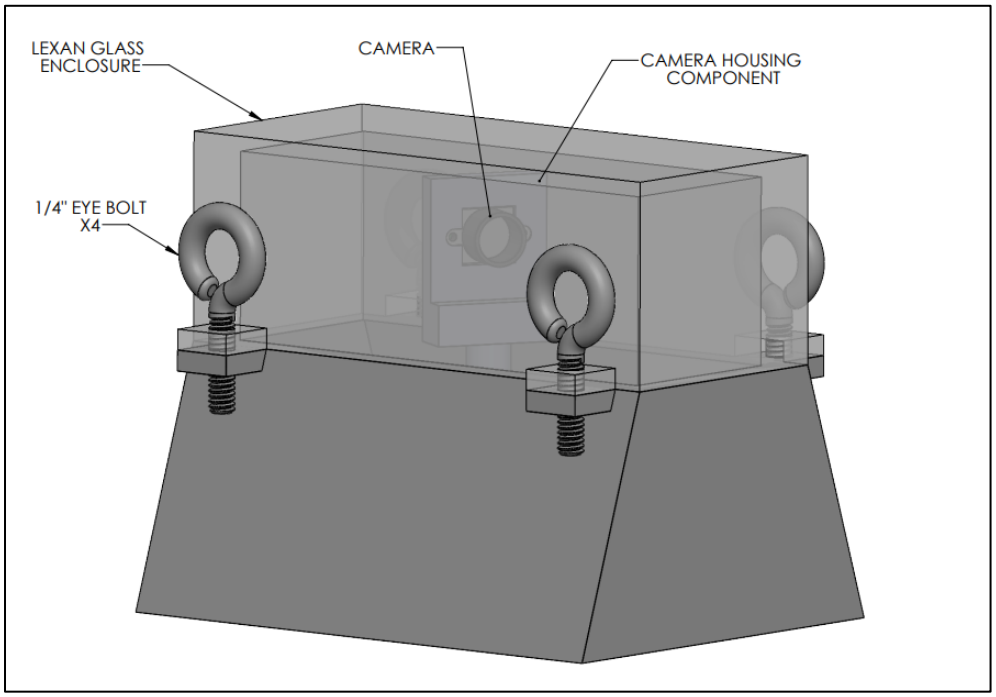



***Figure 4-1. Payload design***

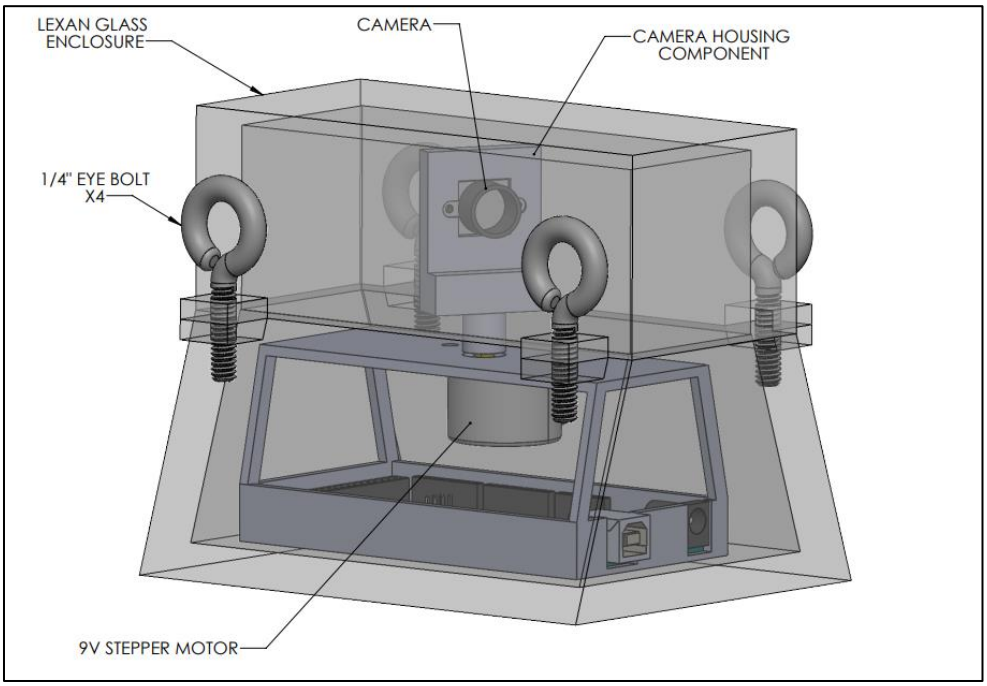



***Figure 4-2. Payload Internal View***

### 4.3.1 Component Integration

The long wide base of the payload, which flares out from the lexan enclosure and contains most of the weight of the system in the stepper motor, is intended to give as wide an initial contact surface and drop the center of gravity as low as possible to prevent tipping or rolling on impact. The working idea is that if the payload does not come to an immediate halt on impact, it will most likely slide. If the payload were to impact at an angle, the mass of the stepper motor in the center of the wide base would quickly bring the base down flat to the ground.

Rather than attach at a single connection point, the payload will be suspended on 4 shock cords running to stainless steel eyebolts at the corners. These four cords will connect to a quick link on the recovery harness in between the main parachute and the upper payload bay. Suspending the enclosure by the corners minimizes the potential for swinging under the parachute, as would certainly happen with a single connection point at the top center of the payload.

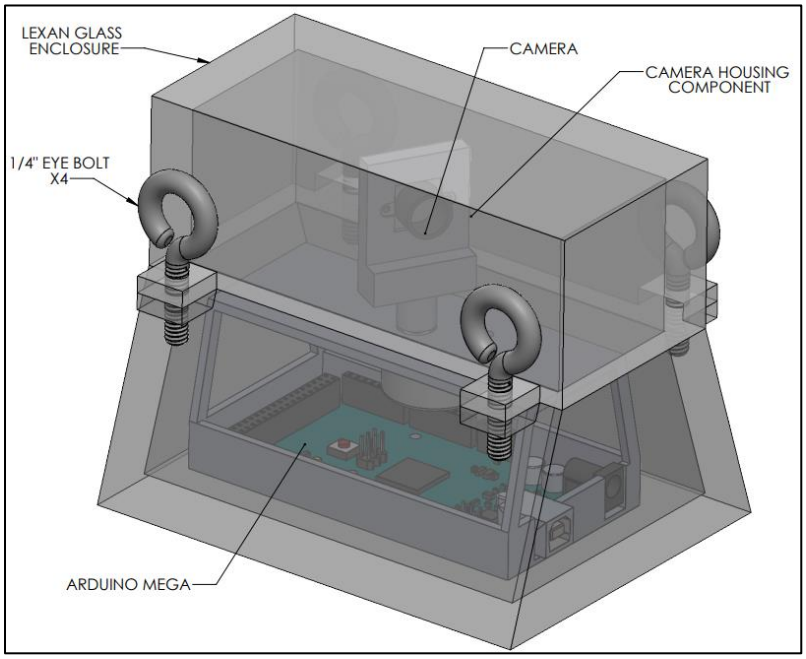



***Figure 4-3. Payload Internal Hardware***

The ArduCam Mini will be enclosed in a 3D printed housing unit which interfaces with the stepper motor. The motor and Arduino Mega will be retained by a 3D printed internal structure with mounting points for each. Electrical wires will be free to rotate with the camera, as firm connections will be made at each end, and wires passed through the upper deck of the internal structure. Payload batteries will be mounted on top of the microcontroller, with the antenna cord passing through the internal upper deck, and antenna fixed horizontally in the lexan housing.

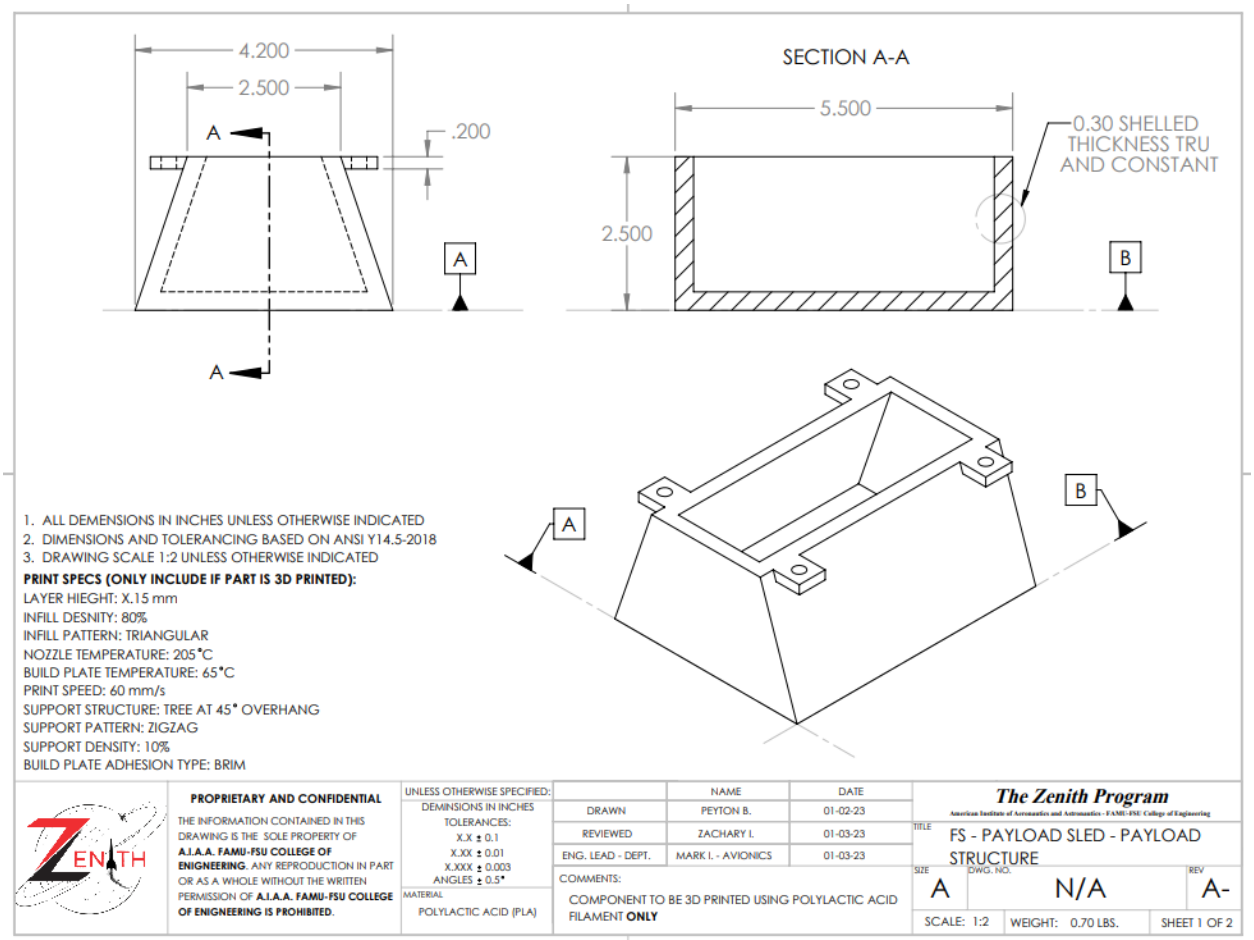



***Figure 4-4. Payload Housing Drawing***

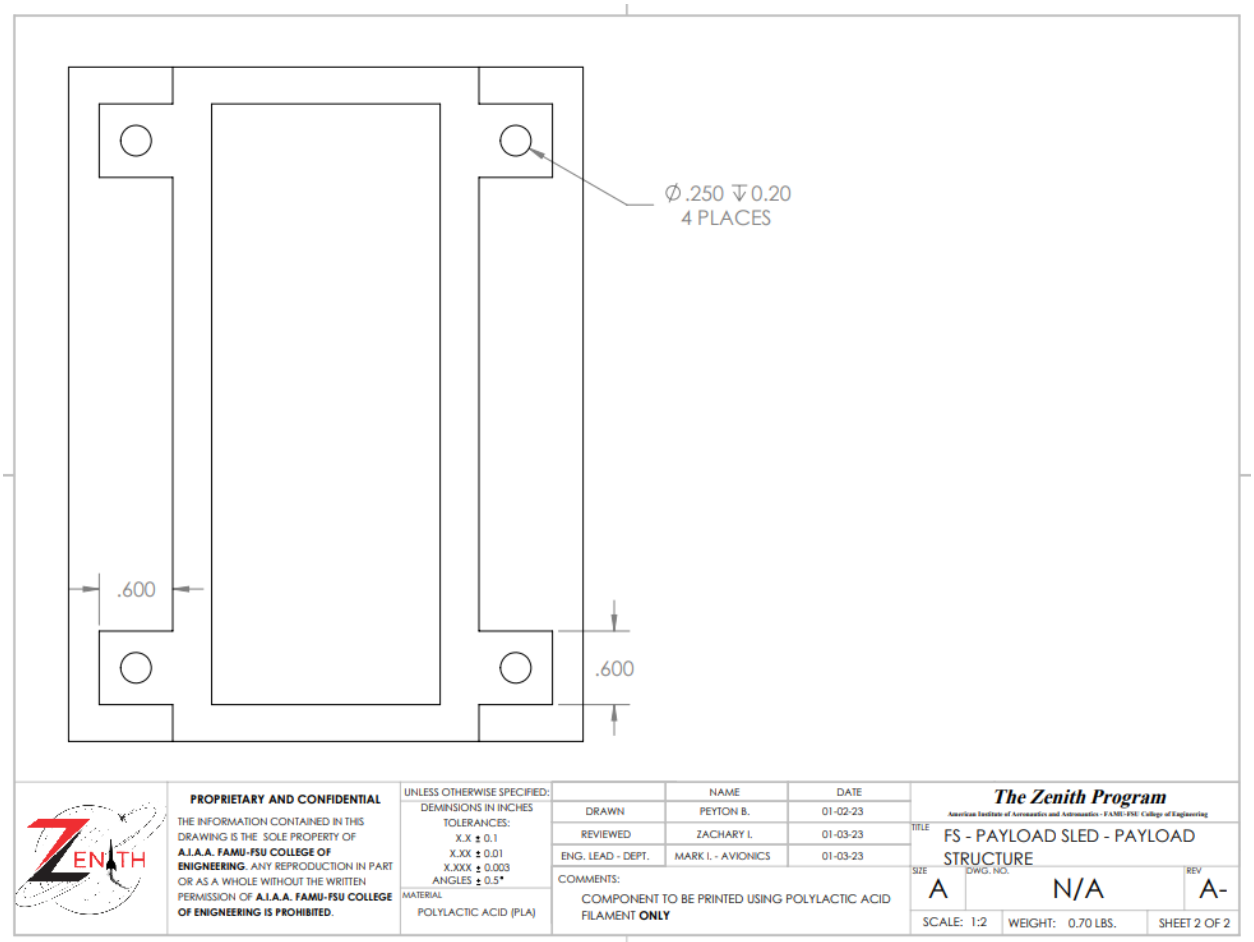



***Figure 4-5. Payload Housing Drawing Continued***

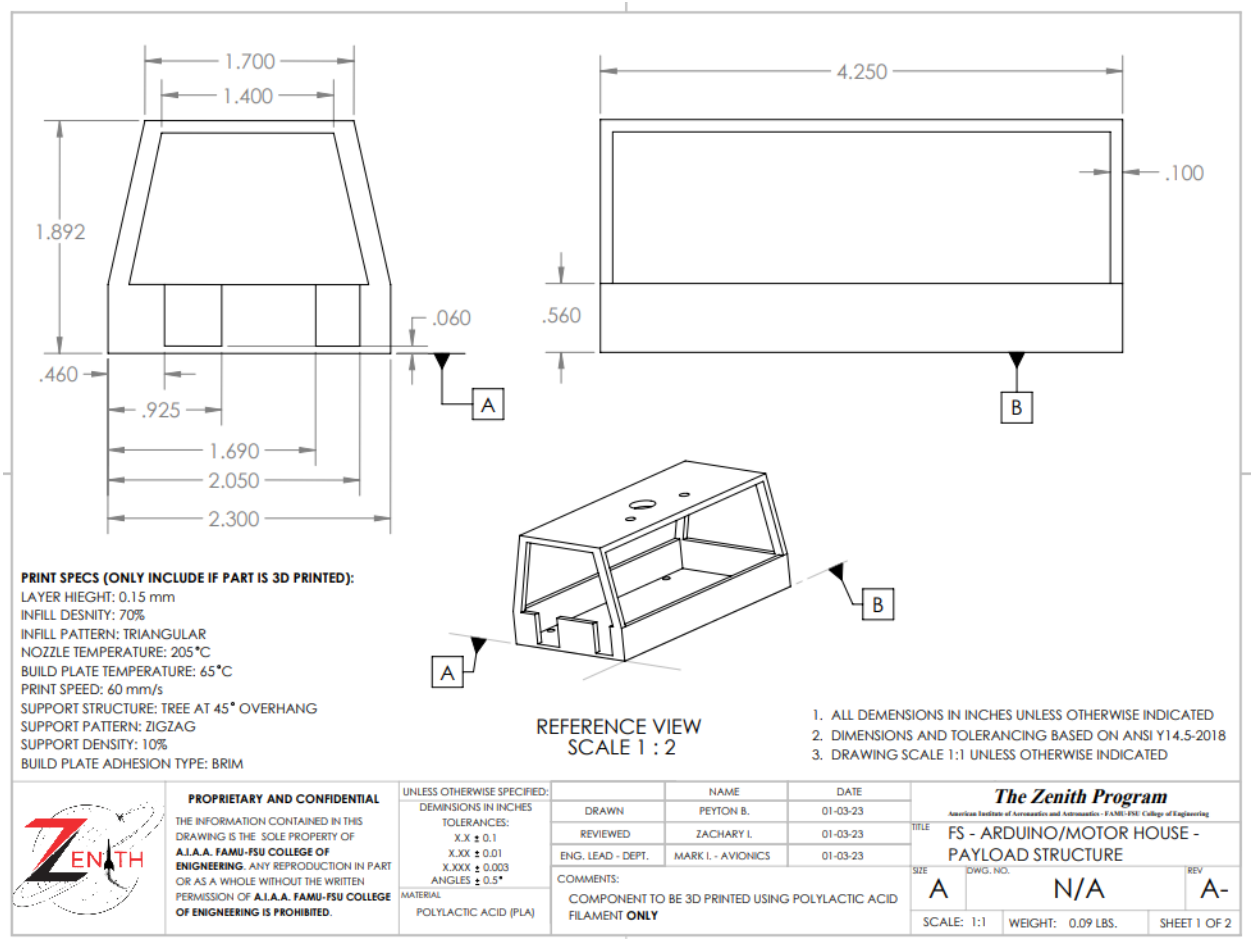



***Figure 4-6. Arduino/Motor Housing Drawing***

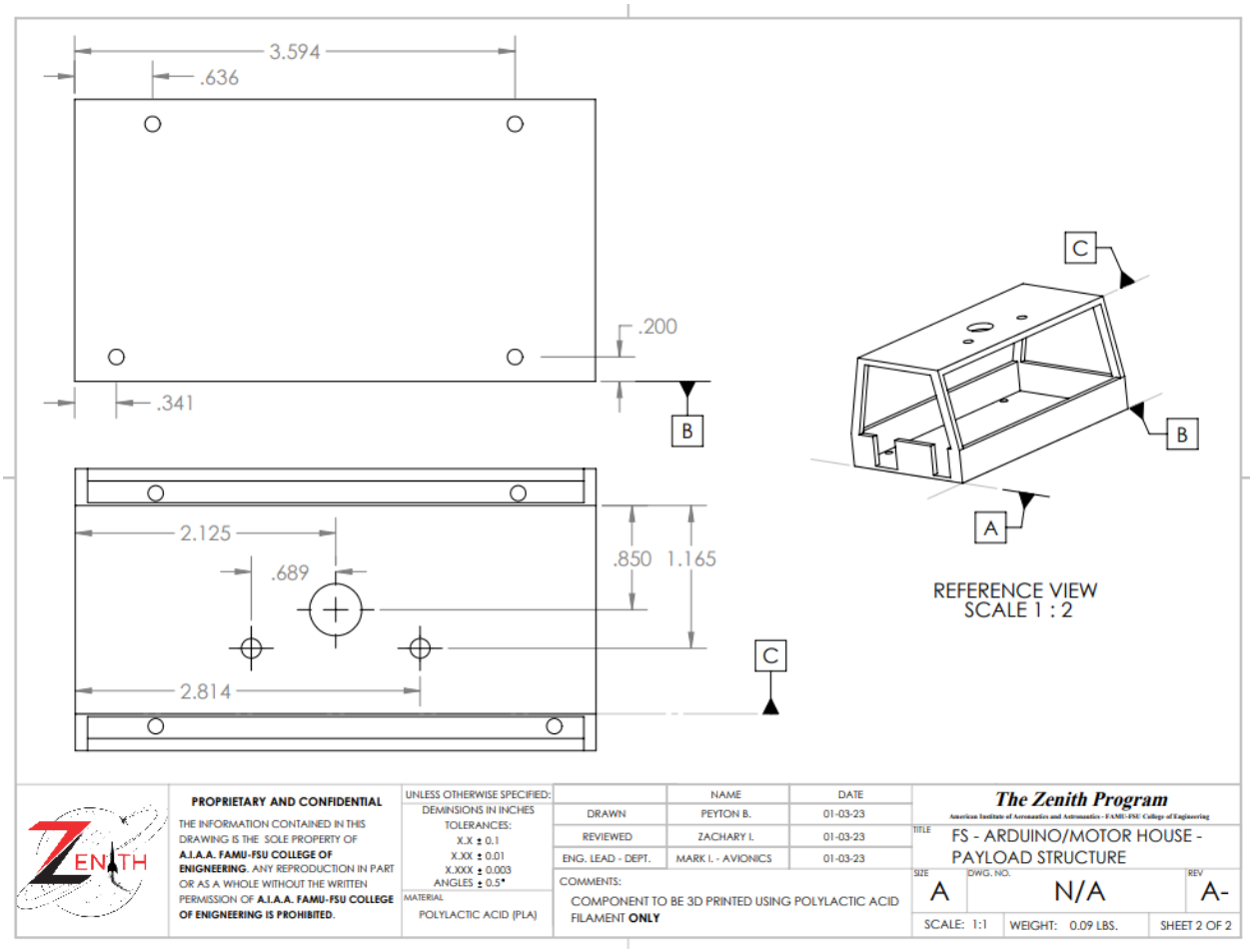



***Figure 4-7 Arduino/Motor Housing Drawing (Continued)***

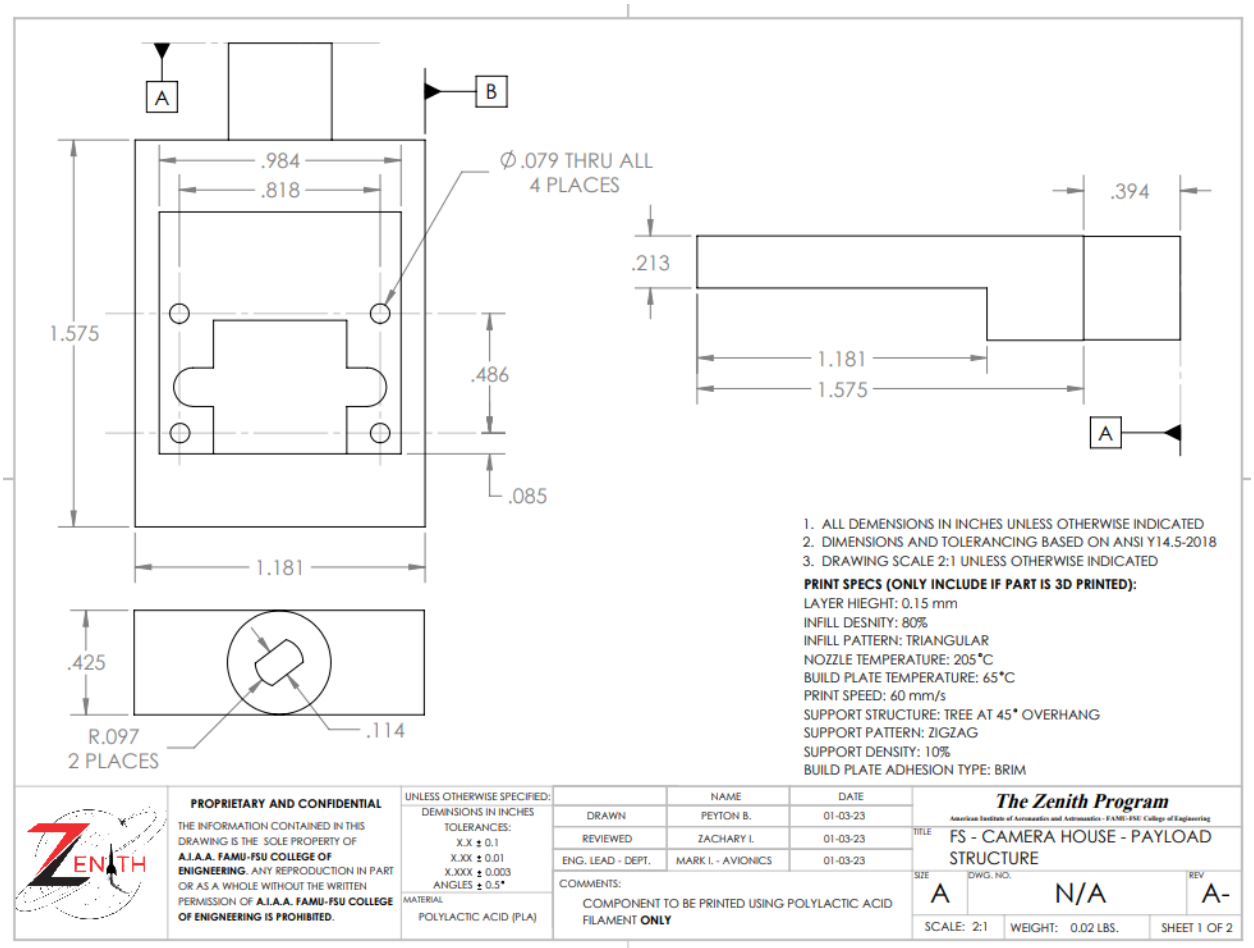



***Figure 4-8 Camera Housing Drawing***

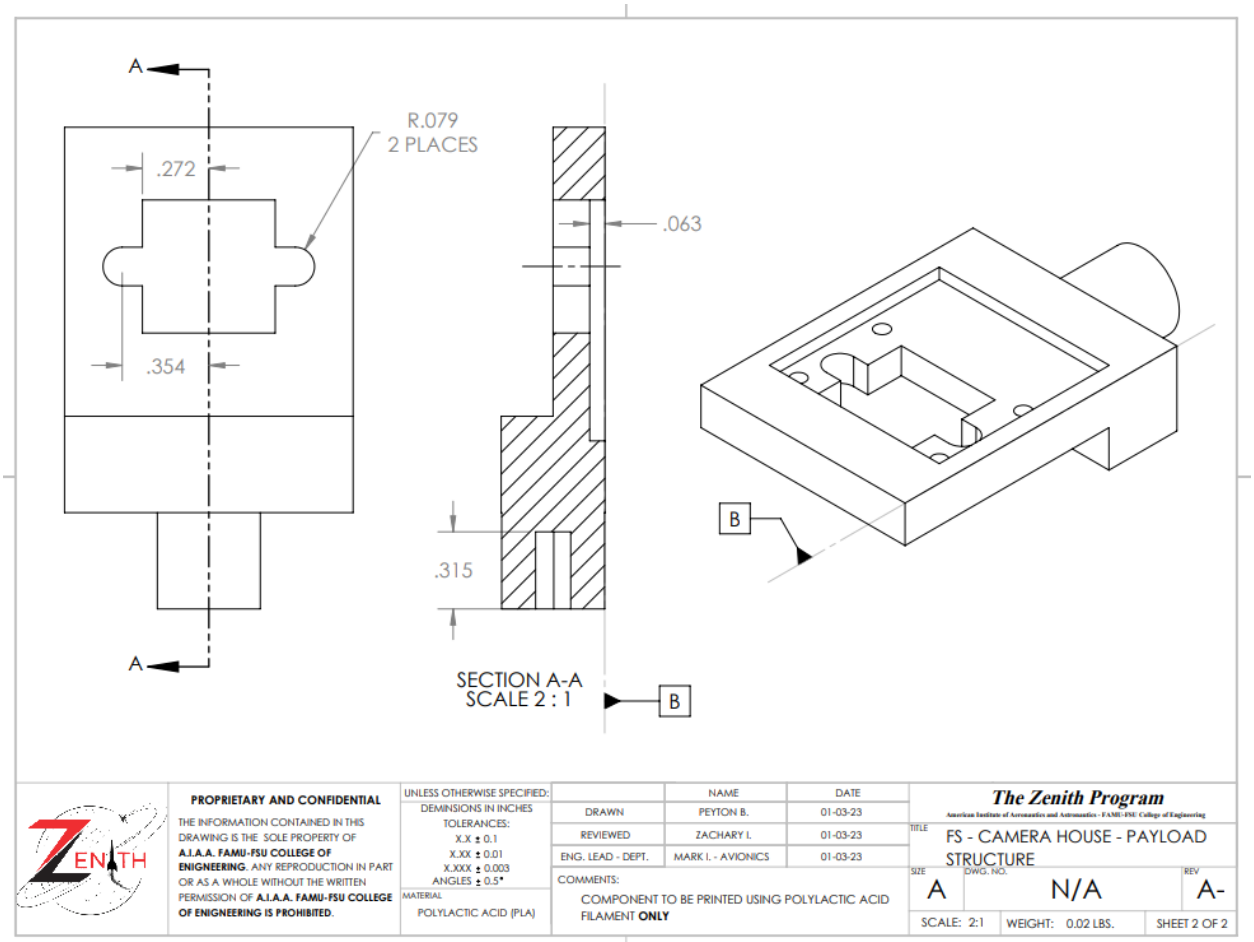



***Figure 4-9 Camera Housing Drawing (Continued)***

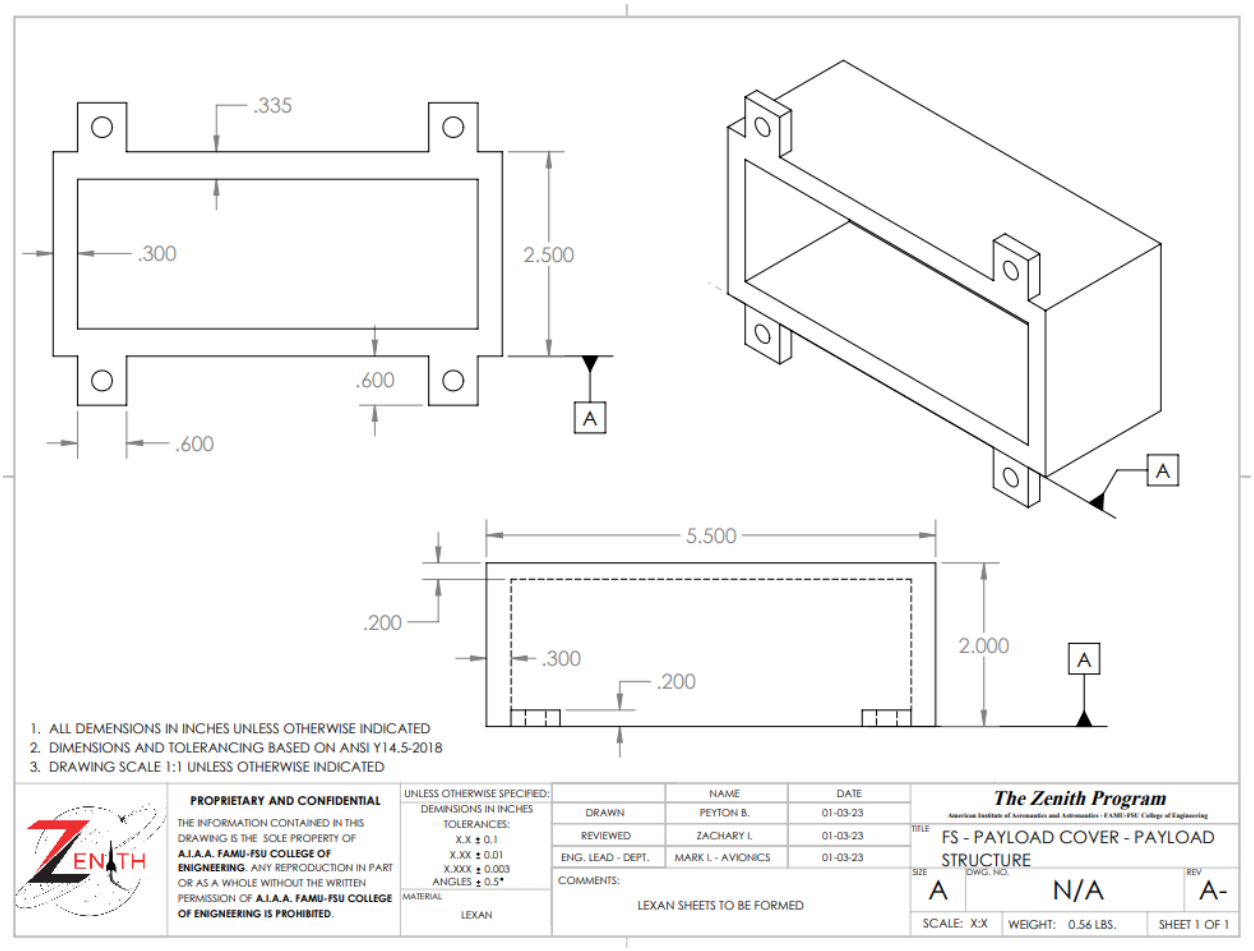



***Figure 4-10. Lexan Camera Enclosure***

### 4.3.2 Vehicle integration

The payload will sandwiched by two 3D printed “bumpers” which follow the surface geometry of the payload housing on their interior, and are rounded externally to the radius of the airframe. The resultant payload package is then effectively a cylinder. The bumpers will be connected to the recovery harness by a short length of shock cord, but not to the payload housing in any way. When seated in the airframe, the bumpers and payload will be effectively immobilized. On main chute deployment, the main parachute will pull the recovery harness from the upper payload bay, pulling out the payload and bumpers. The bumpers will fall away from the payload after exiting the airframe and dangle a ways away from the housing, both exposing the enclosure for ground impact and ensuring the parts do not impede its stable landing.

# 5 Safety

## 5.1 Vehicle Assembly and Operation Checklists

The assembly and operation checklists are a chronological order of operations to be executed by the team during launch day assembly, pre-flight, and post-flight. For steps not including the VERIFY notice, any member of the team may participate and/or execute the action under the supervision of the associated technical lead (ex: recovery lead supervises connection of wire leads to ejection charge e-matches).

Items that include the VERIFY label constitute an all-stop until the Program Director and Safety Officer have both conferred with the associated technical lead, inspected the action described in the VERIFY notice, as well as all unverified work up to that point. Both the PD and SO must sign the checklist at each VERIFY notice, with approval of the relevant lead, before the team can resume working down the checklist. The purpose of the VERIFY notice is to halt progress at mission-critical actions that, if executed incorrectly, could or would result in failure to launch or failures during flight.

A table of justifications for each VERIFY notice will follow all checklists.

**NOTE:**

Checklists announce **Recommended PPE** and **REQUIRED PPE** before an action where PPE would enhance safety or is otherwise required.

While only several checklist steps recommend or require PPE, there are many steps which involve work with low voltage electrical. This is to serve as a blanket notice for all such steps in the interest of brevity on the checklist.

For ANY electrical work, the recommendation of the safety officer is the following:

When making electrical connections – **Recommended PPE: insulating nitrile gloves**

### 5.1.1 Vehicle Assembly Checklist

| Vehicle Assembly Checklist | | | | | |
|---|---|---|---|---|---|
| **Step** | **Verification** | **Action** | **Complete** | **Program Director** | **Safety Officer** |
| **Avionics Bay** | | | | | |
| 1 | **VERIFY** | Batteries are charged prior to assembly. Altimeters turn on when switches pressed | | | |
| 2 | | Fasten avionics sled inside bay | | | |
| 3 | | Route A channel wires and corresponding grounds to one side | | | |
| 4 | | Route B channel wires and corresponding grounds to opposite side | | | |
| 5 | | Screw CO2 cartridges into all charge bases on inside of bulkheads | | | |
| 6 | | Replace avionics bulkhead and fasten | | | |
| 7 | **VERIFY** | Altimeters turn on when switches are pressed | | | |
| | **For Today's Launch** | | | | |
| | **Channel** | **Color** | | | |
| | **A** | | | | |
| | **B** | | | | |
| | **G** | | | | |
| **Ejection Charges** | | | | | |
| 8 | | Place O-ring around base of e-match | | | |
| 9 | | **PPE Recommended: respirator** Place small amount of 5-minute epoxy on O-ring. Pass through charge cup until O-ring contacts bottom | | | |
| 10 | | Wait 10 minutes for e-matches to become secured in place | | | |
| 11 | | **While waiting:** prepare 4 pre-measured black powder loads | | | |
| 12 | | **Once cured:** load black powder into charge cups and cover with red sticker | | | |
| 13 | **VERIFY** | E-matches secure. Charge cups loaded. Stickers firmly attached. | | | |
| 14 | | Unscrew red housings from external AV bay. Place charge cups in red housing | | | |

| | | | | | |
|---|---|---|---|---|---|
| 15 | | Place spring vertical on table. Place steel pointed plug **point side down** on top of screw | | | |
| 16 | | Invert red housing w/ charge cup. Push down against plug until cup is seated at bottom of red housing and plug is directly above | | | |
| 17 | **VERIFY** | Charge cups properly seated and plugs flush with cup tops | | | |
| 18 | | Keeping spring pressed against plug, screw red housing into base on outside of AV bay | | | |
| 19 | | Connect A-channel and ground leads to e-match 1 & 2 leads | | | |
| 20 | | Connect B-channel and ground leads to e-match 3 & 4 leads | | | |
| 21 | **VERIFY** | Each e-match is connected to an A/B channel AND a ground wire. **Reference wire color table above** | | | |
| 22 | | Tape external wires to red charge housings, clear of recovery harness attachment bolts | | | |
| **Upper PL Bay, Payload, and Main Chute** | | | | | |
| 23 | | Connect recovery harness end to foreword nosecone bulkhead | | | |
| 24 | | Connect main parachute to midpoint quick link of recovery harness | | | |
| 25 | **VERIFY** | Payload battery is charged. Payload activates when switch is in "on" position | | | |
| 26 | | Switch payload electronics to "on" | | | |
| 27 | **VERIFY** | Payload is on before installation | | | |
| 28 | | Place payload in housing. Connect to PL quick link between foreword bulkhead and main chute | | | |
| 29 | | Connect recovery harness end to avionics **B side** bulkhead | | | |
| 30 | **VERIFY** | Main parachute harness is connected to avionics **B side** | | | |

| | | | | | |
|---|---|---|---|---|---|
| 31 | | Lay out horizontal: Nose section, payload, main chute, av bay | | | |
| 32 | **VERIFY** | All quick links are attached to the correct location and fully closed | | | |
| 33 | | Insert payload into housing. Insert payload housing into upper payload bay. | | | |
| 34 | | Pack main parachute | | | |
| 35 | **VERIFY** | Main parachute is correctly packed | | | |
| 36 | | Insert packed main chute into upper payload bay. Reeve remaining shock cord | | | |
| 37 | | Join upper payload bay and **B-side** of avionics bay | | | |
| 38 | **VERIFY** | B-channel ejection charges are inserted into upper payload bay | | | |
| 39 | | Screw shear pins into pre-drilled holes to join UPLB and AV bay | | | |
| **Motor Installation** | | | | | |
| 52 | | Unscrew motor retainer ring. Remove motor casing and motor tube from vehicle | | | |
| 53 | | **PPE Recommended: nitrile gloves**<br>Lightly grease aft, forward, and foreword seal disk O-rings | | | |
| 54 | | Install forward seal disk O-ring onto foreword seal disk. Install foreword seal disk in motor case. | | | |
| 55 | | Install foreword closure with threaded adapter to receive eye bolt | | | |
| 56 | **VERIFY** | Eye bolt adapter installed to motor case. Install eye bolt | | | |
| 57 | | **PPE REQUIRED: nitrile gloves, safety goggles, long sleeves, pants, closed-toed shoes**<br>Insert liner containing propellant grains into motor tube. Insert tube into motor casing | | | |
| 58 | **VERIFY** | No motor delay or ejection charge installed. | | | |

| | | | | | |
|---|---|---|---|---|---|
| 59 | | Screw on aft closure. Replace motor retainer | | | |
| 60 | **VERIFY** | Motor retainer reinstalled. Nozzle cap fixed over nozzle. | | | |
| **Lower PL Bay, Fin Can, and Drogue Chute** | | | | | |
| 40 | | Connect recovery harness end to eye bolt at top of motor case | | | |
| 41 | | Connect drogue parachute to midpoint quick link of recovery harness | | | |
| 42 | | Connect recovery harness end to avionics **A side** bulkhead | | | |
| 43 | **VERIFY** | Drogue parachute harness is connected to avionics **A side** | | | |
| 44 | | Lay out horizontal: av bay, drogue chute, LPLB/fin can | | | |
| 45 | **VERIFY** | All quick links are attached to the correct location and fully closed | | | |
| 46 | | Pack drogue parachute | | | |
| 47 | **VERIFY** | Drogue parachute is correctly packed | | | |
| 48 | | Insert packed drogue chute into lower payload bay. Reeve remaining shock cord | | | |
| 49 | | Join lower payload bay and **A-side** of avionics bay | | | |
| 50 | **VERIFY** | A-channel ejection charges are inserted into upper payload bay | | | |
| 51 | | Screw shear pins into pre-drilled holes to join LPLB and AV bay | | | |
| **Final Sign-Off** | | | | | |
| 61 | **VERIFY** | All checklist steps completed. Vehicle prepared for pre-flight. | | | |

### 5.1.2 Pre-flight Checklist

| Pre-Flight Checklist | | | | | |
|---|---|---|---|---|---|
| **Step** | **Verification** | **Action** | **Complete** | **Program Director** | **Safety Officer** |
| 1 | | Confirm launch group/time with NASA RSO | | | |
| 2 | | Confirm launch pad with NASA RSO | | | |
| 3 | **VERIFY** | Cleared by RSO to approach pad | | | |
| 4 | | Inspect launch rail cant. Note and refer to simulations | | | |
| 5 | | Install vehicle on 1515 launch rail | | | |
| 6 | | Switch on flight computers | | | |
| 7 | **VERIFY** | Flight computers both active | | | |
| 8 | | Connect 12V lanch leads to igniter leads on vehicle | | | |
| 9 | | Continuity check | | | |
| 10 | **VERIFY** | Good continuity | | | |
| **Final Sign-Off** | | | | | |
| 11 | **VERIFY** | All checklist steps completed. Vehicle prepared for flight. | | | |

### 5.1.3 Terminal Count and In-Flight Checklist

| Terminal Count and In-Flight Checklist | | | | | |
|---|---|---|---|---|---|
| **Step** | **Verification** | **Action** | **Complete** | **Program Director** | **Safety Officer** |
| 1 | | Ensure active communication with TeleMega flight computer | | | |
| 2 | | Ensure avionics batteries sufficiently charged (live telemetry from TeleMega) | | | |
| 3 | **VERIFY** | Cleared for launch by RSO | | | |
| 4 | | Begin terminal count | | | |
| **Launch** | | | | | |
| 5 | | Avionics lead, using live telemetry, confirms apogee charges fire. **Callout: "Sep 1"** | | | |
| 6 | | Team visually confirms drogue deployment. **Callout: "Good drogue"** | | | |
| 7 | | Avionics lead confirms reduction in descent velocity from telemetry. **Callout: "Av Concurs"** | | | |
| 8 | | Team maintains visual on vehicle during descent | | | |
| 9 | | Avionics lead, using live telemetry, confirms 550ft charges fire. **Callout: "Sep 2"** | | | |
| 10 | | Team visually confirms main deployment. **Callout: "Good main"** | | | |
| 11 | | Avionics lead confirms reduction in descent velocity from telemetry. **Callout: "Av Concurs"** | | | |
| 12 | | Team maintains visual on vehicle during descent | | | |

| | | | | | |
|---|---|---|---|---|---|
| 13 | | Team visually confirms landing.<br>**Callout: "Impact"** | | | |
| 14 | | Avionics lead confirms zero descent velocity from telemetry.<br>**Callout: "Av Concurs"** | | | |
| **Final Sign-Off** | | | | | |
| 15 | **VERIFY** | All checklist steps completed.<br>Vehicle successfully recovered. | | | |

### 5.1.4 Post-Flight Checklist

| Post-Flight Checklist | | | | | |
|---|---|---|---|---|---|
| **Step** | **Verification** | **Action** | **Complete** | **Program Director** | **Safety Officer** |
| 1 | **VERIFY** | Cleared by RSO to approach pad | | | |
| 2 | | Measure distance from pad to point of vehicle impact | | | |
| 3 | | Disconnect recovery harnesses from both sides of avionics bay | | | |
| 4 | **VERIFY** | Avionics bay turned over to avionics lead | | | |
| 5 | | Vehicle components returned to staging area. Lay upper and lower sections on table and inspect for damage | | | |
| 6 | **VERIFY** | Visual confirmation that all ejection charges fired before work on av bay begins | | | |
| 7 | | Detach removable av bay bulkhead and remove sled | | | |
| 8 | | Avionics team connects to flight computers and downloads data | | | |
| 9 | **VERIFY** | Data has been downloaded and saved before computer shutdown | | | |
| 10 | | Flight computers shutdown | | | |
| **Final Sign-Off** | | | | | |
| 11 | **VERIFY** | All checklist steps completed | | | |

### 5.1.5 Verify Notice Justifications

***Table 5-1. Safety Verification(s) Rationale***

| Checklist | Step # | Step to Verify | Reason for Verification |
|---|---|---|---|
| Assembly | 1 | Batteries are charged prior to assembly. Altimeters turn on when switches pressed | Uncharged batteries could cause failure to launch or loss of power in flight |
| Assembly | 7 | Altimeters turn on when switches are pressed | Ensures connections were not disturbed after av bay is sealed |
| Assembly | 13 | E-matches secure. Charge cups loaded. Stickers firmly attached. | Ensures e-matches will not slip from cups and cups cannot spill out black powder. Either case can cause failed separation. |
| Assembly | 17 | Charge cups properly seated and plugs flush with cup tops | Improper cup and plug seating can fail to puncture CO2 cartridge, causing failed separation |
| Assembly | 21 | Each e-match is connected to an A/B channel AND a ground wire. **Reference wire color table above** | Ensures a complete circuit is connected to each e-match. Failure to connect ground would mean a dud charge and no separation |
| Assembly | 25 | Payload battery is charged. Payload activates when switch is in "on" position | Ensures payload will not experience power loss during mission and switch is functional |
| Assembly | 27 | Payload is on before installation | Ensures payload is powered up to execute RAFCO mission |
| Assembly | 30 | Main parachute harness is connected to avionics **B side** | B side is 550ft deployment. If connected to A side, main would deploy at apogee |
| Assembly | 32 | All quick links are attached to the correct location and fully closed | Ensures chute is in proper position and connected to sections to avoid entanglement |
| Assembly | 35 | Main parachute is correctly packed | Poor packing can cause entanglement |
| Assembly | 38 | B-channel ejection charges are inserted into upper payload bay | B side is 550ft deployment. If A side was inserted, upper payload bay would separate at apogee and deploy main chute |
| Assembly | 44 | Eye bolt adapter installed to motor case. Install eye bolt | Ensures non-stock foreword closure is used and connection point to fin can is present |

| Checklist | Step # | Step to Verify | Reason for Verification |
|---|---|---|---|
| Assembly | 46 | No motor delay or ejection charge installed. | Installation of ejection charge could cause motor jettison, or explosion in airframe if motor was retained after blast |
| Assembly | 48 | Motor retainer reinstalled. Nozzle cap fixed over nozzle. | Ensures motor cannot be jettisoned and nozzle will remain debris free |
| Assembly | 52 | Drogue parachute harness is connected to avionics **A side** | A side is apogee deployment. If connected to B, drogue would deploy at 550ft |
| Assembly | 54 | All quick links are attached to the correct location and fully closed | Ensures chute is in proper position and connected to sections to avoid entanglement |
| Assembly | 56 | Drogue parachute is correctly packed | Poor packing can cause entanglement |
| Assembly | 59 | A-channel ejection charges are inserted into upper payload bay | A side is apogee deployment. If B side was inserted, lower payload would separate at 550ft and deploy drogue chute |
| | | | |
| Pre-Flight | 3 | Cleared by RSO to approach pad | Ensures range is safe for team members to exit the viewing and staging areas |
| Pre-Flight | 7 | Flight computers both active | Failure to activate computers would result in failure to launch |
| Pre-Flight | 10 | Good continuity | Bad continuity in 12V igniter system would result in failure to launch |
| | | | |
| Terminal Count | 3 | Cleared for launch by RSO | Ensures pad and range are clear for flight |
| | | | |
| Post-Flight | 1 | Cleared by RSO to approach pad | Ensures pad and range are safe to approach |
| Post-Flight | 4 | Avionics bay turned over to avionics lead | Ensures hand-off of flight data to the team responsible for download and storage |
| Post-Flight | 6 | Visual confirmation that all ejection charges fired before work on av bay begins | Prevents possibility of team accidentally triggering charges that failed to fire |
| Post-Flight | 9 | Data has been downloaded and saved before computer shutdown | Data may be deleted if power to computer is cut |

## 5.2 Hazard Analysis

**for the convenience of the review board: the payload section and vehicle structures regarding payload retention have been updated to reflect the changes to risk as a result of the radical design change, as has recovery with the removal of electronic chute releases. The team felt all other FMEA's were sufficiently detailed and have presented them as they appeared in PDR. A section discussing verification for mitigation strategies has been added after the FMEA's.*

### 5.2.1 Risk Matrix and Definitions

To conduct a Failure Mode and Effects Analysis for each vehicle system, environmental risk assessment, and personnel risk assessment, the risk classification matrix in Table 5-1 was used. Tables 5-1 and 5-2 on the following page define each severity and likelihood class.

***Table 5-2. Risk Classification Matrix***

| Risk Classification Matrix | | | Event Likelihood | | | |
|---|---|---|---|---|---|---|
| | | | Possible | Plausible | Probable | Highly Probably |
| | | | **A** | **B** | **C** | **D** |
| **Event Severity** | Marginal | **1** | 1A | 1B | 1C | 1D |
| | Significant | **2** | 2A | 2B | 2C | 2D |
| | Major | **3** | 3A | 3B | 3C | **3D** |
| | Catastrophic | **4** | 4A | 4B | 4C | **4D** |

***Table 5-3. Severity Classification Definitions***

| Severity | Vehicle Outcomes | Personnel Outcomes |
|---|---|---|
| Marginal | Little to no impact to vehicle integrity. Flight profile consistent with expectation. Safe recovery. Payload intact and deployed. Vehicle can be reused. | No potential for injury created. |
| Significant | Vehicle integrity compromised. Minor repair required. Deviation from expected flight profile. Safe recovery. Payload intact and deployable. Vehicle can be reused. | Minor risk of injury created. No injuries. |
| Major | Vehicle integrity compromised. Substantial repair required. Large deviation from expected flight profile. Recovery may endanger personnel. Payload and deployment mechanism damaged. Vehicle can be reused. | Great risk of injury created. Injuries reported. Injuries are manageable with basic first-aid. |
| Catastrophic | Vehicle breakup in flight. Irreparable damage. Unarrested descent. Recovery not possible. Payload destroyed. Complete loss of vehicle and payload. | Great risk of injury created. Injuries reported. Injuries require professional medical attention. |

***Table 5-4. Likelihood Classification Definitions***

| Likelihood | Definition |
|---|---|
| Possible | Within the set of all conceivable outcomes. Not likely to occur. |
| Plausible | Reasonable chance of occurrence due to uncertainty bounds. |
| Probable | Likley to occur. Uncertainty is now in whether the event will **not** occur. |
| Highly Probable | Near certainty. Statistical chance of occurrence far outweighs the chance of no occurrence. |

### 5.2.2 Vehicle Systems Failure Mode and Effects Analysis

***Table 5-5. Avionics and Power Systems FMEA***

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(PS.1)** Power loss on pad | • Dead battery<br>• Disconnection of leads | 1A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Loss of power to flight computer | • Vehicle launch cannot be commanded<br>• Battery replacement required<br>• Personnel must approach cold vehicle – minimal risk | • Ensure battery is charged pre-flight<br>• Have flight computer transmit battery condition<br>• Firm lead attachment<br>• Redundant power/avionics |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PS.2)** Power loss in flight | • Dead battery<br>• Disconnection of leads | 4A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Loss of power to flight computer | • Loss of vehicle control<br>• No control authority over recovery system<br>• Unable to measure altitude<br>• Unable to command deployment events<br>• Unarrested descent<br>• Risk to personnel | • Ensure battery is charged pre-flight<br>• Have flight computer transmit battery condition<br>• Firm lead attachment<br>• Redundant power/avionics |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PS.3)** Power loss after recovery | • Dead battery<br>• Disconnection of leads | 1A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Loss of power to flight computer | • Loss of control authority over payload deployment mechanism<br>• Unable to deploy payload | • Ensure battery is charged pre-flight<br>• Have flight computer transmit battery condition<br>• Firm lead attachment<br>• Redundant power/avionics |

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(AV.1)** In-flight barometer failure | • Bad component<br>• Poor component calibration<br>• Power loss | 2A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Altitude cannot be determined from atmospheric pressure | • Vehicle relies on double integration of accelerometer data for altitude<br>• Large compounding errors in integration may cause off-nominal main deployment<br>• Nominal drogue deployment using accelerometer | • Purchase components from reputable dealer<br>• Test components extensively before flight<br>• Firm electrical lead attachments<br>• Redundant power/avionics |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(AV.2)** In-flight accelerometer failure | • Bad component<br>• Poor component calibration<br>• Power loss | 2A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Altitude and velocity cannot be determined by integration of acceleration data | • Vehicle relies on inflection of barometric data to determine apogee (pressure begins increasing)<br>• Potential off-nominal drogue deploy<br>• Nominal main chute deployment using barometer | • Purchase components from reputable dealer<br>• Test components extensively before flight<br>• Firm electrical lead attachments<br>• Redundant power/avionics |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(AV.3)** Simultaneous in-flight accelerometer/barometer failure | • Power loss | 2A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Altitude and velocity cannot be determined | • Recovery events reliant on time-commanded backup charges<br>• Off-nominal drogue deploy<br>• Off-nominal main deploy | • Purchase components from reputable dealer<br>• Test components extensively before flight<br>• Firm electrical lead attachments<br>• Redundant power/avionics |

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(AV.4)** In-flight/post-flight GPS unit failure | • Bad component<br>• Poor component calibration<br>• Power loss | 2A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Vehicle landing site cannot be precisely determined | • Sonic beacon becomes primary locator<br>• Visual tracking to ground aids in recovery | • Purchase components from reputable dealer<br>• Test components extensively before flight<br>• Firm electrical lead attachments<br>• Redundant power/avionics |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(AV.5)** Flight computer failure (pre-flight) | • Bad component<br>• Power loss | 2A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Loss of control authority over vehicle | • Vehicle launch cannot be commanded<br>• Personnel must approach cold vehicle – minimal risk | • Same as previous |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(AV.6)** Flight computer failure (in-flight) | • Bad component<br>• Power loss | 4A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Loss of control authority over vehicle | • No control authority over recovery system<br>• Unable to measure altitude<br>• Unable to command deployment events<br>• Unarrested descent<br>• Risk to personnel | • Same as previous |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(AV.7)** Flight computer failure (post-flight) | • Bad component<br>• Power loss | 1A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Loss of control authority over vehicle | • Loss of control authority over payload deployment mechanism<br>• Unable to deploy payload | • Same as previous |
| | | |

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(AV.8)** Wire leads disconnect | • Excessive vehicle vibration<br>• Poor terminal connections | 4D |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Any combination of AV.1 – AV.4, AV.6, and AV.7 failure modes | • Loss of control authority over vehicle<br>• No control authority over recovery system<br>• Unable to measure altitude<br>• Unable to command deployment events<br>• Unarrested descent<br>• Risk to personnel<br>• Loss of control authority over payload deployment mechanism<br>• Unable to deploy payload | • Ensure proper soldering of terminal leads<br>• Extensively test robustness of connections to tension and vibration<br>• Implement vibration damping measures for electrical components<br>• Redundant power/avionics |

***Table 5-6. Avionics and Power Systems Risk Matrix***

| Risk Classification Matrix | | | Event Likelihood | | | |
|---|---|---|---|---|---|---|
| | | | Possible | Plausible | Probable | Highly Probably |
| | | | A | B | C | D |
| Event Severity | Marginal | 1 | PS.1, PS.3, 1A, AV.7 | 1B | 1C | 1D |
| | Significant | 2 | AV.1, AV.2, AV.3, AV.4, AV.5, 2A | 2B | 2C | 2D |
| | Major | 3 | 3A | 3B | 3C | 3D |
| | Catastrophic | 4 | PS.2, AV.6, 4A | 4B | 4C | AV.8, 4D |

***Table 5-7. Energetics and Pyrotechnics FMEA***

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(PRO.1)** Failed motor igniter | • E-match fails to ignite<br>• Black powder pellet fails to ignite after E-match | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Vehicle remains on launchpad in unknown state | • E-match/igniter replacement required<br>• Personnel must approach warm vehicle – significant risk<br>• Dud ignition converts vehicle cold<br>• Random ignition in time following dud – significant risk to personnel approaching | • Redundant e-matches<br>• E-match close proximity to black powder pellet |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PRO.2)** Ejection charge initiation failure | • E-match fails to ignite | 2B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Body sections do not separate | • Separation dependent on backup charge (time initiated)<br>• Off-nominal parachute deployment | • Redundant e-matches |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PRO.3)** Ejection charge fails to separate sections | • Insufficient black powder load<br>• Excessive friction in coupler<br>• Shock cord entanglement | 2B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Body sections do not fully separate | • Structural damage between colliding body sections<br>• Separation dependent on backup charge (time initiated)<br>• Off-nominal parachute deployment | • Redundant ejection charges:<br>• Time-commanded backup charge |
| | | |

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(EN.1)** Unintentional motor ignition | • Static Discharge<br>• Human Error | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Launch vehicle departs launch rails unexpectedly | • Flight computer not prepared to execute profile<br>• Unable to command recovery sequence<br>• Burns and hearing damage to personnel in immediate vicinity of vehicle | • Ensure vehicle is grounded in prep area and on pad<br>• Ensure proper communication during count sequence |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(EN.2)** Unintentional ejection charge initiation (pre-flight) | • Static Discharge<br>• Human Error | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Unexpected black powder detonation | • Creation of large audible signature and expulsion of hot exhaust gasses<br>• Great injury to personnel standing in line with and near charge. Medical emergency<br>• Burns and hearing damage to personnel in immediate vicinity of vehicle<br>• Body section(s) are ejected<br>• Body sections impact nearby personnel. Minor to significant injuries | • Ensure vehicle is grounded in prep area and on pad<br>• Ensure proper communication during count sequence<br>• Implement CO2 ejection system |

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(EN.3)** Uneven combustion in solid fuel | • Poor mixing of fuel and oxidizer<br>• Poor distribution of propellant in case | 4C |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Asymmetric thrust about vehicle z-axis | • Deviation from expected flight path<br>• Loss of vehicle stability<br>• In-flight break up of vehicle. Loss of vehicle<br>• Unarrested descent. Risk to personnel | • Purchase motor from reputable dealer (Cesaroni is the current selection) |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(EN.4)** Motor exhaust in body tube | • Motor case rupture<br>• Nozzle foreword of thrust plate | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Damage to body tube<br>• Loss of vehicle integrity | • Mid-flight fin detachment<br>• Catastrophic body rupture<br>• Vehicle in-flight breakup<br>• Loss of vehicle | • Aluminum motor case, thrust plate, and motor retainer<br>• Extensive sealing in motor compartment |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(EN.5)** Motor jettison | • Thrust plate or motor retainer failure | 3A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Motor and casing separate from launch vehicle after burnout | • Changes to stability margin as Cg shifts towards nose<br>• Deviation from projected flight profile<br>• Risk to personnel from uncontrolled, unarrested descent of metal motor casing | • Aluminum thrust plate and motor retainer to ensure dynamic loading margins are not exceeded |

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(EN.6)** Avionics damage | • Hot/corrosive ejection charge exhaust gasses | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Development of any AV.1 – AV.4 and AV.6 Failure Modes | • No control authority over recovery system<br>• Unable to measure altitude<br>• Unable to command deployment events<br>• Unarrested descent<br>• Risk to personnel | • Insulate void space in body<br>• Implement CO2 ejection system |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(EN.7)** Burned parachute(s) | • Hot/corrosive ejection charge exhaust gasses | 4D |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Drogue and/or main parachute unable to provide sufficient drag to slow descent | • Partially or fully unarrested descent<br>• Fire inside body tube<br>• Fire in canopy on descent | • Kevlar blankets to retain chutes<br>• Insulate void space<br>• Implement CO2 ejection system |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(EN.8)** Chain detonation of ejection charges | • Hot/corrosive ejection charge exhaust gasses | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Multiple separation event at apogee<br>• Simultaneous deployment of drogue and main chute | • Deviation from intended flight profile<br>• Risk to personnel from (4) and (5)<br>• structural damage to colliding body sections<br>• Parachute entanglement. Increased descent rate Uncontrolled descent.<br>• Decreased descent rate. Increased wind drift. Vehicle exits recovery zone | • Insulate void space in body<br>• Implement CO2 cooling system to black powder ejection charges |

***Table 5-8. Energetics and Pyrotechnics Risk Matrix***

| Risk Classification Matrix | | | Event Likelihood | | | |
|---|---|---|---|---|---|---|
| | | | Possible | Plausible | Probable | Highly Probably |
| | | | A | B | C | D |
| Event Severity | Marginal | 1 | 1A | 1B | 1C | 1D |
| | Significant | 2 | 2A | PRO.2 2B PRO.3 | 2C | 2D |
| | Major | 3 | EN.5 3A | PRO.1 3B EN.8 | 3C | 3D |
| | Catastrophic | 4 | 4A | EN.1 EN.4 4B EN.2 EN.6 | EN.3 4C | EN.7 4D |

***Table 5-9. Recovery System FMEA***

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(RS.1)** Drogue parachute entanglement | • Poor shock cord stowage in body<br>• Snag hazards in deployment path | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • High descent rate after apogee<br>• Main parachute deployment at higher speed | • Main parachute canopy damaged in high-speed deployment<br>• Main parachute cords tear or rupture<br>• Partially or fully unarrested vehicle descent<br>• Over tensioning of vehicle shock cord. Cord tearing or rupture<br>• Unarrested descent of body sections<br>• Risk to personnel<br>• Major repair needed | • Design for no snag hazards in deployment path of parachute<br>• Reeve loose shock cord<br>• Implement cord routing solutions |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RS.2)** Main parachute entanglement | • Poor shock cord stowage in body<br>• Snag hazards in deployment path | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • High descent rate after main deployment<br>• High ground impact velocity | • Partially arrested descent<br>• Damage to vehicle structures<br>• Damage to internal components<br>• Major repair required | • Design for no snag hazards in deployment path of parachute<br>• Reeve loose shock cord<br>• Implement cord routing solutions |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(RS.3)** Shock cord rupture | • Excessive tension on cord | 3A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Tether between body sections compromised | • Unarrested descent of body section(s) | • Extensive simulation pre-flight<br>• Select shock cord with large factor of safety |

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(RS.4)** Shock cord entanglement | • Poor shock cord stowage in body<br>• Snag hazards in deployment path | 1B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Shock cord unable to extend to full length | • Collision of body sections on descent<br>• Very minor damage to structure | • Reeve loose shock cord<br>• Implement cord routing solutions |

***Table 5-10. Recovery System Risk Matrix***

| Risk Classification Matrix | | | Event Likelihood | | | |
|---|---|---|---|---|---|---|
| | | | Possible | Plausible | Probable | Highly Probably |
| | | | A | B | C | D |
| Event Severity | Marginal | 1 | 1A | RS.4 1B | 1C | 1D |
| | Significant | 2 | 2A | 2B | 2C | 2D |
| | Major | 3 | RS.3 3A | RS.2 3B | 3C | 3D |
| | Catastrophic | 4 | 4A | RS.1 4B | 4C | 4D |

***Table 5-11. Vehicle Structures FMEA***

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(STR.1)** Melting of fin assembly during motor burn | • Heat transfer from motor case<br>• Lack of heat resistance in fin material | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Loss of flight stability | • Vehicle breakup in-flight<br>• Loss of vehicle<br>• Unarrested descent of body sections<br>• Risk to personnel | • Use heat resistant print material<br>• Treat for heat resistance<br>• Minimize heat transfer |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(STR.2)** Fins shear off | • Fin flutter<br>• Aerodynamic loading | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Loss of flight stability | • Vehicle breakup in-flight<br>• Loss of vehicle<br>• Unarrested descent of body sections<br>• Risk to personnel | • Extensive simulation pre-flight<br>• Ensure flutter speed >> max vehicle velocity |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(STR.3)** Body tube zippering | • Shock cord contact with body on deployment | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Loss of vehicle integrity | • Vehicle damage on descent<br>• Major repair needed | • Implement “bumpers” to avoid cord contact<br>• Implement cord routing |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(STR.4)** Damaged motor retainer | • Defect in part<br>• Excessive dynamic loading | 3A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Potential motor jettison after burnout | • Unarrested descent of motor casing<br>• Risk to personnel<br>• Minor repair required | • Aluminum motor retainer to absorb far larger loads than necessary |
| | | |

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(STR.5)** Bulkhead or U-bolt torn loose | • Excessive loading during chute deployment<br>• Late chute deployment | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Body section(s) disconnected from parachute | • Unarrested descent of body section(s)<br>• Risk to personnel<br>• Major repairs required | • Extensive pre-flight simulation<br>• Extra thick bolts and wide bracing on bulkheads |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(STR.6)** Dislodged centering ring(s) | • Defect in part(s)<br>• Excessive dynamic loading<br>• Poor connection to threaded rods | 3A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Motor long axis no longer colinear with vehicle z-axis | • Deviation from flight profile<br>• Minor loss of stability<br>• Risk to personnel | • Fix centering rings to threaded rods with hex nuts<br>• Use thread lock to fix nuts |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(STR.7)** Damaged payload retainer | • Defect in part(s)<br>• Poor 3D print<br>• Excessive dynamic loading<br>• Excessive ground impact velocity | 1B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Payload sits loose in bay | • Minor decrease in vehicle stability<br>• Minor camera housing damage<br>• Improper or impossible rover deployment | • Extensive pre-flight testing<br>• Minimize ground impact velocity<br>• Cushion landing |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(STR.8)** Damaged avionics sled retainer(s) | • Defect in part(s)<br>• Poor 3D print<br>• Excessive dynamic loading<br>• Excessive ground impact velocity | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Avionics sleds sit loose in av bay | • Potential for AV.8 failure mode<br>• Loss of control authority over vehicle | • Extensive pre-flight testing<br>• Minimize ground impact velocity<br>• Cushion landing |

***Table 5-12. Vehicle Structures Risk Matrix***

| Risk Classification Matrix | | | Event Likelihood | | | |
|---|---|---|---|---|---|---|
| | | | Possible | Plausible | Probable | Highly Probably |
| | | | A | B | C | D |
| Event Severity | Marginal | 1 | STR.7 1A | 1B | 1C | 1D |
| | Significant | 2 | 2A | STR.4 2B | 2C | 2D |
| | Major | 3 | STR.6 3A | STR.3 3B STR.8 | 3C | 3D |
| | Catastrophic | 4 | 4A | STR.1 4B STR.5 STR.2 | 4C | 4D |

***Table 5-13. Payload FMEA***

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(PLD.1)** 3-D printed housing damaged | • High ground impact velocity<br>• Defects in 3D print | 1C |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Structure of camera housing compromised | • Internal wiring shifted. Leads torn from Arduino | • Extensive pre-flight testing<br>• Minimize ground impact velocity<br>• Cushion landing |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PLD.2)** Payload lands in a manner where camera is not right side up | • Improper connection to shock cord<br>• High lateral landing velocity | 1B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Payload may be in a configuration which occludes camera view | • Images gathered during RAFCO sequence are poor | • Design connection points to maximize possibility of landing z-axis up<br>• Implement anti-roll measures in the design |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PLD.3)** Power loss | • Dead battery<br>• Electrical lead disconnection | 1B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Loss of control authority over camera | • RAFCO Mission failure | • Charge battery pre-flight<br>• Firm electrical connections |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PLD.4)** Antenna disconnection from microcontroller | • Excessive vibration in flight<br>• Excessive ground impact velocity | 1D |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Loss of control authority over camera and antenna | • RAFCO Mission failure | • Firm electrical connections<br>• Pad landing, reduce velocity |

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(PLD.5)** Microcontroller unit failure | • Bad component<br>• Power loss | 1A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Loss of control authority over camera and antenna | • RAFCO Mission failure | • Firm electrical connections<br>• Reputable supplier |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PLD.6)** Camera failure | • Broken lens during ground impact<br>• Power loss | 1A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Loss of image capturing ability | • RAFCO Mission failure | • Padding or protection around camera assembly<br>• Firm electrical connections |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PLD.7)** Camera actuation system failure | • Motor failure<br>• Obstructed gears<br>• Power loss | 1B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Camera cannot swivel camera | • RAFCO Mission failure | • Firm electrical connections<br>• Clean gear mechanism<br>• Use self-contained stepper motor |

***Table 5-14. Payload Risk Matrix***

| Risk Classification Matrix | | | Event Likelihood | | | |
|---|---|---|---|---|---|---|
| | | | Possible | Plausible | Probable | Highly Probably |
| | | | A | B | C | D |
| Event Severity | Marginal | 1 | PLD.5 1A PLD.6 | PLD.2 1B PLD.3 PLD.7 | PLD.1 1C | PLD.4 1D |
| | Significant | 2 | 2A | 2B | 2C | 2D |
| | Major | 3 | 3A | 3B | 3C | 3D |
| | Catastrophic | 4 | 4A | 4B | 4C | 4D |

***Table 5-15. Environment FMEA***

| Vehicle Risks to Environment | | |
|---|---|---|
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(ENV.1.1)** Launch pad/recovery area fire (energetic initiated) | • Dry vegetation in vicinity of motor ignition | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Danger to wildlife<br>• Danger to habitat<br>• Danger to personnel | • Potential for fire growth if left unmitigated | • Clear launch area of vegetation |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(ENV.1.2)** Launch pad/recovery area fire (LiPo battery initiated) | • Battery overcharge, over discharge, overtemp | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Danger to wildlife<br>• Danger to habitat<br>• Danger to personnel<br>• HazMat release | • Pollution of crops with HazMat<br>• Pollution of groundwater with HazMat | • Clear launch area of vegetation<br>• Do not use battery improperly |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(ENV.1.3)** Interstage insulation littered in launch/ recovery area | • Insulation used in body tube to minimize void space and insulate parachutes from ejection charge gasses | 1C |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Ingestion of insulation by wildlife | • Disrespectful to property owners to eject litter on their land | • Biodegradable insulation (popcorn) |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(ENV.1.4)** Litter spread over launch site by personnel | • Lack of trashcans<br>• Poor team leadership | 1D |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Ingestion of litter by wildlife | • Disrespectful to property owners to litter on their land | • Bring trash bags<br>• Firm leadership. Zero tolerance for littering |

| Environmental Risks to Vehicle | | |
|---|---|---|
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(ENV.2.1)** Vehicle touches down in nearby trees | • Excessive wind drift | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Difficulty in or inability to recover launch vehicle<br>• Minor damage to vehicle components | • Loss of vehicle<br>• Repairs required | • Extra-long shock cord to bring components closer to ground |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(ENV.2.2)** Vehicle touches down in nearby body of water | • Excessive wind drift | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Damage to body tube structure<br>• Damage to avionics or payload electronics | • Major repairs required | • Extensive sealing of avionics bay and rover GNC unit |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(ENV.2.3)** In-flight Collision | • Tall infrastructure (power lines)<br>• Bird strike | 4A |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Loss of stability<br>• Damage to animal or object impacted | • Loss of vehicle<br>• Repair to damaged infrastructure required | • Ensure vehicle is launched away from all infrastructure<br>• Await clear skies |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(ENV.2.4)** Vehicle or components dropped | • Uneven launch site terrain causes personnel tripping | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Damage to vehicle structures<br>• Damage to payload structures<br>• Damage to avionics<br>• Damage to payload electronics | • Inability to launch<br>• Repairs required | • Practice extreme caution while handling vehicle components |

***Table 5-16. Environmental Risk Matrix***

| Risk Classification Matrix | | | Event Likelihood | | | |
|---|---|---|---|---|---|---|
| | | | Possible | Plausible | Probable | Highly Probably |
| | | | A | B | C | D |
| Event Severity | Marginal | 1 | 1A | 1B | ENV.1.3 1C | ENV.1.4 1D |
| | Significant | 2 | 2A | 2B | 2C | 2D |
| | Major | 3 | 3A | ENV.1.1 3B ENV.2.2 ENV.2.4 | 3C | 3D |
| | Catastrophic | 4 | ENV.2.3 4A | ENV.1.2 4B ENV.2.1 | 4C | 4D |

### 5.2.3 Personnel Risk Assessment

Personnel risk assessment was conducted using the same FMEA format as was used for vehicle systems and environmental risk assessment.

***Table 5-17. Personnel FMEA***

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(PPL.1)** Skin contact with APCP solid propellant | • Improper material handling<br>• Lack of PPE | 3D |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Chemical burns<br>• Eye irritation | • None | • Provide safety training<br>• Provide PPE |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PPL.2)** Electrocution | • Improper safety procedures followed<br>• Live electrical while wiring | 2D |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Discomfort/pain<br>• Burns | • Greater or grave injury with prolonged exposure | • Provide safety training |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PPL.3)** Proximity to high-pressure burst event (CO2 charge) | • Overpressure in pressure vessel<br>• Pressure vessel tipping<br>• Human error | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Hearing damage<br>• Struck/Impaled by flying object(s) | • None | • Provide safety training<br>• Do not overfill pressure vessels<br>• Pressure vessels chained to walls<br>• Declare all testing and clear area prior to initiation |

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(PPL.4)** Proximity to explosive event (Black powder charge) | • Accidental initiation (human error, static discharge) | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Hearing damage<br>• Burns from expanding hot gasses | • Severity increased with proximity<br>• Severity increased with decreased angle-off-bore of charge | • Ground vehicle components<br>• Minimize personnel handling charges<br>• Isolate firing mechanism until range clear |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PPL.5)** Proximity to combustion event | • Motor ignition (intentional)<br>• Motor ignition (unintentional)<br>• Loose black powder burn | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Hearing damage<br>• Burns from expanding hot gasses | • Severity increased with proximity<br>• Severity increased with decreased angle-off-bore of charge | • Ground vehicle components<br>• Minimize personnel handling motor<br>• Isolate ignition mechanism until range clear |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PPL.6)** Injury: slip and fall, minor cuts, accidental collisions | • Uneven terrain<br>• Tripping hazards on flat ground<br>• Improperly stored sharp objects | 3B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Pain/discomfort<br>• Bruises<br>• Small lacerations | • Infection of lacerations not immediately treated | • Situational awareness<br>• Clean lab spaces<br>• Proper safety procedures |
| **Failure Mode** | **Cause(s)** | **Hazard Category** |
| **(PPL.7)** Dehydration, heat exhaustion, heat stroke | • Lack of water<br>• Lack of adequate sun protection or shade | 4B |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Thirst<br>• Disorientation<br>• Loss of consciousness | • None | • Provide ample water<br>• Bring portable awning/tent<br>• Bring sunscreen, hats, etc. |

| Failure Mode | Cause(s) | Hazard Category |
|---|---|---|
| **(PPL.8)** Soldering iron burns | • Improper use or stowage of soldering iron | 3D |
| **Primary Effect(s)** | **Secondary Effect(s)** | **Mitigations** |
| • Minor burns | • Increased severity with prolonged contact | • Proper training in use of soldering iron<br>• Minimize personnel involved |

***Table 5-18. Personnel Risk Matrix***

| Risk Classification Matrix | | | Event Likelihood | | | |
|---|---|---|---|---|---|---|
| | | | Possible | Plausible | Probable | Highly Probably |
| | | | A | B | C | D |
| Event Severity | Marginal | 1 | 1A | 1B | 1C | 1D |
| | Significant | 2 | 2A | 2B | 2C | PPL.2 2D |
| | Major | 3 | 3A | PPL.3 3B PPL.6 | 3C | PPL.1 3D PPL.8 |
| | Catastrophic | 4 | 4A | PPL.4 4B PPL.7 PPL.5 | 4C | 4D |

## 5.3 Verification Strategies for proposed mitigations

***Table 5-19. Risks, Mitigations, and Verifications***

| Avionics and Power Systems | | | |
|---|---|---|---|
| **Failure Mode** | **Cause(s)** | **Mitigations** | **Verification Strategy** |
| **(PS.1)** Power loss on pad | • Dead battery<br>• Disconnection of leads | • Ensure battery is charged pre-flight<br>• Have flight computer transmit battery condition<br>• Firm lead attachment<br>• Redundant power/avionics | • Assembly/Operations Checklist<br>• Pre-flight hardware testing (vibration test) |
| **(PS.2)** Power loss in flight | • Dead battery<br>• Disconnection of leads | • Ensure battery is charged pre-flight<br>• Have flight computer transmit battery condition<br>• Firm lead attachment<br>• Redundant power/avionics | • Assembly/Operations Checklist<br>• Pre-flight hardware testing (vibration test) |
| **(PS.3)** Power loss after recovery | • Dead battery<br>• Disconnection of leads | • Ensure battery is charged pre-flight<br>• Have flight computer transmit battery condition<br>• Firm lead attachment<br>• Redundant power/avionics | • Assembly/Operations Checklist<br>• Pre-flight hardware testing (vibration test) |
| **(AV.1)** In-flight barometer failure | • Bad component<br>• Poor component calibration<br>• Power loss | • Purchase components from reputable dealer<br>• Test components extensively before flight<br>• Firm electrical lead attachments<br>Redundant power | • Mentor input<br>• Pre-flight hardware testing (vibration test) |
| **(AV.2)** In-flight accelerometer failure | • Bad component<br>• Poor component calibration<br>• Power loss | • Purchase components from reputable dealer<br>• Test components extensively before flight | • Mentor input<br>• Pre-flight hardware testing (vibration test) |

| | | | |
|---|---|---|---|
| | | • Firm electrical lead attachments<br>• Redundant power/avionics | |
| **(AV.3)** Simultaneous in-flight accelerometer/ barometer failure | • Power loss | • Purchase components from reputable dealer<br>• Test components extensively before flight<br>• Firm electrical lead attachments<br>• Redundant power/avionics | • Mentor input<br>• Pre-flight hardware testing (vibration test) |
| **(AV.4)** In-flight/post-flight GPS unit failure | • Bad component<br>• Poor component calibration<br>• Power loss | • Purchase components from reputable dealer<br>• Test components extensively before flight<br>• Firm electrical lead attachments<br>Redundant power/avionics | • Mentor input<br>• Pre-flight hardware testing (vibration test) |
| **(AV.5)** Flight computer failure (pre-flight) | • Bad component<br>• Power loss | • Same as previous | • Mentor input<br>• Pre-flight hardware testing (vibration test) |
| **(AV.6)** Flight computer failure (in-flight) | • Bad component<br>• Power loss | • Same as previous | • Mentor input<br>• Pre-flight hardware testing (vibration test) |
| **(AV.7)** Flight computer failure (post-flight) | • Bad component<br>• Power loss | • Same as previous | • Mentor input<br>• Pre-flight hardware testing (vibration test) |
| **(AV.8)** Wire leads disconnect | • Excessive vehicle vibration<br>• Poor terminal connections | • Ensure proper soldering of terminal leads<br>• Extensively test robustness of connections to tension and vibration<br>• Implement vibration damping measures for electrical components<br>Redundant power | • Pre-flight hardware testing (vibration test) |

| Energetics and Pyrotechnics | | | |
|---|---|---|---|
| **Failure Mode** | **Cause(s)** | **Mitigations** | **Verification Strategy** |
| **(PRO.1)** Failed motor igniter | • E-match fails to ignite<br>• Black powder pellet fails to ignite after E-match | • Redundant e-matches<br>• E-match close proximity to black powder pellet | • Assembly/Operations Checklist |
| **(PRO.2)** Ejection charge initiation failure | • E-match fails to ignite | • Redundant e-matches | • Assembly/Operations Checklist |
| **(PRO.3)** Ejection charge fails to separate sections | • Insufficient black powder load<br>• Excessive friction in coupler<br>Shock cord entanglement | • Redundant ejection charges<br>• Time-commanded backup charge | • Assembly/Operations Checklist<br>• Pre-flight hardware testing (separation test)<br>• Pre-flight simulations (Shear pin FEA) |
| **(EN.1)** Unintentional motor ignition | • Static Discharge<br>• Human Error | • Ensure vehicle is grounded in prep area and on pad<br>• Ensure proper communication during count sequence | • Assembly/Operations Checklist |
| **(EN.2)** Unintentional ejection charge initiation (pre-flight) | • Static Discharge<br>• Human Error | • Ensure vehicle is grounded in prep area and on pad<br>• Ensure proper communication during count sequence<br>• CO2 ejection system | • Assembly/Operations Checklist |
| **(EN.3)** Uneven combustion in solid fuel | • Poor mixing of fuel and oxidizer<br>• Poor distribution of propellant in case | • Purchase motor from reputable dealer | • Mentor input |
| **(EN.4)** Motor exhaust in body tube | • Motor case rupture<br>Nozzle foreword of thrust plate | • Aluminum motor case, thrust plate, and motor retainer<br>• Extensive sealing in motor compartment | • Assembly/Operations Checklist<br>• Mentor input |

| | | | |
|---|---|---|---|
| **(EN.5)** Motor jettison | • Thrust plate or motor retainer failure | • Aluminum thrust plate and motor retainer to ensure dynamic loading margins are not exceeded | • Pre-flight hardware testing (load test)<br>• Pre-flight simulations (FEA) |
| **(EN.6)** Avionics damage | • Hot/corrosive ejection charge exhaust gasses | • Insulate void space in body<br>• Implement CO2 ejection system | • Pre-flight hardware testing (separation test)<br>• Pre-flight simulations (CFD heat transfer) |
| **(EN.7)** Burned parachute(s) | • Hot/corrosive ejection charge exhaust gasses | • Kevlar blankets to retain chutes<br>• Insulate void space<br>• Implement CO2 ejection system | • Pre-flight hardware testing (separation test)<br>• Pre-flight simulations (CFD heat transfer) |
| **(EN.8)** Chain detonation of ejection charges | • Hot/corrosive ejection charge exhaust gasses | • Insulate void space in body<br>• Implement CO2 cooling system to black powder ejection charges | • Pre-flight hardware testing (separation test)<br>• Pre-flight simulations (CFD heat transfer) |
| **Recovery System** | | | |
| **Failure Mode** | **Cause(s)** | **Mitigations** | **Verification Strategy** |
| **(RS.1)** Drogue parachute entanglement | • Poor shock cord stowage in body<br>• Snag hazards in deployment path | • Design for no snag hazards in deployment path of parachute<br>• Reeve loose shock cord<br>• Implement cord routing solutions | • Assembly/Operations Checklist<br>• Mentor input |
| **(RS.2)** Main parachute entanglement | • Poor shock cord stowage in body<br>• Snag hazards in deployment path | • Design for no snag hazards in deployment path of parachute<br>• Reeve loose shock cord<br>• Implement cord routing solutions | • Assembly/Operations Checklist<br>• Mentor input |
| **(RS.3)** Shock cord rupture | • Excessive tension on cord | • Extensive simulation pre-flight<br>• Select shock cord with large factor of safety | • Pre-flight hardware testing (weighted drop test)<br>• Pre-flight simulations |
| **(RS.4)** Shock cord entanglement | • Poor shock cord stowage in body<br>• Snag hazards in deployment path | • Reeve loose shock cord<br>• Implement cord routing solutions | Assembly/Operations Checklist<br>• Mentor input |

| Vehicle Structures | | | |
|---|---|---|---|
| **Failure Mode** | **Cause(s)** | **Mitigations** | **Verification Strategy** |
| **(STR.1)** Melting of fin assembly during motor burn | • Heat transfer from motor case<br>• Lack of heat resistance in fin material | • Use heat resistant print material<br>• Treat for heat resistance<br>• Minimize heat transfer | • Material testing with High Performance Materials Institute |
| **(STR.2)** Fins shear off | • Fin flutter<br>• Aerodynamic loading | • Extensive simulation pre-flight<br>• Ensure flutter speed >> max vehicle velocity | • Aerodynamic testing with Florida Center for Advanced Aero Propulsion |
| **(STR.3)** Body tube zippering | • Shock cord contact with body on deployment | • Implement “bumpers” to avoid cord contact<br>• Implement cord routing | • Assembly/Operations Checklist<br>• Mentor input |
| **(STR.4)** Damaged motor retainer | • Defect in part<br>• Excessive dynamic loading | • Aluminum motor retainer to absorb far larger loads than necessary | • Pre-flight simulations (FEA) |
| **(STR.5)** Bulkhead or U-bolt torn loose | • Excessive loading during chute deployment<br>• Late chute deployment | • Extensive pre-flight simulation<br>• Extra thick bolts and wide bracing on bulkheads | • Pre-flight hardware testing (jerk)<br>• Pre-flight simulations (FEA) |
| **(STR.6)** Dislodged centering ring(s) | • Defect in part(s)<br>• Excessive dynamic loading<br>• Poor connection to threaded rods | • Fix centering rings to threaded rods with hex nuts<br>• Use thread lock to fix nuts | • Pre-flight hardware testing (jerk)<br>• Pre-flight simulations (FEA) |
| **(STR.7)** Damaged payload retainer | • Defect in part(s)<br>• Poor 3D print<br>• Excessive dynamic loading<br>• Excessive ground impact velocity | • Extensive pre-flight testing<br>• Minimize ground impact velocity<br>• Cushion landing | • Material testing with High Performance Materials Institute<br>• Pre-flight hardware testing (vibration and drop test) |
| **(STR.8)** Damaged avionics sled retainer(s) | • Defect in part(s)<br>• Poor 3D print<br>• Excessive dynamic loading<br>• Excessive ground impact velocity | • Extensive pre-flight testing<br>• Minimize ground impact velocity<br>• Cushion landing | • Material testing with High Performance Materials Institute<br>• Pre-flight hardware testing (vibration and drop test) |

| Payload | | | |
|---|---|---|---|
| **Failure Mode** | **Cause(s)** | **Mitigations** | **Verification Strategy** |
| **(PLD.1)** 3-D printed housing damaged | • High ground impact velocity<br>• Defects in 3D print | • Extensive pre-flight testing<br>• Minimize ground impact velocity<br>• Cushion landing | • Pre-flight hardware testing (drop test) |
| **(PLD.2)** Payload lands in a manner where camera is not right side up | • Improper connection to shock cord<br>• High lateral landing velocity | • Design connection points to maximize possibility of landing z-axis up<br>• Implement anti-roll measures in the design | • Pre-flight hardware testing (drop test) |
| **(PLD.3)** Power loss | • Dead battery<br>• Electrical lead disconnection | • Charge battery pre-flight<br>• Firm electrical connections | • Assembly/Operations Checklist<br>• Pre-flight hardware testing (vibration test) |
| **(PLD.4)** Antenna disconnection from microcontroller | • Excessive vibration in flight<br>• Excessive ground impact velocity | • Firm electrical connections<br>• Pad landing, reduce velocity | • Pre-flight hardware testing (vibration test) |
| **(PLD.5)** Microcontroller failure | • Bad component<br>• Power loss | • Firm electrical connections<br>• Reputable supplier | • Pre-flight hardware testing (vibration test) |
| **(PLD.6)** Camera failure | • Broken lens during ground impact<br>• Power loss | • Padding or protection around camera assembly<br>• Firm electrical connections | • Pre-flight hardware testing (drop test)<br>• Pre-flight hardware testing (vibration test) |
| **(PLD.7)** Camera actuation system failure | • Motor failure<br>• Obstructed gears<br>• Power loss | • Firm electrical connections<br>• Clean gear mechanism<br>• Use self-contained stepper motor | • Pre-flight hardware testing (drop test)<br>• Pre-flight hardware testing (vibration test) |
| **Vehicle Risks to Environment** | | | |
| **Failure Mode** | **Cause(s)** | **Hazard Category** | **Verification Strategy** |
| **(ENV.1.1)** Launch pad/recovery area fire (energetic initiated) | • Dry vegetation in vicinity of motor ignition | • Clear launch area of vegetation | • Team has no control over this. NASA has stated pad will be in plowed field (only topsoil) |

| | | | |
|---|---|---|---|
| **(ENV.1.2)** Launch pad/recovery area fire (LiPo battery initiated) | • Battery overcharge, over discharge, overtemp | • Clear launch area of vegetation<br>• Do not use battery improperly | • Team has no control over this. NASA has stated pad will be in plowed field (only topsoil)<br>• Assembly/Operations Checklist<br>• Battery storage/charging rules implemented in fabrication shop |
| **(ENV.1.3)** Interstage insulation littered in launch/recovery area | • Insulation used in body tube to minimize void space and insulate parachutes from ejection charge gasses | • Biodegradable insulation (popcorn) | • Assembly/Operations Checklist<br>• May not need to insulate interstage…subscale did fine without any |
| **(ENV.1.4)** Litter spread over launch site by personnel | • Lack of trashcans<br>• Poor team leadership | • Bring trash bags<br>• Firm leadership. Zero tolerance for littering | • Pre-launch week departure purchase and packing list |
| **Environmental Risks to Vehicle** | | | |
| **Failure Mode** | **Cause(s)** | **Mitigations** | **Verification Strategy** |
| **(ENV.2.1)** Vehicle touches down in nearby trees | • Excessive wind drift | • Extra-long shock cord to bring components closer to ground | • Assembly/Operations Checklist |
| **(ENV.2.2)** Vehicle touches down in nearby body of water | • Excessive wind drift | • Extensive sealing of avionics bay and camera system | • Assembly/Operations Checklist |
| **(ENV.2.3)** In-flight Collision | • Tall infrastructure (power lines)<br>• Bird strike | • Ensure vehicle is launched away from all infrastructure<br>• Await clear skies | • Assembly/Operations Checklist |
| **(ENV.2.4)** Vehicle or components dropped | • Uneven launch site terrain causes personnel tripping | • Practice extreme caution while handling vehicle components | • Assembly/Operations Checklist |

| Personnel | | | |
|---|---|---|---|
| **Failure Mode** | **Cause(s)** | **Mitigations** | **Verification Strategy** |
| **(PPL.1)** Skin contact with APCP solid propellant | • Improper material handling<br>• Lack of PPE | • Provide safety training<br>• Provide PPE | • Posted laboratory safety rules<br>• Safety Officer supervision<br>• PPE freely available in fabrication shop<br>• PPE included in launch week packing list |
| **(PPL.2)** Electrocution | • Improper safety procedures followed<br>• Live electrical while wiring | • Provide safety training | • Posted laboratory safety rules<br>• Safety Officer supervision<br>• PPE freely available in fabrication shop |
| **(PPL.3)** Proximity to high-pressure burst event (CO2 charge) | • Overpressure in pressure vessel<br>• Pressure vessel tipping<br>• Human error | • Provide safety training<br>• Do not overfill pressure vessels<br>• Pressure vessels chained to walls<br>• Declare all testing and clear area prior to initiation | • Posted laboratory safety rules<br>• Safety Officer supervision |
| **(PPL.4)** Proximity to explosive event (Black powder charge) | • Accidental initiation (human error, static discharge) | • Ground vehicle components<br>• Minimize personnel handling charges<br>• Isolate firing mechanism until range clear | • Posted laboratory safety rules<br>• Safety Officer supervision |
| **(PPL.5)** Proximity to combustion event | • Motor ignition (intentional)<br>• Motor ignition (unintentional)<br>• Loose black powder burn | • Ground vehicle components<br>• Minimize personnel handling motor<br>• Isolate ignition mechanism until range clear | • Posted laboratory safety rules<br>• Safety Officer supervision |
| **(PPL.6)** Injury: slip and fall, minor cuts, accidental collisions | • Uneven terrain<br>• Tripping hazards on flat ground<br>• Improperly stored sharp objects | • Situational awareness<br>• Clean lab spaces<br>• Proper safety procedures | • Posted laboratory safety rules<br>• Safety Officer supervision<br>• Fabrication shop manager appointed to |

| | | | |
|---|---|---|---|
| | | | ensure clean/safe environment |
| **(PPL.7)** Dehydration, heat exhaustion, heat stroke | • Lack of water<br>• Lack of adequate sun protection or shade | • Provide ample water<br>• Bring portable awning/tent<br>• Bring sunscreen, hats, etc. | • Safety Officer supervision<br>• Water, sunscreen, portable tents included in launch week packing list |
| **(PPL.8)** Soldering iron burns | • Improper use or stowage of soldering iron | • Proper training in use of soldering iron<br>• Minimize personnel involved | • Safety Officer supervision<br>• PPE (thick gloves) provided freely in fab shop<br>• Training offered before use |

# 6 Project Plan

## 6.1 Testing

***Table 6-1. Vehicle Component and Assembly Tests***

| Test | Objective | Items of Interest | Success Criteria | Methodology |
|---|---|---|---|---|
| Drop | Determine impact resistance of vehicle sections | Breaks or cracks in vehicle or payload structures<br><br>Electrical leads disconnecting | Fins do not crack<br><br>Airframe does not crack or rupture<br><br>Payload housing and clear camera shroud do not crack or break | Simple Newtonian physics calculation using known mass and desired impact velocity to determine drop height. Drop vehicle sections and/or payload. Inspect |
| Jerk | Verify connection points do not fail under large instantaneous load | Bending, warping, or cracking of bulkheads, hardware, or epoxied connections | U-bolts and eyebolts remain intact<br><br>No deformation of bulkheads<br><br>No dislodging of epoxied bulkhead to airframe connections<br><br>No unintended breakage of shear pins | Connect recovery harness to U-bolt or eyebolt. Affix end of harness to test rig on second story of college.<br>Drop individual vehicle sections, multiple tethered sections, or avionics pinned to upper or lower payload bay. Inspect airframe structures. Inspect shear pins. |

Continued on following page

| | | | | |
|---|---|---|---|---|
| Vibration | Ensure electrical and hardware connections are robust enough to withstand powered ascent phase | Severity of vibration or RPM of spin before connections begin to loosen | No electrical leads disconnect<br><br>No nuts, bolts, etc begin to come undone | Affix vehicle section to LabView controlled electric motor. Spin section about z-axis to max RPM from simulations. Inspect hardware connections and av bay.<br><br>Physically shake vehicle section (by hand) progressively harder and faster so as to well exceed the minor vibrations experienced on launch. Inspect hardware connections and av bay. |
| Separation | Validate that shear pins will break and sections will forcefully separate when ejection charges are fired | Grams in $CO_2$ cartridge<br><br>Shear pin size<br><br>Distance vehicle section is ejected from avionics bay | Shear pins break<br><br>Vehicle section is ejected from test rig<br><br>Vehicle section travels far enough to deploy parachute from payload bay | Load ejection charges in av bay with long alligator leads to be manually attached to a battery. Join av bay to vehicle section with shear pins. Place joined sections onto “test sled” rig, ensuring the rear of the av bay is firm against the rear brace. Connect alligator clips to battery terminal to light charge. Inspect result. |

## 6.2 Requirements Verification

### 6.2.1 Team Derived Requirements

***Table 6-2: Safety Team Derived Verification Matrix***

| Safety Team Derived Requirements | | | | |
|---|---|---|---|---|
| **Number** | **Description** | **Justification** | **Success Criteria** | **Verification Method** |
| 1 | Proper safety equipment shall be provided to all personnel | The use of PPE helps to reduce the likelihood of injury while working | Entrances to all team shops are stocked with all necessary PPE | Fabrication Shop Manager |
| 2 | Launch day attendees shall keep a reasonable pace during all aspects of activities | Maintaining a steady pace reduces the likelihood of falling or tripping | Team members are to walk, meaning having one foot on the ground at a time | Safety Officer Supervision<br><br>Operations Checklists |
| 3 | All major hazards identified in the risk assessment matrix shall be decreased to yellow or green by CDR through mitigations | Mitigating potentially dangerous/frequent hazards creates a more robust system | All hazards identified in the CDR document fall in the yellow or green zones after the mitigation. | Operations Checklists |

***Table 6-3: Launch Vehicle Team Derived Verification Matrix***

| Launch Vehicle Team Derived Requirements | | | | |
|---|---|---|---|---|
| **Number** | **Description** | **Justification** | **Success Criteria** | **Verification Method** |
| 1 | The launch vehicle shall not exceed 16Gs of acceleration during ascent | Acceleration higher than 16Gs could cause problems for the payload or vehicle structure | Simulations are done in OpenRocket | Pre-flight Simulation |
| 2 | The launch vehicle shall have symmetrical fins | This ensures that the launch vehicle is aerodynamic and ensures the CG is on center by causing equal aerodynamics on both sides and equal weight distribution | The launch vehicle has four fins equally spaced from each other around the airframe along with one camera positioned at the center of the nosecone | Visual Inspection |
| 3 | The lower payload bay shall have at least 6 inches of interior length | This is to give the payload team enough space for any lower payload electronics | The lower payload bay is designed to have 6 inches of interior length | Physical Measurement<br><br>Assembly checklist |
| 4 | The airframe shall be capable of launching in temperatures between 20- and 100-degrees Fahrenheit | The launch vehicle is planned to operate in a variety of launch fields and seasons | The airframe material is rated to not be damaged or deformed under these temperatures | Pre-flight Testing |
| 5 | The launch vehicle shall not go above Mach 0.7 | Higher speeds and accelerations are not necessary they endanger the payload and other structural components | Simulations are done is OpenRocket to confirm the launch vehicles maximum velocity | Pre-flight Simulation |
| 6 | The launch vehicle shall use at least 2 centering rings to support the motor tube | This ensures that the motor tube has the adequate support to experience the high force caused by the motor | Two centering rings along with the engine block will be used to support the motor tube | Pre-flight Simulation<br>Pre-flight testing<br><br>Assembly checklist |

| | | | | |
|---|---|---|---|---|
| 7 | The launch vehicle shall have a stability margin between 2.5 and 3.5 calibers | Stability margins lower than 2 are prohibited by NASA. Margins of stability greater than 2.2 are more stable | The aerodynamics lead designs the launch vehicle such that minimum stability margin of 2.5 calibers. | Pre-flight simulation<br><br>Sub-scale result verification |

***Table 6-4. Recovery Team Derived Requirements***

| **Recovery Team Derived Requirements** | | | | |
|---|---|---|---|---|
| **Number** | **Description** | **Justification** | **Success Criteria** | **Verification Method** |
| 1 | Fully charged batteries shall be used for the altimeters before every flight | Insufficient voltage supply can lead to the altimeter powering off | New batteries will be chosen and verified to be full before being placed on the AV sled | Operations checklist |
| 2 | U-bolts shall be used for all shock cord connections | U-bolts provide two points where shock can go through the bulkhead to increase stability | U-bolts are installed on the bulkheads as anchor points for the recovery harness | Assembly Checklist |
| 3 | All electronic components in the launch vehicle shall be removable. | Removable electronics allow for easier changes and adjustments to design | None of the electronic components in the launch vehicle are permanently fixed in place | Pre-flight testing<br><br>Assembly checklist |
| 4 | There shall be no more than 4 sections of the vehicle recovered | NASA gives a requirement that there can be no more than 4 of the vehicle | The vehicle will be designed to have only 4 sections | Pre-flight simulation<br>Pre-flight testing<br><br>Assembly checklist |
| 5 | The secondary ejection charges shall be based off a configured time set on the redundant altimeter | This will guarantee proper parachute deployments if the primary altimeter fails | Both altimeters are completely independent of each other | Pre-flight testing<br><br>Sub-scale flight result verification |

***Table 6-5. Payload Team-Derived Requirments***

| Payload Team Derived Requirements | | | | |
|---|---|---|---|---|
| **Number** | **Description** | **Justification** | **Success Criteria** | **Verification Method** |
| 1 | The payload vehicle SHALL have a diameter of less than 4.5 inches. | The Inner diameter of the launch vehicle is already limited to 6 inches. The extra space is needed for the rover housing | The Payload fits inside of its housing. | Physical measurement<br><br>Assembly checklist |
| 2 | The payload shall be supported within the launch vehicle | The payload is subjected to the different forces during the launch. To limit the movement during the launch it must be supported from all sides. | The payload integration system supports the payload so that it is not dislodged before deployment | Pre-flight testing |
| 3 | The payload integration system shall be a maximum of 7 inches long | Limiting the length of the integration system also limits the payload length. This all lends to a more favorable static stability margin | The payload integration system is less than 7 inches | Pre-flight simulation<br><br>Pre-flight testing<br><br>Assembly checklist |

## 6.3 Budgeting and Timeline

### 6.3.1 Budget

The following table summarizes the remaining project expenses for full-scale and payload component acquisition and shipping, propellant for test flights, and travel to test launches and launch week.

***Table 6-6. Project Budget Summary***

| Project Component | Expected Cost |
|---|---|
| Full-scale airframe and propellant | $1900.00 |
| Avionics system improvements | $650.00 |
| Payload Materials | $50.00 |
| Shipping and Handling | $125.00 |
| Transportation and logistics | $1,900.00 |
| **Remaining Project Cost:** | **$4,625.00** |

### 6.3.2 Funding and Material Acquisition

#### 6.3.2.1 Funding Sources

Funding for this year's project team is being graciously provided through two sources: the Aero-Propulsion, Mechatronics, and Energy (AME) center has diverted $2,000 of their NASA MUREP Grant funding to Zenith Program to facilitate Florida A&M student involvement with a complex aerospace project, and to facilitate FAMU student relations with NASA at large, in hopes of creating a firm feeder pipeline of underrepresented minority students to NASA. This MUREP funding has been expended to cover a portion of the subscale vehicle. The FAMU-FSU COE Mechanical Engineering Department has generously agreed to cover the difference in project costs for parts and material, transportation to the test launch facility, and transportation and lodging for Launch Week. At this point in the project the ME Department has taken on material acquisition after the AME funding was expended.

#### 6.3.2.2 Funding Allocation

Using the budget sheet, now excluding all purchased components, a determination of project cost vs. time (or milestones) was made. These expenditures to achieve each milestone will be used to coordinate with the project sponsors for funding disbursement and to monitor the whether the project is on-budget when reaching each milestone.

| Remaining Expenditure by Milestone | | | |
|---|---|---|---|
| Full-scale | $1,884.83 | | |
| Propellant | $289.99 | | |
| Logistics | $103.60 | | **Test Flight 2** |
| **Add:** | **$2,278.42** | | **$2,278.42** |
| | | | |
| Payload | $43.85 | | |
| Propellant | $289.99 | | |
| Logistics | $103.60 | | **Test Flight 3** |
| **Add:** | **$437.44** | | **$2,715.86** |
| | | | |
| | | | |
| Propellant | $289.99 | | |
| Logistics | $1,678.40 | | **Competition Flight** |
| **Add:** | **$1,968.39** | | **$4,684.25** |

***Figure 6-1. Expenditure by Flight Milestone***

6.3.2.3 Material Acquisition Plan

Material acquisition has been streamlined with the initial investment by the AME Center expended and the full and sole support of the Mechanical Engineering department. The Program Director was given a point of contact in the office of the ME Department Chair to relay all material requests. The department then either places online orders with expedited shipping using Florida State P-Cards (university issued credit cards), or coordinates with local hardware vendors who have existing accounts with the University.

### 6.3.3 Project Timeline

The updated project Gantt chart has been attached as Appendix B.

From the Gantt chart, major project milestones and their corresponding completion dates and expected durations are summarized in the table below, which lists activities through the payload demonstration flight, submission of FRR, and completion of project phase 3.

The team has assessed adherence to the Gantt chart from Proposal to CDR and has determined that engineering milestones are being met appropriately. STEM engagement, however, has been chronically delayed. The updated timeline submitted in PDR pushed back establishing points of contact and event planning into mid-November and December of 2022. Points of contact were established in mid-December 2022 and event planning will not begin until roughly a week after the public school system begins their spring semester. The team plans to aggressively pursue firm dates for STEM engagement events to not allow any further delay.

***Table 6-7. Project Timeline Summary Sub-Scale through FRR***

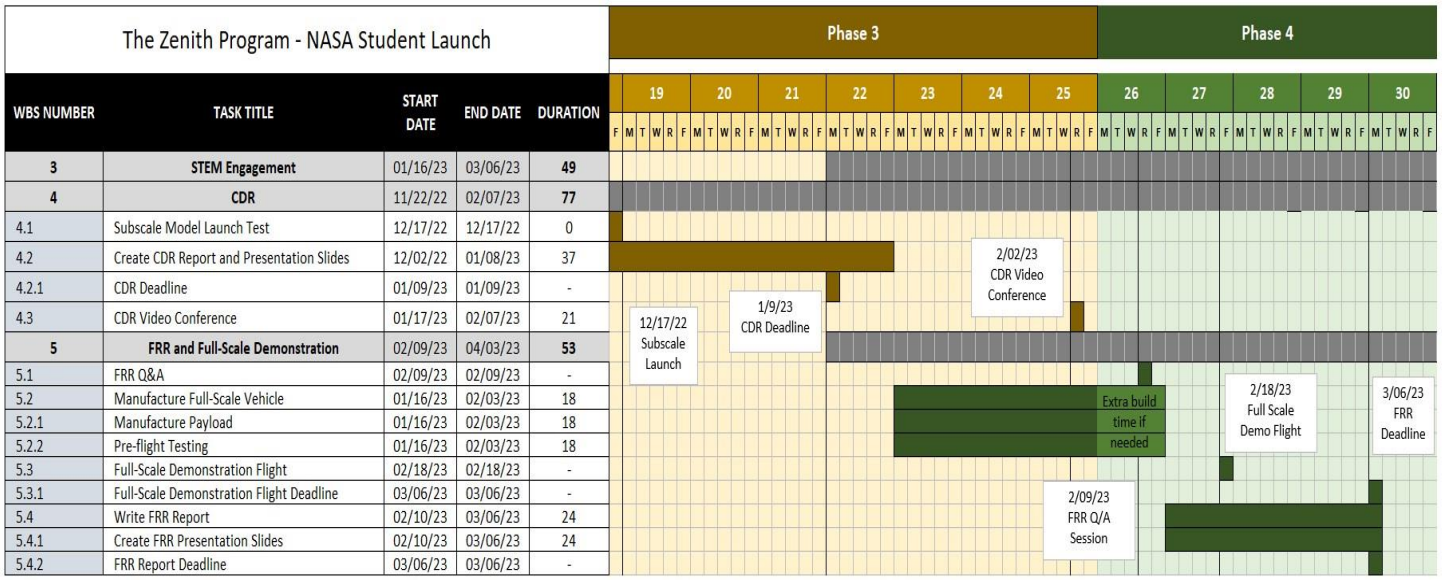
| Goal Owner | Milestone or Deliverable | Expected (*Required) Completion Date | Estimated Activity Duration |
|---|---|---|---|
| Zenith | Subscale test flight | 12/17/2022 | 1 day |
| Zenith | Begin CDR Report and sub-scale data analysis | *1/9/2023 | 30 days |

| | | | |
|---|---|---|---|
| NASA SLI | Submit CDR Report and slides | *1/9/2023 | 30 days |
| Zenith | Submit full-scale parts order to ME department | 1/13/2023 | 5 days |
| Zenith | Schedule STEM Engagement events with points of contact | 1/16/2023 | 7 days |
| Zenith | Full-scale assembly and testing | 2/3/2023 | 30 days |
| Zenith | Payload assembly and testing | 2/3/2023 | 30 days |
| NASA SLI | FRR Q/A Session | 2/9/2023 | 1 day |
| Zenith | STEM Engagement Events | 3/1/2023 | 30 days |
| Zenith | Begin FRR Report | *3/6/2023 | 25 days |
| Zenith | Full-Scale demonstration flight | NET: 2/11/2023 2/18/2023 | 1 day |
| Zenith | Full-Scale data analysis | NET: 2/15/2023 | 2 days |
| NASA SLI | Submit FRR Report and slides | *3/6/2023 | 25 days |

# Appendix A. Revised Budget

| Zenith Program Budget (Rev: 12/2022) | | | |
|---|---|---|---|
| **Part Name** | **Quantity** | **Cost** | **Quantity Cost** |
| **Avionics System** | | | |
| TeleMega | 1 | $400.00 | $400.00 |
| TeleBT Ground Module | 1 | $165.00 | $165.00 |
| Arrow Antenna 3E Yagi | 1 | $74.99 | $74.99 |
| | | **Subtotal:** | **$639.99** |
| **Full-Scale Vehicle** | | | |
| ID = 6.0", L = 48" Airframe - Blue Tube 2.0 | 2 | $77.42 | $154.84 |
| 6" to 75mm Centering Ring - Baltic Birch | 3 | $9.50 | $28.50 |
| 6" Airframe Bulkhead | 6 | $8.95 | $53.70 |
| OD = 6", L = 12" Avionics Bay w/ Hardware | 1 | $72.00 | $72.00 |
| AeroPack 75mm retainer (flanged) | 1 | $75.83 | $75.83 |
| AeroTech 75mm Hardware Kit | 1 | $629.99 | $629.99 |
| Aerotech L1150-R | 3 | $289.99 | $869.97 |
| | | **Subtotal:** | **$1,884.83** |
| **Payload** | | | |
| 12V DC brushed motor | 1 | $17.86 | $17.86 |
| Arducam Mini 8MP | 1 | $25.99 | $25.99 |
| | | **Subtotal:** | **$43.85** |
| **General/Uncategorized Components** | | | |
| Shipping and handling - all budget bulk estimate | 1 | $125.00 | $125.00 |
| | | **Subtotal:** | **$125.00** |
| **Transportation and Logistics** | | | |
| Gas reimbursement - SRA test launches (Orlando) | 2 | $103.60 | $207.20 |
| Gas reimbursement - NASA MSFC (Huntsville) | 1 | $118.40 | $118.40 |
| Student IHG Hotel Rooms (4 days, $90/day) | 2 | $360.00 | $720.00 |
| Food Stipend (4 comp. days, $35/day/student) | 6 | $140.00 | $840.00 |
| | | **Subtotal:** | **$1,885.60** |

# Appendix B. Gantt Chart




| WBS NUMBER | TASK TITLE | START DATE | END DATE | DURATION |
|---|---|---|---|---|
| **3** | **STEM Engagement** | 01/16/23 | 03/06/23 | **49** |
| **4** | **CDR** | 11/22/22 | 02/07/23 | **77** |
| 4.1 | Subscale Model Launch Test | 12/17/22 | 12/17/22 | 0 |
| 4.2 | Create CDR Report and Presentation Slides | 12/02/22 | 01/08/23 | 37 |
| 4.2.1 | CDR Deadline | 01/09/23 | 01/09/23 | - |
| 4.3 | CDR Video Conference | 01/17/23 | 02/07/23 | 21 |
| **5** | **FRR and Full-Scale Demonstration** | 02/09/23 | 04/03/23 | **53** |
| 5.1 | FRR Q&A | 02/09/23 | 02/09/23 | - |
| 5.2 | Manufacture Full-Scale Vehicle | 01/16/23 | 02/03/23 | 18 |
| 5.2.1 | Manufacture Payload | 01/16/23 | 02/03/23 | 18 |
| 5.2.2 | Pre-flight Testing | 01/16/23 | 02/03/23 | 18 |
| 5.3 | Full-Scale Demonstration Flight | 02/18/23 | 02/18/23 | - |
| 5.3.1 | Full-Scale Demonstration Flight Deadline | 03/06/23 | 03/06/23 | - |
| 5.4 | Write FRR Report | 02/10/23 | 03/06/23 | 24 |
| 5.4.1 | Create FRR Presentation Slides | 02/10/23 | 03/06/23 | 24 |
| 5.4.2 | FRR Report Deadline | 03/06/23 | 03/06/23 | - |

## Appendix C. Stability and Flutter Speed MATLAB Code

# Flutter Speed (Material --> ABS Fialment)

```
% Defining Initial parameters

E = 416258.3; % Young's Modulus  (psi) v = 0.37; %
Poisson's Ratio (unitless) Cr = 11; % Root Chord in
inches Ct = 3; % Tip Chord in inches t = 0.47; %
Thickness in inches b = 9;  % Fin Height relative to the
root chord in inches


% The following equations will calculate the fin flutter speed for the
% leading design's fin configuration using ABS filament as the
material of % choice

G = E/(2*(1+v));
h = 4600; % Max height the rocket will reach in feet S = (1/2)*(Cr +
Ct)*b; % Wing Area (inches squared) AR = (b.^2)/S; % Aspect Ratio
(unitless) lambda = Ct/Cr; % Taper Ratio (unitless) T = 59 -
0.00356*h; % Temp (Fahrenheit) P = (2116/144)*((T +
459.7)/518.6).^5.256; % Pressure (also converts  to lb/in^2)
a = sqrt(1.4*1716.59*(T + 459.7)); %Speed of sound (ft/s)
Vf = a*sqrt((G/(1.337*(AR.^3)*P*(lambda+1)))*(2*(AR+2)*((t/
Cr).^3))); % Fin Flutter Speed


% The follwing code is written simply to output the answers on the
script % publication

fprintf('The flutter speed of the fin is %.4f ft/s. \n\n', Vf)
```

*The flutter speed of the fin is 1446.2738 ft/s.*

# Stability Margin Calculations

```
L_N = 20;
S = 9;
X_R = 6.773;
C_T = 3;
C_R = 11;
R = 3.077;
N = 4;
X_B = 83.5;
X_CG = 58.575;
C_N = 2; d =
6.154;

X_N = 0.466*L_N;

theta = 37; L_F = sqrt(S^2 + ((1/2)*C_T - (1/2)*C_R +

(S/tan(theta))));

% C_F = (1 + (R/(S+R)))*((4*N*(2/(2*R))^2)/ (1 + sqrt(1+((2*L_F)/C_R
+C_T)^2)));

a = 1 + ((R)/(S+R)); b =
4*N*((S/d)^2); c =
((2*L_F)/(C_R + C_T))^2; g =
1+sqrt(1+c); C_F = a*(b/g);




X_F = X_B + (X_R/3)*((C_R + 2*C_T)/(C_R + C_T)) + (1/6)*(C_R + C_T -
 (C_R*C_T/(C_R + C_T))); X_CP =

(C_N*X_N + C_F*X_F)/(C_N + C_F);

S_M = (X_CP - X_CG)/d;
```

*Published with MATLAB® R2021a*

# Appendix D. Apogee Calculation MATLAB Code

```
clc
clear all
```

**Finding Apogee of Zenith Rocket with air resistance and changing mass**

```
burntime = 4.4; %burntime in seconds
totimp = 3646.2; %Total impulse in Newton seconds
m_takeoff = 17.368; %Mass of rocket at takeoff in kg
m_prop = 2.095; %Mass of propellant in kg


M = m_takeoff - 0.5*m_prop; %average weight of the rocket in kg
M2 = m_takeoff - m_prop; %weight of the vehicle after powered ascentg in kg

g = 9.81; %acceleration of gravity m/s^2
rho = 1.2; %density of the atmosphere kg/m^3
Cd = 0.5; %coefficient of drag
A = 0.0182; %cross sectional area of the rocket m^2

k = 0.5*rho*Cd*A;
T = totimp/burntime; %thrust forc

v_burnout = (sqrt((T - M*g) / k))*(1-exp(-(2*k*(sqrt((T - M*g) / k)) / M)*burntime)) / (1+exp(-(2*k*(sqrt((T - M*g) / k)) / M)*burntime));
alt_burnout = (-M / (2*k))*log((T - M*g - k*v_burnout^2) / (T - M*g));


alt_coast = (+M2 / (2*k))*log((M2*g + k*v_burnout^2) / (M2*g));

totalalt = alt_burnout + alt_coast;

fprintf('The apogee of the rocket is %.2f ft  \n', 3.28*totalalt)
```

```
The apogee of the rocket is 4431.75 ft
```

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# Appendix E. RAFCO Mission Preliminary Arduino Code

```
1. // This code is a rough draft for camera operation and control for the FAMU-FSU College of
   Engineering Student Launch "Zenith" Team.
2. // Image filtering is still in development.
3.
4. //================================================================
================================
5. //==                    ArduCam Camera Initialization                    ==
6. //================================================================
================================
7. #include "Arducam_Mega.h"
8. // #include "Platform.h"
9. #include <SD.h>
10. #include <ArduCAM.h> 11. #include "image_provider.h"
11.
12.
13. #define  BUFFER_SIZE  0xff
14.
15. #if defined(ARDUINO) && !defined(ARDUINO_ARDUINO_NANO33BLE)
16. #define ARDUINO_EXCLUDE_CODE
17. #endif  // defined(ARDUINO) && !defined(ARDUINO_ARDUINO_NANO33BLE) 18.
19. #ifndef ARDUINO_EXCLUDE_CODE
20.
21. // Required by Arducam library
22. #include <SPI.h>
23. #include <Wire.h>
24. #include <memorysaver.h>
25. // Arducam library
26. #include <ArduCAM.h>
27. // JPEGDecoder library 28. #include <JPEGDecoder.h>
28.
```

```
29.
30. // The size of our temporary buffer for holding
31. // JPEG data received from the Arducam module
32. #define MAX_JPEG_BYTES 4096
33. // The pin connected to the Arducam Chip Select
34. #define CS 7
35.
36. int8_t* image_send;
37. int index_test;
38.
39. // Camera library instance
40. ArduCAM myCAM(OV2640, CS);
41. // Temporary buffer for holding JPEG data from camera
42. uint8_t jpeg_buffer[MAX_JPEG_BYTES] = {0};
43. // Length of the JPEG data currently in the buffer 44. uint32_t jpeg_length = 0;
44.
46.
47. const int CS = 7;
48. const int SD_CS = 9;
49. uint8_t count = 0;
50. char name[10] = {0}; 51. uint8_t rtLength = 0;
51.
52.
53. File outFile;
54. uint8_t imageData = 0;
55. uint8_t imageDataNext = 0;
56. uint8_t headFlag = 0;
57. unsigned int i = 0;
58. uint8_t imageBuff[BUFFER_SIZE] = {0};
59.
60. Arducam_Mega myCAM( CS );
61.
```

```
62. uint8_t keyState = 0;
63. uint8_t isCaptureFlag = 0;
64.
65.
66. //========================================================================
================================
67. //==                    ArduCam Camera Initialization                    ==
68. //========================================================================
================================
69.
70.
71.
72.


73. //========================================================================
================================
74. //==                      Reciever Initialization                        ==
75. //========================================================================
================================
76. // Receives and displays data message formats for RF sensors
77.
78. // Input port for RF receiver data
    79. #define Pulse_In 2 // INT0 80.
81. // All times in microseconds
82. #define Min_Gap_Time 3000
83. #define Max_Gap_Time 16000
84. #define Min_Bit_Time 100
85. #define Max_Bit_Time 1500
86. #define Uncertainty 200 // Data bit pulse width uncertainty
87.
88. byte RF_Bit_Count = 0;
```

```
89. byte RF_Byte_Count = 0;
90. byte RF_Byte = 0;
91. char ASCII[] = "0123456789ABCDEF";
92. byte RF_Message[] = {0, 0, 0, 0, 0, 0, 0};
93. unsigned long Start_Time = 0;
94. int Pulse_Width;
95. byte Started = false;
96. int Gap_Time;
97. int Bit_Time1; // elapsed time of first bit
98. int Bit_Time2; // elapsed time of bit that mismatches first bit
99. byte Invert_Flg; // invert message byte if first bit was actually "0" instead of "1"
100.    byte Msg_Complete;
101.    char command[];
102.    //=================================================================
==================================
103.    //==                  Reciever Initialization                    ==
104.    //=================================================================
==================================
105.
106.
107.
108.
109.    //=================================================================
==================================
110.    //==                  Motor Initialization                       ==
111.    //=================================================================
==================================
112.    //Array of half steps for motor, 0.9 degrees per half step
113.    int halfSteps[8] = {0b0001, 0b1001, 0b1000, 0b1010, 0b0010, 0b0110, 0b0100, 0b0101
    };
114.
115.    //global variables
116.    int desPos = 0;    //desired position
```

```
117.  int curPos = 0;    //current position
118.  //================================================================
==================================
119.  //==                    Motor Initialization                    ==
120.  //================================================================
==================================
121.
122.
123.
124.
125.  void setup() {
126.  start_capture = 0;
127.  char str[8];
128.  File outFile;
129.  char VH,VL;
130.  int i,j = 0;
131.  int h=3;
132.
133.  //================================================================
==================================
134.  //==                      Motor Setup                           ==
135.  //================================================================
==================================
136.  DDRA = 0xFF;   //motor port on arduino
137.  Serial.begin(9600);
138.  //================================================================
==================================
139.  //==                      Motor Setup                           ==
140.  //================================================================
================================== 141.
142.
143.
144.
145.
```

```
146.
147.  //================================================================
==================================
148.  //==                    ArduCam Camera Setup                      ==
149.  //================================================================
==================================
150.  pinMode(SD_CS, OUTPUT);
151.  myCAM.begin();
152.  myCAM.takePicture(CAM_IMAGE_MODE_QVGA,CAM_IMAGE_PIX_FMT_JPG);
153.
154.  while(!SD.begin(SD_CS))
155.  {
156.  Serial.println(F("SD Card Error!"));
157.  arducamDelayMs(1000);
158.
159.      }
160.
161.  Serial.println(F("SD Card detected."));
162.  //================================================================
==================================
163.  //==                    ArduCam Camera Setup                      ==
164.  //================================================================
==================================
165.
166.
167.
168.
169.
170.
171.  //================================================================
==================================
```

```
172.  //==                    Reciever Setup                    ==
173.  //================================================================
================================
174.  digitalWrite(Pulse_In, INPUT_PULLUP); //turn on pullup
175.  Msg_Complete = false;
176.
177.  // Enable INT0 external interrupt, trigger on both edges
178.  bitSet(EICRA, ISC00);
179.  bitSet(EIMSK, INT0);
180.  //================================================================
================================
181.  //==                    Reciever Setup                    ==
182.  //================================================================
================================
183.
184.  }
185.
186.
187.
188.
189.
190.  void loop() {
191.
192.  //================================================================
================================
193.  //==                    Reciever Loop                     ==
194.  //================================================================
================================
195.  byte i;
196.        byte temp;
197.
```

```
198.  if ((Msg_Complete == true) && (RF_Byte_Count > 2) && (RF_Byte_Count < 8)) {
199.  noInterrupts();
200.  Msg_Complete = false;
201.  Serial.write("Gap_Time: ");
202.  Serial.print(Gap_Time);
203.  Serial.write("   Bit_Time1: ");
204.  Serial.print(Bit_Time1);
205.  Serial.write("   Bit_Time2 ");
206.  Serial.print(Bit_Time2); 207.  Serial.write("   Raw Bytes: ");
207.
208.
209.  i = 0;
210.  while (i < RF_Byte_Count) {
211.  if (Invert_Flg == true)
212.  RF_Message[i] = ~RF_Message[i]; 213.
214.  Serial.write(ASCII[RF_Message[i] >> 4]); // display upper nibble first
215.  Serial.write(ASCII[RF_Message[i] & 0x0F]);
216.  i++;
217.  }
218.
219.  Serial.println();
220.  RF_Byte_Count = 0;
221.  Started = false;
222.  PCIFR = 0; // clear all pin change interrupt flags
223.  interrupts();
224.  }
225.
226.
227.  // INT0 interrupt handler
228.  ISR (INT0_vect)
229.  {
230.  //when the pin goes LOW record the pulse start time
231.  if (digitalRead(Pulse_In) == LOW) {
232.  Start_Time = micros();
```

```
233.    }
234.    else // pin went high
235.    if (Start_Time != 0) {
236.    //calculate the pulse width
237.    Pulse_Width = ((volatile int)micros() - Start_Time);
238.    //clear the timer
239.    Start_Time = 0;
240.
241.    // Now check for valid message
242.    if (Pulse_Width < Max_Gap_Time) { 243.      if (Started == true) {
244.
245.    if ((Pulse_Width > Min_Bit_Time) && (Pulse_Width <
    Max_Bit_Time)) {
246.    // bit value in range
247.
248.    if (Bit_Time1 == 0) {
249.    // first bit
250.    Bit_Time1 = Pulse_Width;
251.    }
252.
253.    if ((Pulse_Width > (Bit_Time1 - Uncertainty)) && (Pulse_Width < (Bit_Time1 +
    Uncertainty))) {
254.    // bit = 1
255.    RF_Bit_Count--; // bits received MSB first
256.    bitSet(RF_Message[RF_Byte_Count], RF_Bit_Count);
257.    if (RF_Bit_Count == 0) {
258.    RF_Byte_Count++;
259.    RF_Bit_Count = 8;
260.    }
261.    }
262.    else {
263.    // bit = 0
264.    RF_Bit_Count--; // bits received MSB first
265.    bitClear(RF_Message[RF_Byte_Count], RF_Bit_Count);
```

```
266.  if (RF_Bit_Count == 0) {
267.  RF_Byte_Count++;
268.  RF_Bit_Count = 8;
269.  }
270.  if (Bit_Time2 == 0) {
271.  // Mismatch of first bit
272.  Bit_Time2 = Pulse_Width;
273.          if (Bit_Time1 > Bit_Time2)
274.  Invert_Flg = true;
275.  else
276.  Invert_Flg = false;
277.  }
278.  }
279.  }
280.
281.  else { // bad bit or end of message
282.  if (Pulse_Width > Min_Gap_Time) {
283.  Msg_Complete = true;
284.  }
285.  Started = false;
286.  }
287.  } // Started
288.
289.  else if (Pulse_Width > Min_Gap_Time) {
290.  // start of the message
291.  Started = true;
292.  RF_Byte_Count = 0;
293.  RF_Bit_Count = 8;
294.  Gap_Time = Pulse_Width; // save for display
295.  Bit_Time1 = 0;
296.  Bit_Time2 = 0;
297.  }
298.  }
299.  else { // invalid message
```

```
300.    Started = false;
301.    }
302.    }
303.    //================================================================
==================================
304.    //==                      Reciever Loop                         ==
305.    //================================================================
==================================
306.
307.
308.    //================================================================
==================================
309.    //==                      Decoder Loop                          ==
310.    //================================================================
==================================
311.    //1 A1-Turn camera 60° to the right
312.    //2 B2-Turn camera 60° to the left
313.    //3 C3-Take picture
314.    //4 D4-Change camera mode from color to grayscale
315.    //5 E5-Change camera mode back from grayscale to color
316.    //6 F6-Rotate image 180° (upside down).
317.    //7 G7-Special effects filter (Apply any filter or image distortion you want and state
    what filter or distortion was used).
```

```
318.  //8 H8-Remove all filters.
319.
320.  // Parse the JPEG headers. The image will be decoded as a sequence of Minimum
321.  // Coded Units (MCUs), which are 16x8 blocks of pixels.
322.  JpegDec.decodeArray(jpeg_buffer, jpeg_length);
323.
324.  // Crop the image by keeping a certain number of MCUs in each dimension
325.  const int keep_x_mcus = image_width / JpegDec.MCUWidth;
326.          const int keep_y_mcus = image_height / JpegDec.MCUHeight;
327.
328.  // Calculate how many MCUs we will throw away on the x axis
329.  const int skip_x_mcus = JpegDec.MCUSPerRow - keep_x_mcus;
330.  // Roughly center the crop by skipping half the throwaway MCUs at the
331.  // beginning of each row
332.  const int skip_start_x_mcus = skip_x_mcus / 2;
333.  // Index where we will start throwing away MCUs after the data
334.  const int skip_end_x_mcu_index = skip_start_x_mcus + keep_x_mcus;
335.  // Same approach for the columns
336.  const int skip_y_mcus = JpegDec.MCUSPerCol - keep_y_mcus;
337.  const int skip_start_y_mcus = skip_y_mcus / 2;
338.  const int skip_end_y_mcu_index = skip_start_y_mcus + keep_y_mcus;
339.
340.  int error_reporter;
341.  int image_width;
342.  int image_height;
343.  int8_t image_data;
344.
345.  switch (command)
346.
347.  //A1-Turn camera 60° to the right ----------
348.  case 1:
349.  desPos = curPos + 67; //sets desired pos to 60.3 degrees to right
```

```
350.  break;
351.
352.  //B2-Turn camera 60° to the left --------------------
353.  case 2:
354.  desPos = curPos - 67; //sets desired pos to 60.3 degrees to left
355.  break;
356.
357.  //C3-Take picture -------------------
358.  case 3:
359.  imageData = imageDataNext; 360.     imageDataNext = myCAM.readByte(); 361.
362.  if (headFlag == 1)
363.  {
364.  imageBuff[i++]=imageDataNext;
365.
366.  if (i >= BUFFER_SIZE)
367.  {
368.  outFile.write(imageBuff, i);
369.  i = 0;
370.  }
371.  }
372.
373.  if (imageData == 0xff && imageDataNext ==0xd8)
374.  {
375.  headFlag = 1;
376.  sprintf(name,"%d.jpg",count);
377.  count++;
378.
379.              outFile = SD.open(name,FILE_WRITE|FILE_READ);
380.
381.  if (! outFile)
382.  {
383.  Serial.println(F("File open failed"));
```

```
384.    while (1);
385.    }
386.    imageBuff[i++]=imageData;
387.    imageBuff[i++]=imageDataNext;
388.    }
389.
390.    if (imageData == 0xff && imageDataNext ==0xd9)
391.    {
392.    headFlag = 0;
393.    outFile.write(imageBuff, i);
394.    i = 0;
395.    outFile.close();
396.    Serial.println(F("Image save succeed"));
397.    break;
398.    }
399.    break;
400.
401.    //D4-Change camera mode from color to grayscale ----------
402.    case 4:
403.    TF_LITE_REPORT_ERROR(error_reporter, 404.        "Decoding JPEG and converting to
    greyscale");
405.
406.
407.    // Pointer to the current pixel
408.    uint16_t* pImg;
409.    // Color of the current pixel
410.    uint16_t color;
411.
412.    // Loop over the MCUs
413.    while (JpegDec.read()) {
414.    // Skip over the initial set of rows
415.    if (JpegDec.MCUy < skip_start_y_mcus) {
416.    continue;
417.    }
```

```
418.  // Skip if we're on a column that we don't want
419.  if (JpegDec.MCUx < skip_start_x_mcus ||
420.  JpegDec.MCUx >= skip_end_x_mcu_index) {
421.  continue;
422.  }
423.  // Skip if we've got all the rows we want
424.  if (JpegDec.MCUy >= skip_end_y_mcu_index) {
425.  continue;
426.  }
427.  // Pointer to the current pixel
428.  pImg = JpegDec.pImage;
429.
430.  // The x and y indexes of the current MCU, ignoring the MCUs we skip
431.  int relative_mcu_x = JpegDec.MCUx - skip_start_x_mcus;
432.  int relative_mcu_y = JpegDec.MCUy - skip_start_y_mcus;
433.
434.  // The coordinates of the top left of this MCU when applied to the output
435.  // image
436.  int x_origin = relative_mcu_x * JpegDec.MCUWidth;
437.  int y_origin = relative_mcu_y * JpegDec.MCUHeight;
438.
439.  // Loop through the MCU's rows and columns
440.  for (int mcu_row = 0; mcu_row < JpegDec.MCUHeight; mcu_row++) {
441.  // The y coordinate of this pixel in the output index
442.  int current_y = y_origin + mcu_row;
443.  for (int mcu_col = 0; mcu_col < JpegDec.MCUWidth; mcu_col++) {
444.  // Read the color of the pixel as 16-bit integer
445.  color = *pImg++;
446.  // Extract the color values (5 red bits, 6 green, 5 blue)
447.  uint8_t r, g, b;
448.  r = ((color & 0xF800) >> 11) * 8;
449.  g = ((color & 0x07E0) >> 5) * 4;
450.  b = ((color & 0x001F) >> 0) * 8;
451.  // Convert to grayscale by calculating luminance
```

```
452.
453.    float gray_value = (0.2126 * r) + (0.7152 * g) + (0.0722 * b);
454.
455.    // Convert to signed 8-bit integer by subtracting 128.
456.    gray_value -= 128;
457.
458.    // The x coordinate of this pixel in the output image
459.    int current_x = x_origin + mcu_col;
460.    // The index of this pixel in our flat output buffer
461.    int index = (current_y * image_width) + current_x;
462.              image_data[index] = static_cast<int8_t>(gray_value);
463.
464.    /* Additional part needed for BLE image transfer */
465.    index_test = index;
466.    image_send[index] = static_cast<int8_t>(gray_value);
467.    }
468.    }
469.    }
470.    TF_LITE_REPORT_ERROR(error_reporter, "Image decoded and processed");
471.    break;
472.
473.    //E5-Change camera mode back from grayscale to color ----------
474.    case 5:
475.    //Cam control
476.    break;
477.
478.    //F6-Rotate image 180° (upside down). ----------
479.    case 6:
480.    h=3;
481.    while(h!=0)
482.    {
483.    gpio_trig = myCAM.read_reg(ARDUCHIP_PIN);   //Leggi il trigger da GPIO0~5 484.
485.    if(gpio_trig & 0x01)
```

```
{
h=h-1;
}
else h=3;
if(h==0) start_capture = 1;
}

if(start_capture)
{
//Flush the FIFO
myCAM.flush_fifo();
//Start capture
myCAM.start_capture();
}

//Polling the capture done flag
if(myCAM.read_reg(ARDUCHIP_TRIG) & CAP_DONE_MASK)
{

k = k + 1;
itoa(k, str, 10); strcat(str,".bmp");


outFile = SD.open(str,FILE_WRITE);
if (! outFile)
return;

for( i = 0; i < 54; i++)
{
char ch = pgm_read_byte(&bmp_header[i]);
outFile.write((uint8_t*)&ch,1);
}
```

```
519.  //Abilita FIFO
520.  myCAM.enable_fifo();
521.  //Read the first dummy byte from FIFO
522.  temp = myCAM.read_fifo();
523.  //Read 320x240x2 byte from FIFO
524.  for(i = 0; i < 240; i++)
525.  for(j = 0; j < 320; j++)
526.  {
527.  VH = myCAM.read_fifo();
528.  VL = myCAM.read_fifo();
529.  //RGB565 to RGB555 Conversion
530.  VL = (VH << 7) | ((VL & 0xC0) >> 1) | (VL & 0x1f);
531.  VH = VH >> 1;
532.  //Write image data to file
533.  outFile.write(VL);
534.  outFile.write(VH);
535.  }
536.  //Disable FIFO when all the image data is saved to the file
537.  myCAM.disable_fifo();
538.  //Close the file
539.  outFile.close();

541.  //Clear the capture done flag
542.  myCAM.clear_fifo_flag();
543.  //Clear the start capture flag
544.  start_capture = 0;
545.  }
546.  break;
547.
548.  //G7-Special effects filter (Apply any filter or image distortion you want and state what
     filter or distortion was used).
549.  case 7:
550.  while (JpegDec.read()) {
551.  // Skip over the initial set of rows
```

```
552.  if (JpegDec.MCUy < skip_start_y_mcus) {
553.  continue;
554.  }
555.  // Skip if we're on a column that we don't want
556.  if (JpegDec.MCUx < skip_start_x_mcus ||
557.  JpegDec.MCUx >= skip_end_x_mcu_index) {
558.  continue;
559.  }
560.  // Skip if we've got all the rows we want
561.  if (JpegDec.MCUy >= skip_end_y_mcu_index) {
562.  continue;
563.  }
564.  // Pointer to the current pixel
565.  pImg = JpegDec.pImage;
566.
567.  // The x and y indexes of the current MCU, ignoring the MCUs we skip
568.  int relative_mcu_x = JpegDec.MCUx - skip_start_x_mcus;
569.  int relative_mcu_y = JpegDec.MCUy - skip_start_y_mcus;
570.
571.  // The coordinates of the top left of this MCU when applied to the output
572.  // image
573.  int x_origin = relative_mcu_x * JpegDec.MCUWidth;
574.  int y_origin = relative_mcu_y * JpegDec.MCUHeight;
575.
576.  // Loop through the MCU's rows and columns
577.  for (int mcu_row = 0; mcu_row < JpegDec.MCUHeight; mcu_row++) {
578.  // The y coordinate of this pixel in the output index
579.  int current_y = y_origin + mcu_row;
580.  for (int mcu_col = 0; mcu_col < JpegDec.MCUWidth; mcu_col++) {
581.  // Read the color of the pixel as 16-bit integer
582.  color = *pImg++;
583.  // distort color values (5 red bits, 6 green, 5 blue)
584.  uint8_t r, g, b;
585.  r = ((color & 0xF800) >> 11) * 2;
```

```
586.    g = ((color & 0x07E0) >> 5) * 10;
587.    b = ((color & 0x001F) >> 0) * 2;
588.    // Convert to grayscale by calculating luminance
589.
590.    float gray_value = (0.2126 * r) + (0.7152 * g) + (0.0722 * b);
591.
592.    // Convert to signed 8-bit integer by subtracting 128.
593.    gray_value -= 128;
594.
595.    // The x coordinate of this pixel in the output image
596.    int current_x = x_origin + mcu_col;
597.    // The index of this pixel in our flat output buffer
598.    int index = (current_y * image_width) + current_x;
599.            image_data[index] = static_cast<int8_t>(gray_value);
600.
601.    /* Additional part needed for BLE image transfer */
602.    index_test = index;
603.    image_send[index] = static_cast<int8_t>(gray_value);
604.    }
605.    }
606.    }
607.    break;
608.
609.    //H8-Remove all filters. ----------
610.    case 8:
611.    desPos = 0;
612.    myCAM.clear_fifo_flag();
613.    start_capture = 0;
614.    h=3;
615.
616.    break;
617.    //================================================================
==================================
```

```
618.  //==                    Decoder Loop                    ==
619.  //================================================================
==================================
620.
621.
622.
623.
624.  //================================================================
==================================
625.  //==                    Motor Loop                    ==
626.  //================================================================
==================================
627.  //runs until the motor is at the desired position
628.  while (curPos != desPos)
629.  {
630.
631.  //if current position is less than desired,
632.  if (curPos < desPos)
633.  {
634.  curPos ++; //add 1 to curPos
635.  PORTA = halfSteps[curPos%24]; //sends to motor
636.
637.  delay(3);
638.  }
639.
640.  //if current position is more than desired,
641.  if (curPos > desPos)
642.  {
643.  curPos --; // subtract 1 from curPos
644.  PORTA = halfSteps[curPos%24]; //sends to motor
645.
646.  delay(3);
647.  }
```

```
}
//================================================================
==================================
//==                          Motor Loop                          ==
//================================================================
==================================



//================================================================
==================================
//==                      ArduCam Camera Loop                       ==
//================================================================
==================================
// This code takes a picture using the Arducam every 5 seconds and saves it to an SD
   card, independently of commands.
myCAM.takePicture(CAM_IMAGE_MODE_QVGA,CAM_IMAGE_PIX_FMT_JPG);
while (myCAM.getReceivedLength())
{
imageData = imageDataNext; 668.    imageDataNext = myCAM.readByte();


if (headFlag == 1)
{
imageBuff[i++]=imageDataNext;

if (i >= BUFFER_SIZE)
{
```

```
outFile.write(imageBuff, i);

i = 0;
}
}

if (imageData == 0xff && imageDataNext ==0xd8)
{

headFlag = 1;
sprintf(name,"%d.jpg",count);
count++;

            outFile = SD.open(name,FILE_WRITE|FILE_READ);

if (! outFile)
{
Serial.println(F("File open failed"));
while (1);
}
imageBuff[i++]=imageData;
imageBuff[i++]=imageDataNext;
}

if (imageData == 0xff && imageDataNext ==0xd9)
{
headFlag = 0;
outFile.write(imageBuff, i);
i = 0;

outFile.close();
Serial.println(F("Image save succeed"));
```

```
708.
709.    break;
710.    }
711.    }
712.
713.    arducamDelayMs(5000);
714.    //=====================================================================
====================================
715.    //==                      ArduCam Camera Loop                        ==
716.    //=====================================================================
====================================
717.
718.    }
719.    720.
721.    //=====================================================================
====================================
722.    //==                      END OF PROGRAM                             ==
723.    //=====================================================================
====================================
```