NASA Student Launch Initiative

2019-2020 Preliminary Design Review Report

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1 Summary of PDR Report

1.1 Team Summary

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1.2 Launch Vehicle Summary

The launch vehicle is made up of three independent sections consisting of a nose cone with telemetry housing, payload bay, avionics bay and a booster bay which incorporates the motor and fin retention system. The launch vehicle has a diameter of 6.17", length of 105", static stability margin of 2.52 cal and a mass of 49.3 lbm. An Aerotech L1420R-P was chosen to propel the vehicle to a target apogee of 4500 ft.

1.3 Recovery System

The recovery system is going to be a dual deployment system, in which a drogue parachute will be deployed at apogee (4500 ft) and the main parachute will be deployed at an altitude of 600 ft. Two fully redundant altimeters in the avionics bay will allow for the system to know when to deploy the parachutes, as well as allow for a backup if one fails to function. When the rocket reaches its desired deployment points, the altimeters will produce a signal that results in an electrical match igniting black powder, which will then break the shear pins that keep the parachute bays connected to the rest of the rocket. This will deploy the chutes, which will allow for a safe and controlled descent and touchdown of the rocket.

1.4 Payload Summary

Payload Title: Lunar Ice Collecting Tank

The payload is going to be a tank shaped rover, primary function of which is to collect a sample of simulated lunar ice. The rover will be secured inside the launch vehicle via the Tank Exiting and Reorienting System (TEARS) during the flight and recovery portions of the launch. TEARS will act as deployment mechanism to reorient rover right side up after landing and push it out through the nose cone. The entire process will be remotely controlled by our team. Once fully deployed, the rover will drive to one of the recovery areas where a scoop mechanism will be engaged. Once enough material is sampled, the rover will be driven a safe distance from the recovery area.

Table 1: Summary of the Launch Vechicle

Diameter	Length	Mass	Static Stability	Official Target Apogee	Preliminary Motor Choice
6.17”	104.6”	49.3 lbs	2.52 cal	4500 ft	L1420R-P

2 Changes Made Since Proposal

2.1 Changes Made to Vehicle Criteria

Table 2: Changes Made to Vehicle Criteria

Change	Reason
Total length of the rocket changed from 113” to 104.6”	The payload bay and the booster bay was shortened significantly to make the design lighter and more robust.
Total mass decreased from 54.1 lbs to 49.3 lbs.	The weight of the booster bay, avionics bay and propulsion bay were lowered to scale the vehicle design down to more reasonable standards based on budget constraints.
Motor changed from L2200G to the L1420R-P	A motor with a lower average thrust was selected to decrease the projected apogee due to the decrease in weight of the rocket
Target apogee decreased from 5218 ft to 4500 ft	The motor selection process led to the selection of a different motor
Design of VDS changed from airbrakes to extending blades.	The airbrakes system required a much larger section of the rocket and also demanded a larger motor, which increased weight. The BEDS (blades section drag system) system is more robust and safe.
Fin shape changed from elliptical to trapezoidal.	The tradeoff between higher apogee and ease of manufacturing ruled out the elliptical design due to the difficulty associated with cutting out the exact profile. The decrease in overall apogee was accounted for by choosing a different motor and decreasing the overall weight of the rocket
Number of fins changed from 5 to the more conventional 3.	The 3 fin design offers significantly less drag and is a lot easier to implement.
Static stability dropped from 3.97 cal to 2.52 cal	The lower stability margin means that the launch vehicle is not over-stable.
Metal nose cone tip was incorporated in design.	The metal tip will ensure vehicle survivability after landing while also offering an additional method of securing the telemetry sled.
Coupler sections added to payload bay and booster bay.	The design of the avionics bay was changed in order to make the deployment of the parachutes safer

Parachute	79 lb rated parachute was replaces with 50 lb rated Iris Ultra 96 Standard Parachute since the overall mass of the rocket was decreased.
Parachute Bags	Parachute bags that have been replaces with Nomex fire blankets to conserve space.
End Plate Material	Fiberglass end plates were replaces with plywood endplates with a thin fiberglass layer in order to safe weight.
Avionics Sled Material	Fiberglass sled was replaces with ABS plastic sled to safe weight and simplify fabrication.

2.2 Changes Made to Payload Criteria

Table 3: Changes Made to Payload Criteria

Change	Reason
Sampling Device	Auger has been replaced with a scoop design after more details about sampling material were provided by NASA. It has been decided that scoop would be a better choice for sampling granular material.
Tread Design	Two driving wheels with a flat treads have been replaces with two driving wheels, two idle wheels and trapezoid shape treads. This increases ground clearance which improves rover terrain traversability.
Retention Mounts	Retention mount design have been changes to increase stability during flight and landing.
Reorientation Plate	Reorientation plate is no longer directly driven by the motor, instead it is connected to the motor via a pinon gear to increase stability of the TEARS mechanism.

2.3 Changes Made to Project Plan

Table 4: Changes Made to Project Plan

Change	Reason
Requirement Verification	Requirement Verification section was added ensure that all NASA provided requirements from sections 1-5 in the handbook are met.
Team Derived Requirements	Additional team derived requirements were added that are beyond the minimum requirements presented by NASA but are still important for our team’s project success.
Project Timeline	Project timeline was updated to account for changes in project progress speed. More details were added to the timeline to give it a better representation of the team’s progress.
Budget	Budget was updated to include direct donations to the team and correct for the incorrectly estimated values.

3 Vehicle Criteria

3.1 Mission Statement & Success Criteria

The launch vehicle will be safely designed to propel the payload to an apogee of 4500 ft while ensuring that all subsystems are functional. The recovery system will be deployed at apogee and will allow the vehicle to safely land. The overall mission will be deemed successful if the following criteria are met:

- The launch vehicle avoids any safety risks to students, bystanders or property.
- The launch vehicle achieves the designed length to within a reasonable tolerance
- The launch vehicle achieves the designed mass to within a reasonable tolerance
- The launch vehicle reaches the target apogee to within 150 ft.
- The drogue chute will deploy successfully at apogee.
- The main chute will deploy successfully at the designated altitude.
- The launch vehicle will land safely to within a 2,500 ft radius.
- The launch vehicle will be undamaged after landing and will allow the TEARS system to safely deploy the payload.

3.2 Design Choice and Justification Method

All design choices will employ the decision matrix as standardized by the team below. Each design choice will be given a score depending on the weight of specification which ranges from 1 to 10 while ensuring that all weights sum to 10. The rating for each design will similarly range from 1 to 10. Therefore the product of the weight and rating results in a design score which will be compared with the other designs in order to select the best option which wins across various criteria.

Table 5: Decision Matrix Template

Design		**Design 1**		**Design 2**		**Design 3**	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Specification 1							
Specification 2							
Specification 3							
Specification 4							
Total							

3.3 Vechicle Trade Studies

3.2.1 Body Tube Diameter

The diameter of the body tube affects all aspects of the rocket design. Three common diameters, the 4-inch tube, the 6-inch tube and the 7.5-inch, were vetted against each other in the following decision matrix. The volume of the tube has the greatest impact on the other subsystems and is weighed accordingly. A larger airframe diameter would increase the room that the payload team has for designing their rover and reorientation system. The success of the payload mission is a paramount factor in this competition; therefore, steps should be taken to maximize its success. The 4-inch diameter tube does not have the adequate volume necessary for a robust rover design. While the 7.5-inch diameter tube has the greatest volume, it also has the highest weight, cost and is more difficult to source from vendors.

Table 6: Body Tube Diameter Decision Matrix

Design		4''		6''		7.5''	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Volume	4	2	8	6	24	8	32
Availability	2	4	8	8	16	6	12
Weight	2	6	12	4	8	1	2
Cost	2	6	12	5	10	2	4
Total		40		58		50	

The 6-inch body tube diameter was selected as the final design through the decision matrix. It provides more volume than the 4-inch tube and is more readily available from vendors than the 7.5 diameter tubing.

3.2.2 Body Tube Material

The body tube must be durable enough to withstand the forces during flight and reusable according to the competition requirements. Therefore, a high strength to weight ratio is a leading factor in the material selection. To determine the best material for this purpose, fiberglass, carbon fiber and phenolic tubing were considered with regards to their durability, weight, cost and strength. Fiberglass is a common choice for high-powered rockets, but it is the heaviest of all three options. Carbon fiber is an attractive alternative due to its durability and high strength to weight ratio. However, it is the most expensive material which makes it less accessible to a club with limited funding. Phenolic tubing is the least expensive of the three but also the least durable. Durability is an important factor in ensuring the rocket can undergo multiple launches per day without repairs or modifications.

Figure 1: Carbon fiber tubing (left) versus fiberglass tubing (right)

Table 7: Airframe Material Decision Matrix

Design		**G12 Fiberglass**		**Carbon Fiber**		**Phenolic Tubing**	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Durability	1	8	8	9	9	3	3
Weight	2	4	8	9	18	8	16
Cost	3	8	24	2	6	9	27
Strength	4	6	24	6	24	2	8
Total		**64**		**57**		**54**	

Of the three options, fiberglass was chosen as it provides the best good balance between durability, weight, cost and strength.

3.2.3 Nose Cone Shape

The nose cone reduces the vehicle drag during launch and flight. The three nose cone shapes are based on the readily available on the Madcow Rocketry website. Volume is weighed heavily because the telemetry bay will be housed in the nose cone. The nose cone will also be the anchoring point for the payload reorientation system. It was determined that the rocket will be traveling at subsonic speeds based on kinematic calculations and OpenRocket simulations. At those speeds, the nose cone will primarily experience friction drag, and minimal pressure drag. The conical profile is easy to manufacture but the benefits are primarily in the transonic region. Similarly, the Von Karman nose cone is most beneficial in the transonic region. A 4:1 ratio was chosen based-off requirements from the payload and avionics team to have a certain length and volume available for their systems.

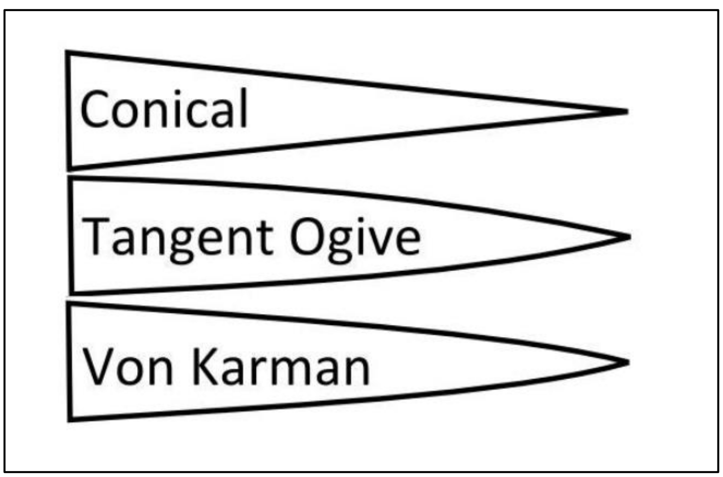

Figure 2: Profiles of the three leading designs that were considered

Table 8: Nose Cone Shape Decision Matrix

Design		Tangent Ogive		Conical		Von Karman	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Volume	5	7	35	5	25	6	30
Drag Coefficient	3	6	18	5	15	7	21
Availability	2	7	14	6	12	6	12
Total		67		52		63	

For a high-powered rocket, the tangent ogive nose cone from Madcow Rocketry was chosen. Ogive nose cones are often used in high powered rocketry more readily available from vendors. It is also the best option in terms of volume and drag characteristics.

3.2.4 Nose Cone Material

An important consideration for the nose cone material is Radio-Frequency (RF) transparency. The telemetry bay which includes the GPS and transmitter antenna is located in the nose cone. Fiberglass has high mechanical strength and does not interfere with RF signals. Previous teams from Stony Brook University have used 3D-printed ABS plastic nose cones, but they lacked structural integrity and had gaps along the surface upon further inspection. Carbon fiber was also considered an option; however, the material is not RF transparent which would require a major redesign of the telemetry bay. Carbon fiber is also the most expensive option of the three with ABS plastic being the least expensive.

Table 9: Nose Cone Material Decision Matrix

Design		G12 Fiberglass		Carbon Fiber		ABS Plastic	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Weight	1	4	4	8	8	5	5
Strength	3	6	18	8	24	2	6
Cost	2	6	12	2	4	8	16
RF-Transparency	4	6	24	2	8	4	16
Total		58		44		43	

It was determined that the 4:1 ogive fiberglass nose cone from Madcow Rocketry is the best option. It has the best weight to strength ratio while maintaining RF-transparency. A metal tip was substituted for the plastic tip to increase the survivability of the traditional fiberglass nose cone. The metal tip also serves as a second mounting point for the telemetry bay.

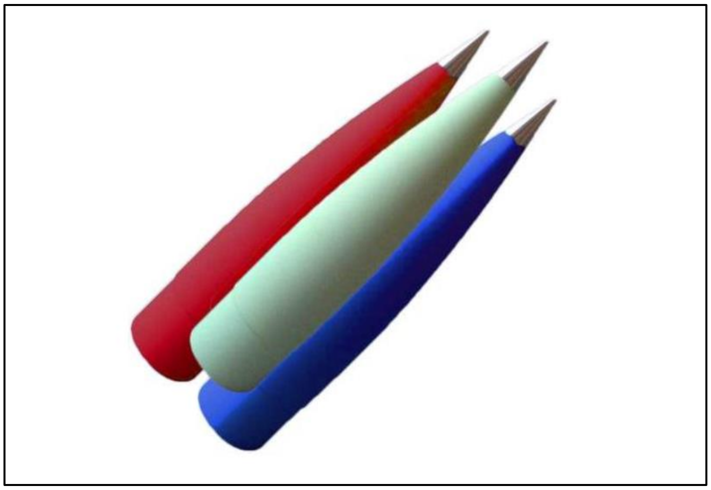

Figure 3: Fiberglass nose cones with a metal tip from Madcow Rocketry

3.2.5 Camera Bay

An onboard camera system will be responsible for taking video footage from launch to landing, thus providing an additional perspective of flight. Due to dimensional restrictions, cameras will be mounted to a dedicated camera bay.

For this task, two camera types were considered: action and 360° cameras. For these camera types, the viewport is fundamentally different. The lens of an action camera would barely protrude from a small hole in the airframe. This design results in a large field of view per each action camera. However, the 360° camera must be mounted within the center of the camera bay. As such, a viewport surrounding the camera bay must be constructed using a transparent material. For this reason, the vertical field of view for 360° video will be greatly limited.

For the decision matrix below, three cameras were selected. Due to budget limitations, only cost-effective cameras with acceptable video quality were considered. The GoPro Hero7 Silver was selected because of its high prominence within the action camera industry; the Insta 360 ONE is rated highly among 360° cameras; the Akaso EK7000 is an exceedingly cost-effective action camera alternative.

Table 10: Camera Bay

Design		**Hero7 Silver**		**Insta360 ONE**		**EK7000**	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Weight	2	5	10	8	16	10	20
Aerodynamics	3	9	27	10	30	9	27
Cost	3	2	6	8	24	10	30
Video Quality	2	10	20	2	4	8	16
Total		**63**		**74**		**93**	

3.2.6 Variable Drag System

The Variable Drag System (VDS) allows the team of adjust the drag characteristics of the rocket in-flight. It would help the rocket reach the target apogee by increasing the surface area of the launch vehicle and disrupting air flow. Two designs were considered for this, a blade system that extends perpendicular to the airframe called BEDS (Blade Section Drag System), and an airbrake system that extends outward from the surface of the body tube itself. The main considerations for determining which system to develop was complexity, drag, weight and volume. Airbrakes would take up more space on the rocket due to the linkages and actuators required to open the panels.

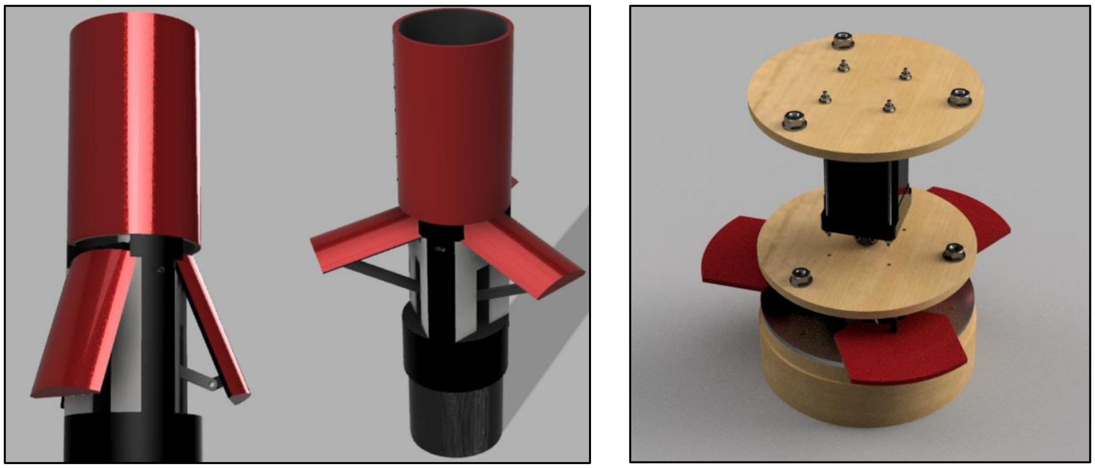

Figure 4: CAD models for airbrakes (left) and BEDS (right)

While the blades system does not provide as much surface area to induce drag, the other design requirements make it the more optimal choice in terms of volume needed on the launch vehicle, lower weight and lower complexity.

Table 11: Variable Drag System

Design		**BEDS**		**Airbrakes**	
Requirement	Weight	Rating	Score	Rating	Score
Volume	2	8	16	6	12
Weight	2	7	14	6	12
Drag	3	5	15	7	21
Complexity	3	6	18	3	9
Total		**63**		**54**	

After BEDS was chosen, multiple ways to actuate the system were explored. A common method uses a central gear and the matching gear teeth on each of the blade. However, this introduced complexities in designing and machining the gear system due to the tight tolerances required. A novel approach is a CAM and spring system that only requires motion in one direction. This method would require an in-depth study on the timing and profile of the CAM. The piston approach uses three rods attached to a central disc controlled by a servo motor that pushes the blades out. A guiderail on the underside of the blade ensures that the outward motion is smooth and controlled.

Table 12: Blade Actuation System

Design		Pistons		CAM		Gears	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Weight	2	5	10	6	12	5	10
Complexity	4	6	24	3	12	5	20
Manufacturability	4	6	24	4	16	5	20
Total		**58**		**40**		**50**	

Ultimately, the piston design was agreed upon because of its simplicity and ease of manufacturing.

3.2.7 Fins

In choosing fin shape for the rocket, four standard shapes were considered: Elliptical, Trapezoidal, Delta, Cropped Delta. In selecting a fin shape, it is important to choose a design that maximizes apogee without sacrificing stability. By holding the margin of stability constant across simulations, maximum apogee scores could be assigned to various fin designs. Thus, high scoring designs effectively maximize both apogee and stability.

However, the apogee height variation between designs is relatively small compared to maximum apogee. Therefore, these apogee scores are given a small weight. On the other hand, cost and safety factor variation among designs is much greater. Thus, these characteristics are weighted more heavily.

Table 13: Fin Shape

Design		Elliptical		Trapezoidal		Delta		Cropped Delta	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Cost	3	2	6	8	24	8	24	8	24
Apogee	2	8	16	4	8	10	20	6	12
Safety Factor	5	4	20	10	50	6	30	8	40
Total		**42**		**82**		**74**		**76**	

As shown, trapezoidal fins are the most effective design for this rocket. Upon more in-depth simulations, these trapezoidal fins are particularly effective when the trailing edge is small. The resulting design is a trapezoidal/cropped delta hybrid fin.

3.2.8 Motor Tube and Retainer

The motor tube chosen by SBSW is a fiberglass model manufactured by Madcow Rocketry. This motor tube is cost effective as well as reputable for being consistently high quality and sufficiently strong for housing L-class motors. Many teams in the past have used Madcow fiberglass motor tubes with great success, and while a motor tube could be fabricated in house, the time and monetary cost of doing such could not be justified when an inexpensive, reliable alternative is available. Additionally, an AeroPack 6061 Anodized Aluminum flange motor retainer will be utilized along with JB Weld high temperature epoxy to retain the motor inside the fiberglass housing tube. This will allow for quick motor changes between flights while maintaining thoroughly secure retention. This particular motor retainer was chosen in a similar manner to the motor tube as it has been used in past years by other teams with great success and is also recommended by Madcow for use with their motor tubes. The combination of aluminum threads with the high temperature epoxy will ensure a strong and secure fit to the fiberglass motor tube.

Figure 5: AeroPack aluminum motor retainer

3.2.9 Bulkheads

Bulkheads are an important feature in rocket design as they must be able to withstand large amounts of force from the motor, black powder charges, and shock cords during recovery, all while protecting and containing important equipment in the different bays. For this reason multiple materials have been taken into consideration to determine what will provide sufficient strength and protection while still being light and cost effective. Aluminum, marine grade plywood, and fiberglass have all been considered for use as bulk plate material, with the criterion for choosing the best one as weight, manufacturability, yield stress, and cost.

The yield stress is the most important criteria listed as the bulk plates must be able to withstand the forces presented during launch first and foremost, which is why it is weighted the highest of the criteria. After that, the weight of each material when being used must be taken into account as the higher the weight contribution to the rocket, the higher the strength of the motor must be to obtain a sufficient apogee. Additionally, the manufacturability of the material must be taken into account as each bulk plate must make a tight seal with the body tube and any errors in fabrication could lead to wasted material which would slow down the fabrication process. Finally, cost of material must be considered for budgeting reasons, however this is lower in importance than the actual functionality of the bulk plates and so are weighted lower than the rest of the criteria.

Table 14: Bulkhead Material

Design		**Aluminum**		**Marine Grade Plywood**		**Fiberglass**	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Weight	2	2	4	4	8	4	8
Manufacturability	2	3	6	5	10	2	4
Yield Stress	5	5	25	2	10	5	25
Cost	1	2	2	5	5	3	3
Total		**37**		**33**		**40**	

Using this decision matrix the ultimate outcome shows that fiberglass is the best material suited for bulk plates. This is due to its highs strength to weight ratio as well as its ready accessibility and moderate cost. For this reason the bulk plates which will be undergoing the most stress will be made out of fiberglass, namely the bulk plates connected to the shock cords as well as the ones directly up against the motor and black powder charges. For cost reasons the rest of the bulk plates will be made of marine grade plywood as it has high manufacturability and easy processing while maintaining a relatively low weight as well as low cost. The yield stress of marine grade plywood is admittedly lower than fiberglass which is why it will strictly be used in sections that will not be experiencing large forces.

3.2.10 Centering Rings

In addition to making sure that the motor housing is parallel, the SBSW team has decided on a fin design that utilizes the centering rings for mounting purposes. These rings will be made out of fiberglass because, although it is a little bit difficult to process, it has high yield stress which is critical for centering rings as they are in charge of holding the motor housing in place and will experience high forces from both the motor accelerating upwards as well as the fins that are slotted into them vibrating and providing drag.

3.2.11 Retention: Adhesives

Adhesives are used in several aspects of the launch vehicle to permanently join two surfaces together. This feature would also inhibit reusability as cracks in the epoxy are difficult or impossible to repair. Therefore, we limited our use cases to when there are two flat surfaces present and when mechanical retention methods might not be the most efficient. Excessive use of adhesives would also increase the weight of rocket and should be used sparingly with the right technique. One primary application is attaching the fins to the centering rings and airframe. Fin fillets can be made with epoxy to increase the bonding area on the surface of the airframe where the fins attach.

Figure 6: Adhesives used to attach the fins to an airframe

Figure 7: G5000 RocketPoxy in 2-pint containers

Three adhesives were compared with different cure times, costs, weight and strength. RocketPoxy has the highest bonding and shear strength, but the longest cure time. The Quick-Cure Epoxy and Two-Part Epoxy do not have the strength needed to withstand forces during launch.

Table 15: Adhesive Retention Methods

Design		Quick-Cure Epoxy		Two-Part Epoxy		RocketPoxy	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Cure Time	3	6	18	4	12	2	6
Cost	2	8	16	6	12	4	8
Weight	1	4	4	6	6	8	8
Strength	4	2	8	6	24	8	32
Total		**28**		**42**		**48**	

3.2.12 Retention: Mechanical

In designing the telemetry bay, there are many ways to mechanically affix electronics to the nose cone bulkhead. Because the data collected by the electronics must be accessed after every flight, it is highly beneficial to implement a reusable access method. For this reason, simply attaching a conventional bulkhead to the airframe is not a good design. Instead, a removable plate may be attached to the permanent bulkhead. Using nuts and bolts ensures this attachment is reusable.

Furthermore, the design must be durable enough to survive a violent rocket launch. As such, a threaded rod may be connected from the bulkhead to a metal tipped nosecone. Such a design would increase the number of attachments securing the electronics. However, over engineering leads to excess weight and costs. It is important to note that the forces expected to act on the telemetry bulkhead are relatively low. For this reason, this design is not ideal.

Table 16: Telemetry Bay Mechanical Retention

Design		Simple		Two Parts		Threaded Rod	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Reusable	5	2	10	10	50	9	45
Weight	3	10	30	8	24	6	18
Safety Factor	2	7	14	6	12	10	20
Total		**54**		**86**		**83**	

For the VDS and camera bay a similar design process was followed. Like before, the electronics in this section should be easily accessible. Therefore, screws into the plywood plates are not a desirable option. A traditional L-bracket design would also prevent reusability considering there are multiple bays stacked upon each other.

Since this section of the rocket is within propulsion bay, the forces expected to act upon this section are much larger than before too. As such, threaded rods may be used to secure the plates. Using bolts, each section may be secured in place. When necessary, the bolts may be unscrewed and the electronics accessed.

Table 17: VDS/Camera Bay

Design		Screws		L-Brackets		Threaded Rod	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Reusable	4	2	8	5	20	9	36
Weight	2	10	20	9	18	4	8
Safety Factor	4	7	28	9	36	10	40
Total		**56**		**74**		**84**	

3.2.13 Subsystem Retention

The camera bay will be housed in a canister that acts as a coupler, along with the VDS system, which will go inside of the main body above the propulsion bay. Inside this canister, just above the motor housing, there will be a fiberglass bulk plate that is epoxied in place. This will have three lead screws which will propagate up through both the VDS system and the camera bay which will affix another fiberglass bulk plate to the top of the canister. This top bulk plate will have a small lip on the outside of it that will overlap with the coupler region giving the bulk plate a contact surface with which it can use to compress against ensuring all components are steadily secured. This coupled with two shear pins as well as two retention bolts inserted perpendicular to the airframe will completely constrain both the camera bay and the VDS.

3.3 Motor Choices

During the design process a few motors were considered including the L2200, the L1420, and the L1365, all of which are manufactured by AeroTech. In order to select a motor properly the weight of the rocket and aerodynamic profile must be taken into account in order to project the apogee that would result from each motor. These preliminary calculations were done using Open Rocket to get a rough estimate of what the apogee may be close to in order to choose which motor best fit the rocket.

Table 18: Motor Selection

Design		L2200		L1420		L1520T	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Total Impulse	5	4	20	5	25	3	15
Burn Time	2	4	8	5	10	5	10
Average Thrust	3	4	12	5	15	3	9
Total		**40**		**50**		**34**	

This decision matrix was formed based on a projected total rocket weight of 49.3lbs and an apogee goal of 4500ft. Through the use of Open rocket, each one of these motors were simulated and the hypothetical apogee corresponding to each was calculated. For the L2200 it was found that the projected height was well over the apogee goal to 5653 ft which was not ideal. Conversely, when the L1520T-P was simulated the apogee was well under what was being looked for, only reaching 3710 ft. The L1420T-P though, had a projected apogee of 4824ft which is within 250 ft of the apogee goal. This slight difference can be accounted for using the VDS designed for this express purpose.

3.4 Leading Vehicle Design

The launch vehicle was designed to propel the payload to an altitude of 4500 ft in a safe and calculated manner. The trade studies conducted were used in order to converge to the most economic and efficient design consisting of a nose cone, payload bay, avionics bay (including fore and aft recovery bays) and a booster bay consisting of the chosen motor and VDS canister. The launch vehicle can be seen as follows:

Figure 8: Vehicle Overview

3.4.1 Body Tube

The body tube diameter chosen for the design was 6" in order to accommodate for the payload rover and internal avionics components. This size was also very readily available at vendors such as *Madcow* and *Apogee*. Based on the requirements of the stresses on the airframe and the necessary safety factors, fiberglass was chosen and the inside diameter of the tubing was increased to 6" while the outside diameter was increased to 6.17."

Table 19: Airframe Component Lengths

Airframe Component	Length (inches)
Nose Cone	24
Payload Bay	20 (without coupler)
Avionics Bay	28.6
Booster Bay	32 (without coupler)
TOTAL Vehicle Length	104.6

3.4.2 Nose Cone Shape

The selected nose cone was chosen to be 4:1 ogive tangent with a BR of 0.15. The nose cone will be purchased from Madcow Rocketry which comes with an aluminum tip. The design was chosen due it its availability and versatility. The metal tip will allow for a more sturdy design and will ensure that the vehicle can be recovered undamaged after landing. Additionally, the metal tip of the nose can be utilized as an anchoring point for the telemetry sled with the use of a threaded rod.

Figure 9: Nose Cone Overview

The detailed dimensions of the nose cone can be described generally by the following equations:

$$\rho = \frac{R^2 + L^2}{2R}$$

Where ρ is the ogive radius which dictates the outer shape of the nose cone. This can be used to formulate a relationship which relates the y value at every point on the curve to the x as shown in the below:

$$y = \sqrt{\rho^2 - (L - x)^2} + R - \rho$$

However, this equation does not take the spherically blunted tip into account, which requires some additional formulations. The equation below depicts the center of the spherical nose cap where r_n is the radius of the tip, L is the length of the nose cone and R is the radius of the base. The position of the center of the spherically blunted tip can be acquired as follows:

$$x_0 = L - \sqrt{(\rho - r_n)^2 - (\rho - R)^2}$$

It is also possible to define a tangency point which mathematically formulates where the ogive tangent surface intersects the spherically blunted tip:

$$y_t = \frac{r_n(\rho - R)}{\rho - r_n}$$
$$x_t = x_0 - r_n$$

3.4.3 Nose Cone & Telemetry Equipment Integration

The telemetry equipment is integrated into the nose cone with the use of a removal plate. The section view of the assembly can be seen below.

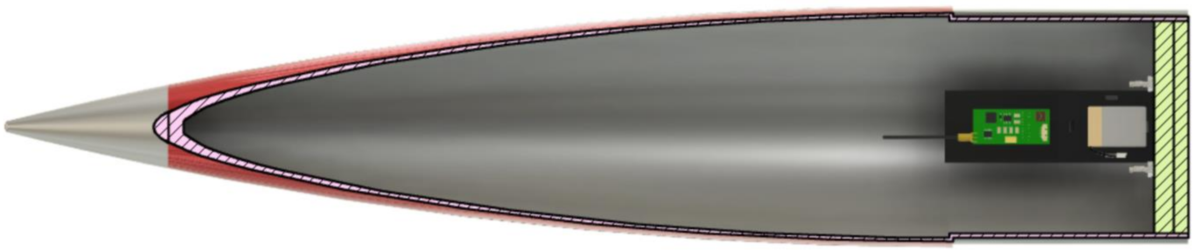

Figure 10: Section View of the Nose Cone 7 Telemetry Bay Assembly

The payload is integrated into the back plate of the telemetry equipment which is then attached to the nose cone. The assembly can be seen as follows:

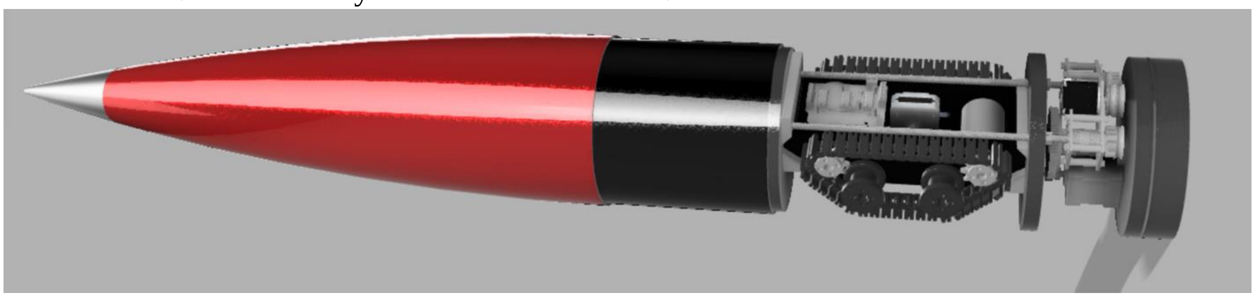

Figure 11: Nose Cone and Payload Integration

3.4.4 Camera Bay

The camera bay housing contains 3 GoPro Hero7 Silver cameras which will record the launch footage. The independently running systems will ensure that even if one camera stops functioning, the other two will contain video footage. The video taken from the 3 cameras can also be stitched together to give a 360 degree overview of the launch.

Figure 12: GoPro Hero7 Silver

Using mounting plates and threaded rods, the cameras can be safely mounted to face 120 degrees away from each other. The bottom moutning stand and the top mounting connector of the camera will be 3D printed to accommodate for retention purposes which can then be utilized to mount the system firmly.

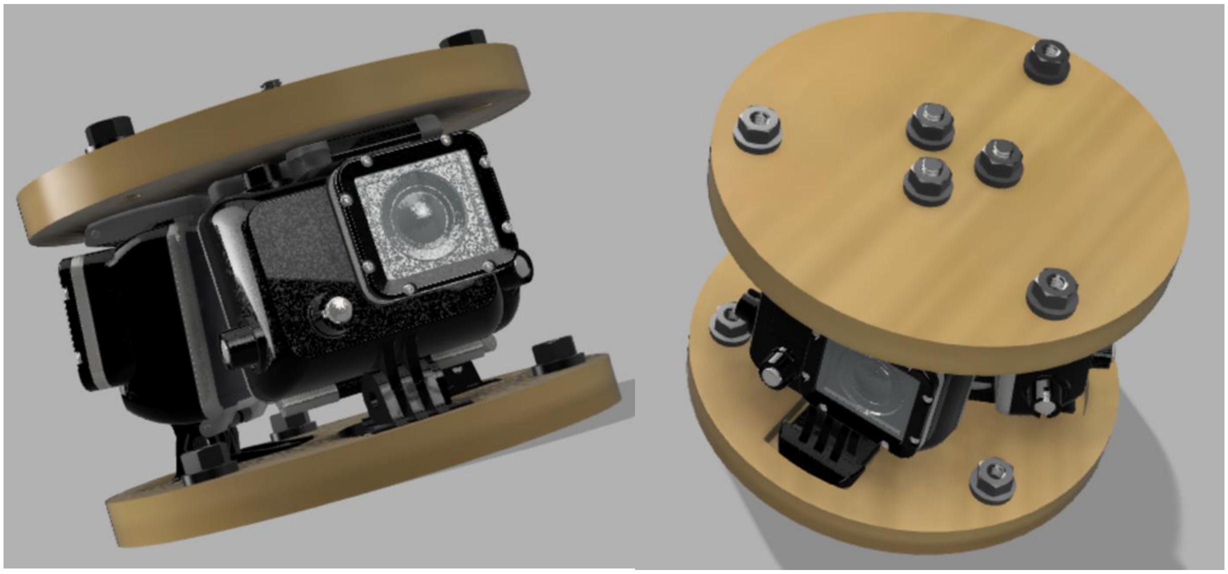

Figure 13: Camera Mounting System

3.4.5 Variable Drag System

The BEDS (Blade Extension Drag System) was chosen as the final design which will serve as the altitude control unit for the vehicle. The system has three extending blades which are mounted on individual rails. The sliding mechanism has a small stainless steel wheel on the blade side and a stainless steel dual track system on the rail. This method minimizes friction while ensuring the highest amount of loading forces which the system will face during flight.

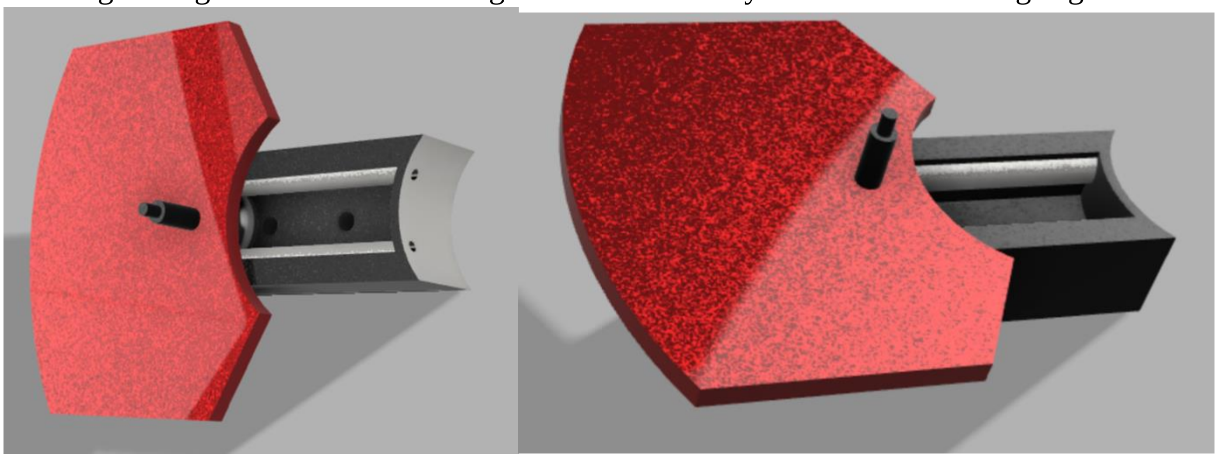

Figure 14: BEDS Sliding mechanism

The mechanism system for BEDS consists of a combination bearing which sits on the center of an aluminum disk with a carefully machined shaft on which the roller bearing can slide on. The driving disk sits on top this this bearing with a linkage system which drives each blade simultaneously in a very fluid manner.

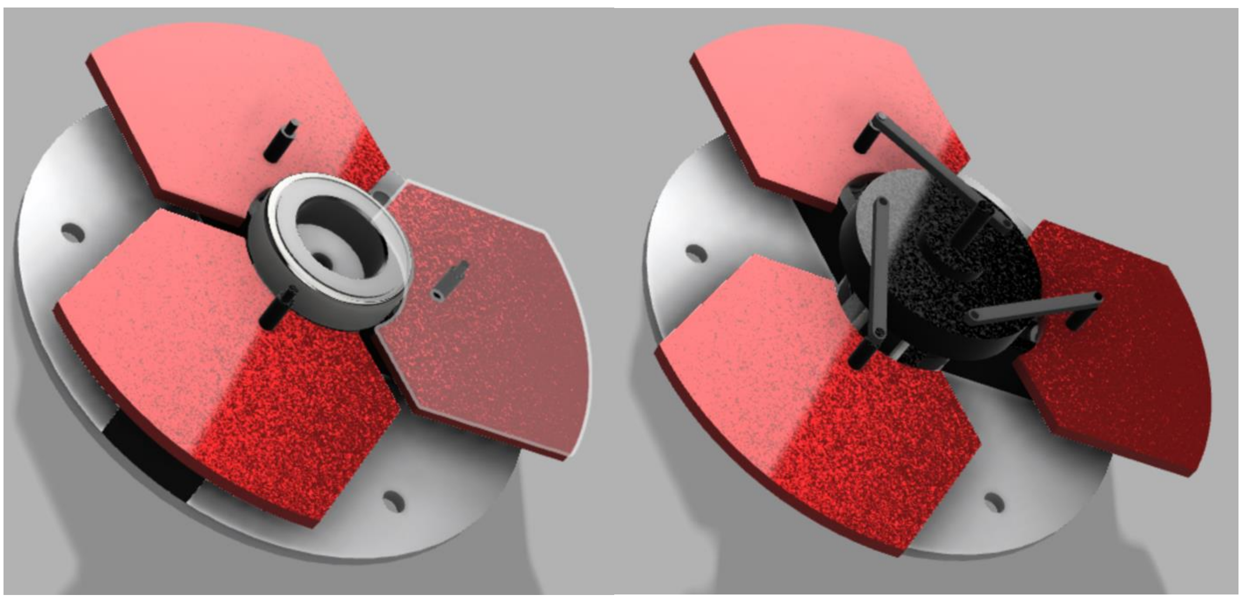

Figure 15: BEDS Bearing and Linkage Assembly

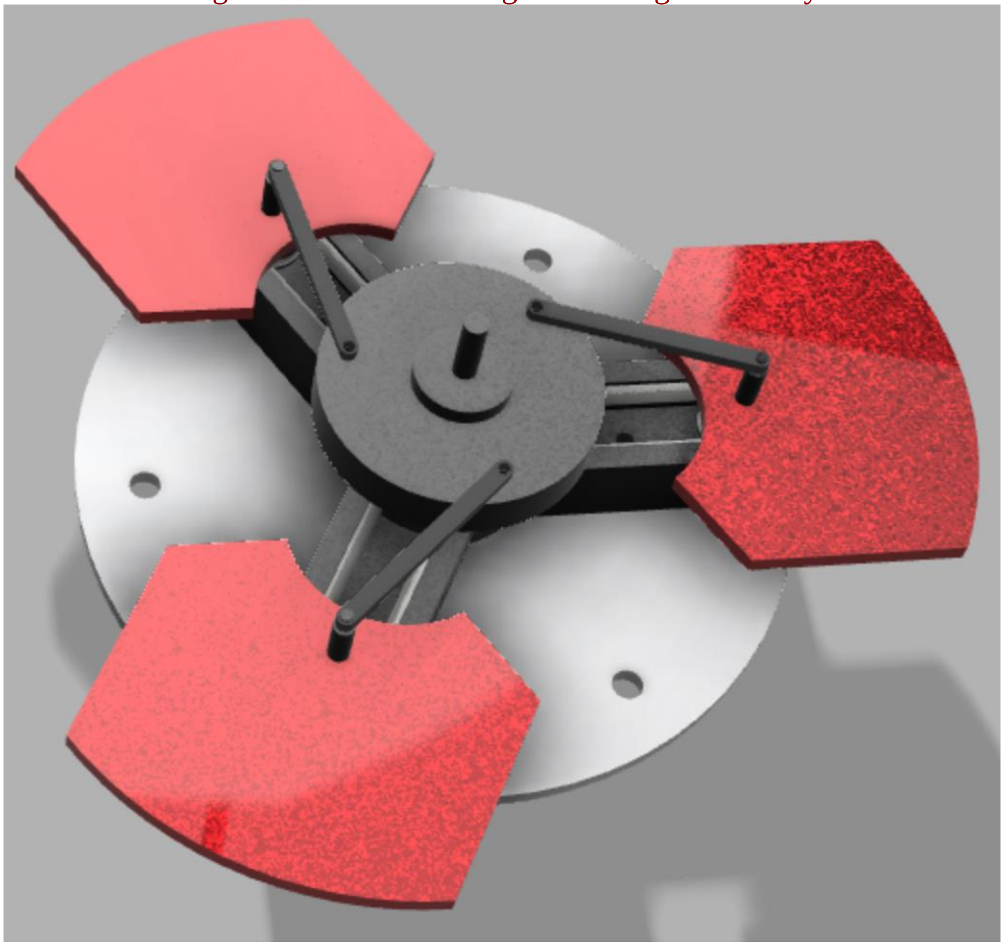

Figure 16: BEDS Actuation system

The chosen servo motor, capable of handling at least 350 oz-in of torque, drives the rotating disk while mounted on a top plate. There is another thrust bearing aft of the shaft collar which allows the shaft to drive the system while maintain a constant normal force with the baseplate. The first and second plywood plates gives the BEDS a constant normal force from both directions after fastened using threaded rods. The third plywood plate retains the motor safely using the same set of threaded rods.

Figure 17: BEDS Mounting system

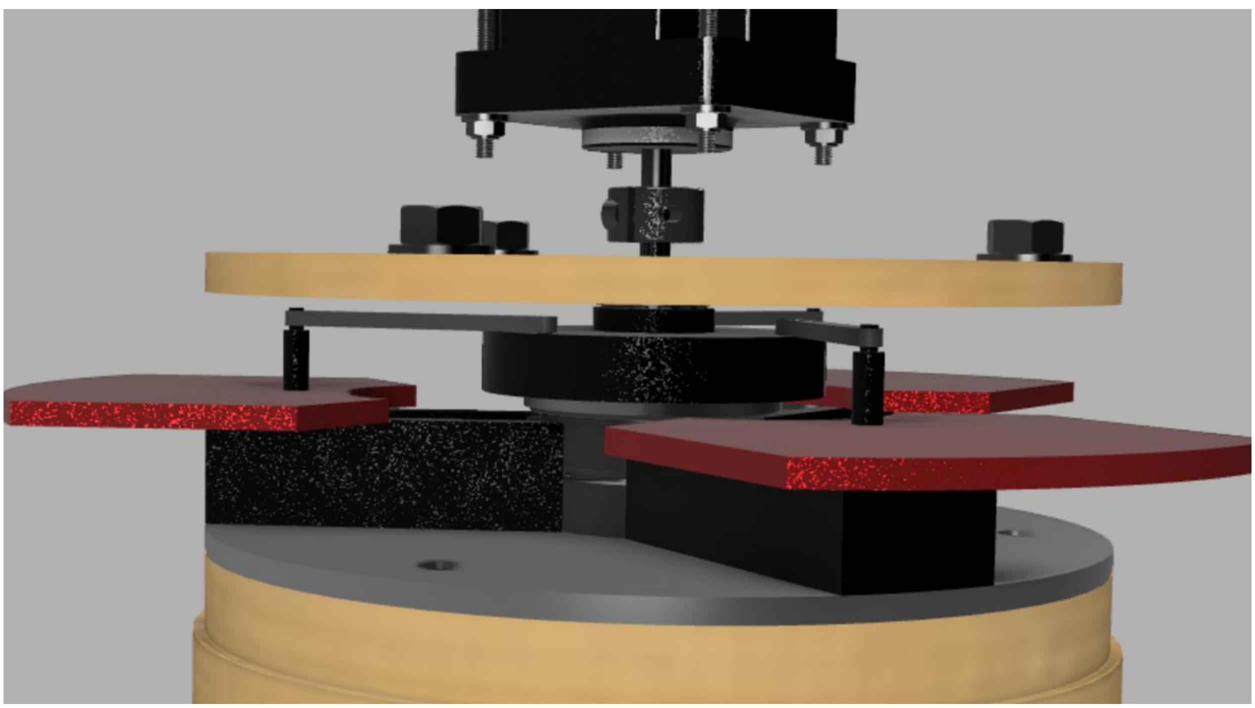

Figure 18: BEDS Servo Motor Actuation

Using real-time altitude information, a Teensy 4.0 microcontroller will control the actuation of the servo motor. While the microcontroller and servo will have different power supplies, they will be connected via one of the PWM pins. With its ARM Cortex-M7 processor, the Teensy 4.0 CPU is capable of a 600 MHz clock speed. This high clock speed ensures a moment-to-moment prediction of apogee and adjusts the VDS accordingly.

3.4.6 BEDS Canister

The subsystems for the drag control system and the camera bay will be integrated into a single canister for ease of housing and access. By utilizing three threaded rods in conjunction with wingnuts and washers, both subassembly will be fixed tightly against the baseplate.

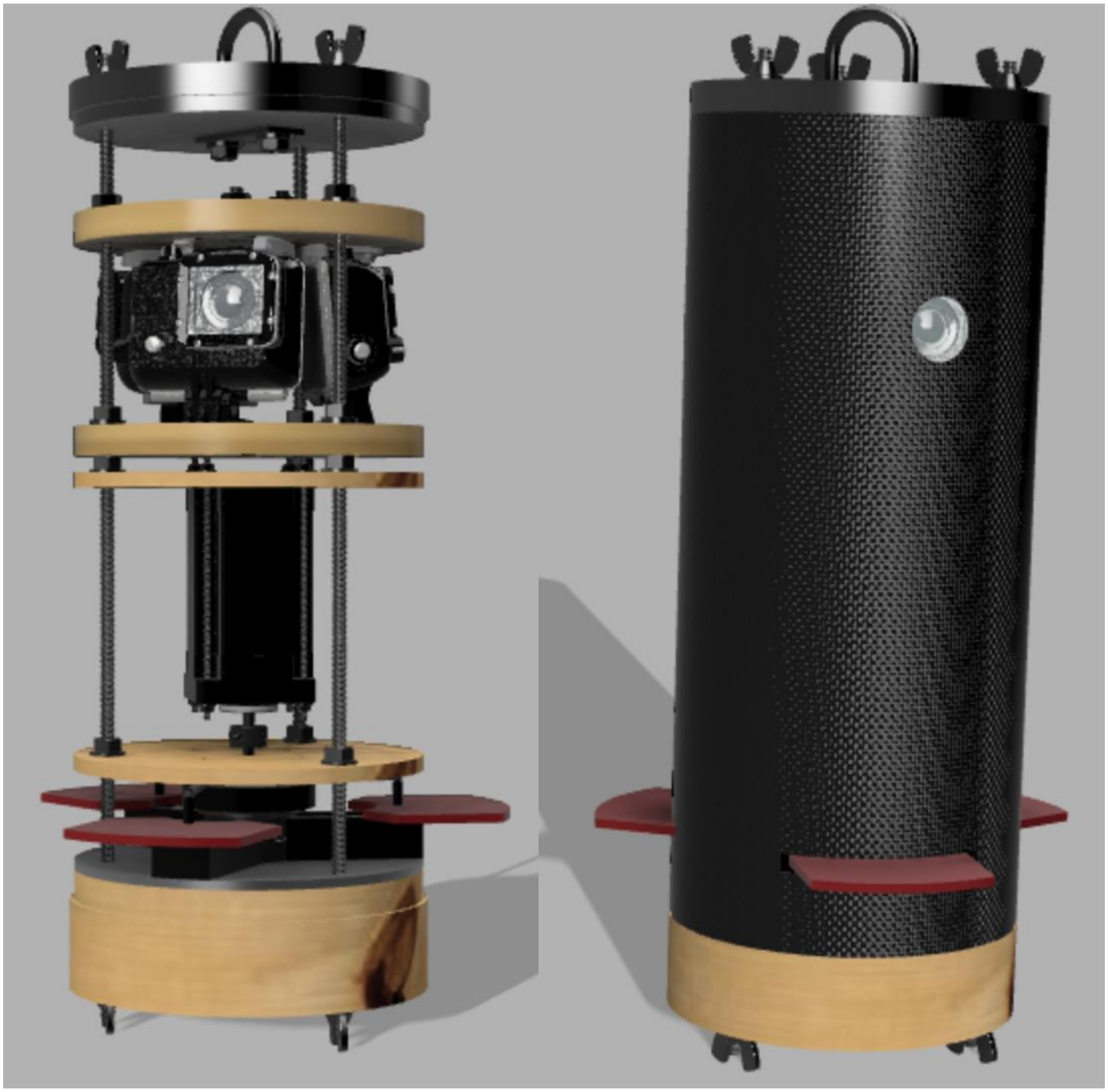

Figure 19: BEDS Canister

The BEDS canister will also be used as the coupler for the avionics bay. The reasoning behind this was to save 6 inches of space on the rocket which would cut down on weight and costs by a significant amount.

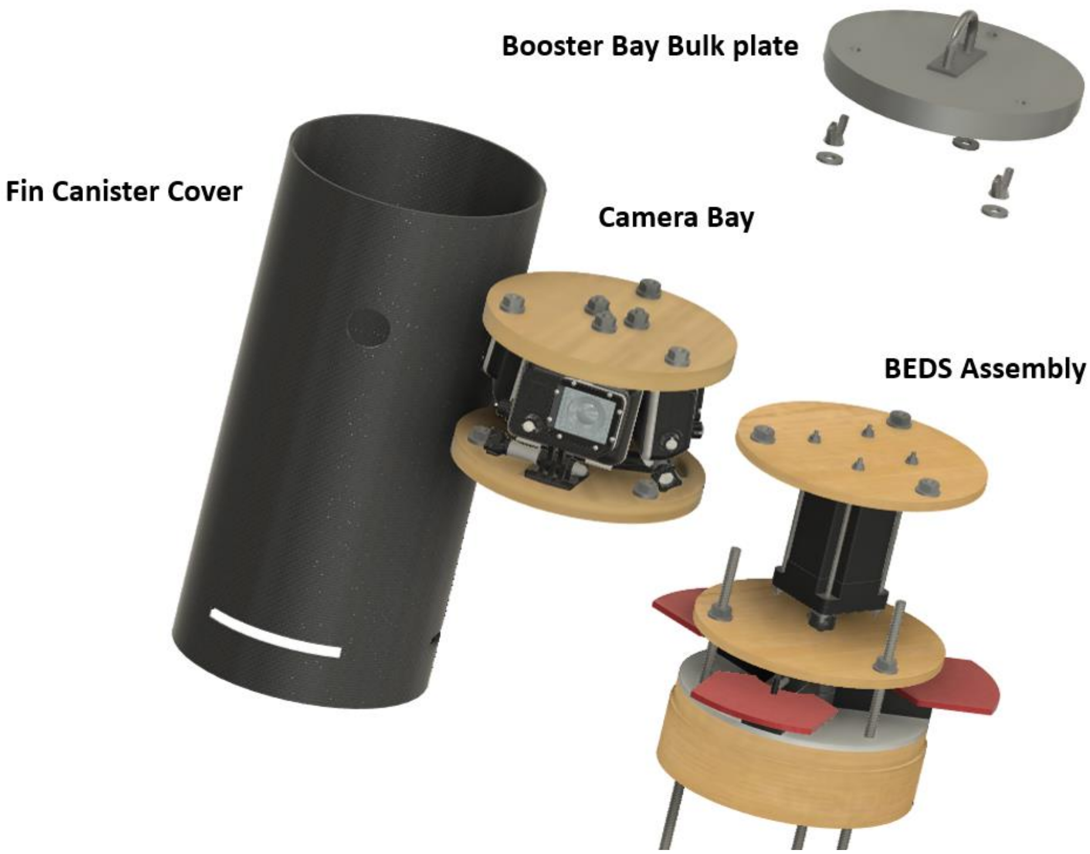

Figure 20 Exploded BEDS Canister

3.4.7 Fins

A trapezoidal set of 3 fins was chosen for the final design. The fins will have an airfoiled profile and will be machined in-house. The fin set ensures a stability of 2.52 cal while minimizing drag and maximizing apogee. The following table lists the dimensions of the fins:

Table 20: Fin Dimensions

Dimension	Value
Root Chord	14 inches
Tip Chord	4.5 inches
Height	6.5 inches
Sweep Length	7 inches
Sweep Angle	47.1 degrees

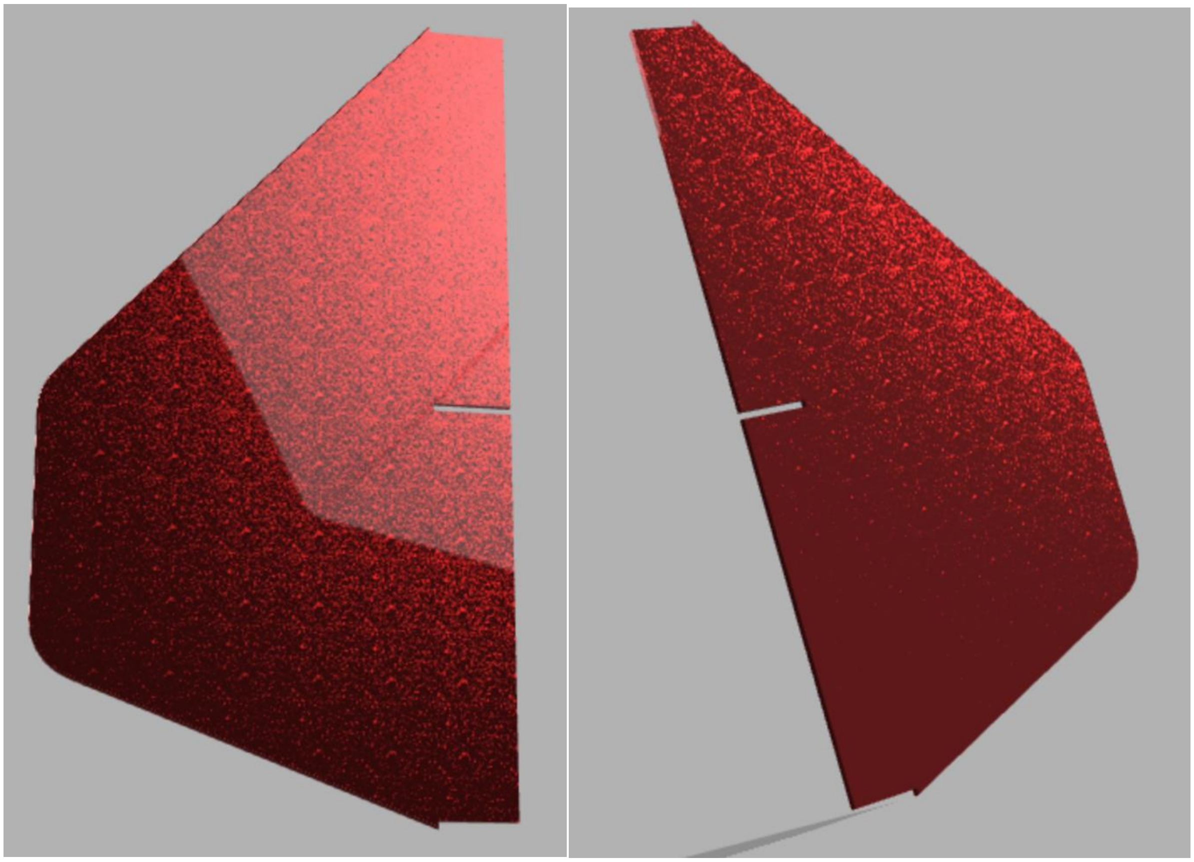

Figure 21: Trapezoidal Fin Design

The fin tang will be prepared such that it slides into three centering rings and rests on top of the motor mount. The fins will be mounted to the airframe using the TTW mounting method by utilizing RocketPoxy after careful alignment.

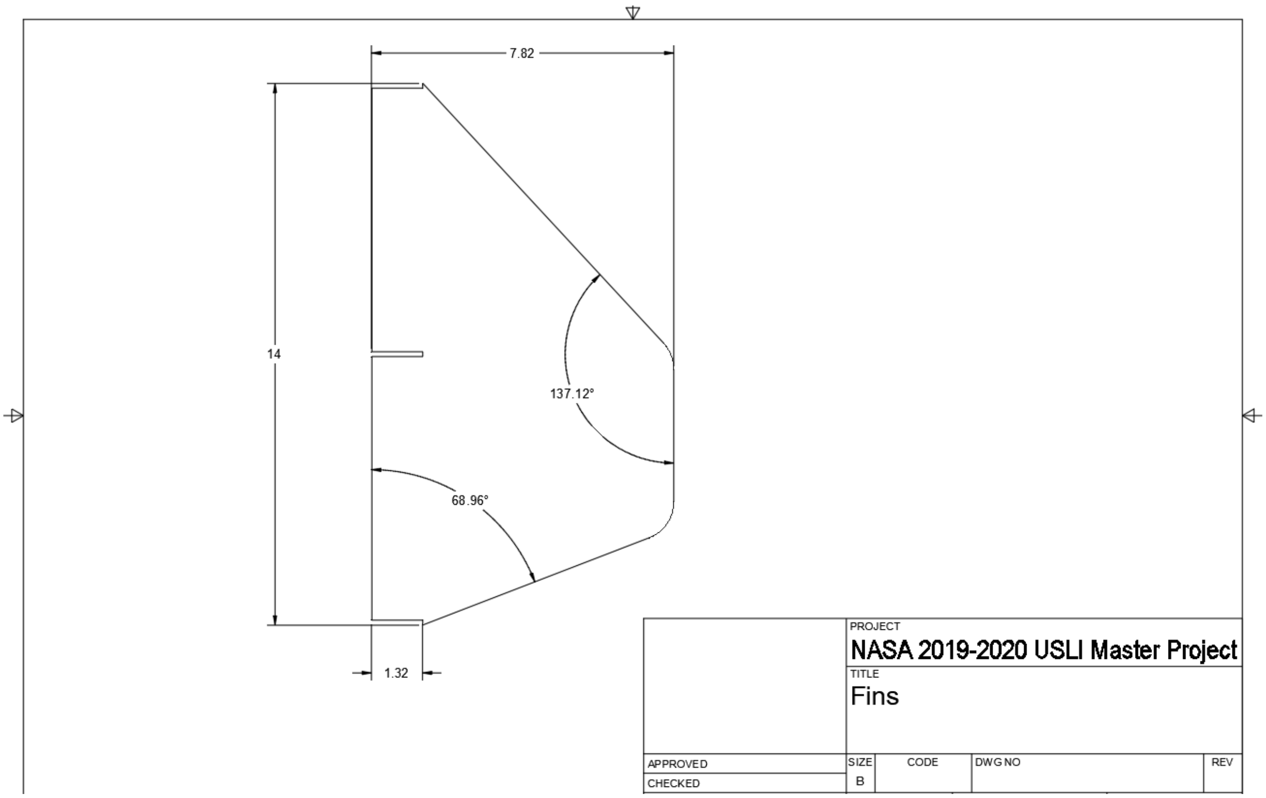

Figure 22: Technical drawing of the fin

3.4.8 Motor Tube and Retainer

The 22” motor mount for a 75 mm motor will be purchased from *Madcow* which will then be used in conjunction with the fins and the retaining rings to keep the reloadable motor in place in the booster bay. An AeroPack 6061 Anodized Aluminum flange motor retainer will be utilized along with JB Weld in order to retain the motor.

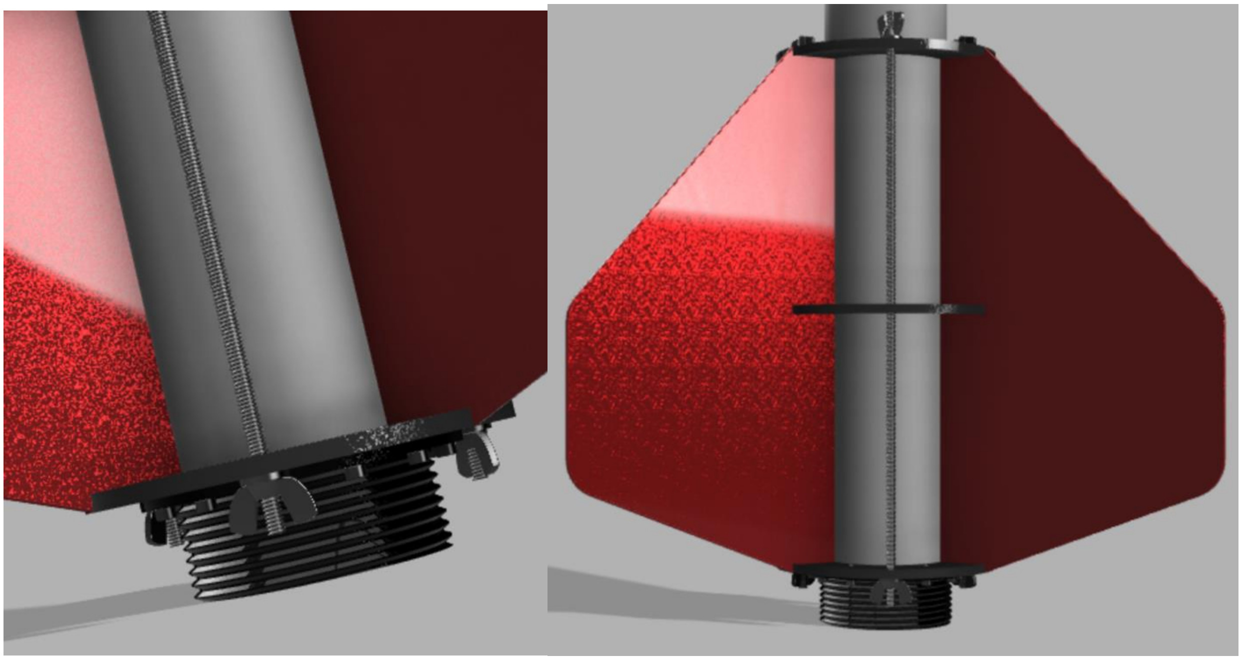

Figure 23: Motor Mount System

3.4.9 Booster Bay

The booster bay will consist of fiberglass tubing, fin retention system, and BEDS canister. The bay is end slotted for the fin can which will allow the team to simply slide the entire fin assembly into the bay without any issues. The fiberglass tubing also has cutouts for the blades in the BEDS. FEA was performed in order to maximize the surface area of the blades while ensuring that the fiberglass tubing will retain its structural strength. The aft retaining ring of the fin can will provide the flat surface onto which the motor retainer will be attached.

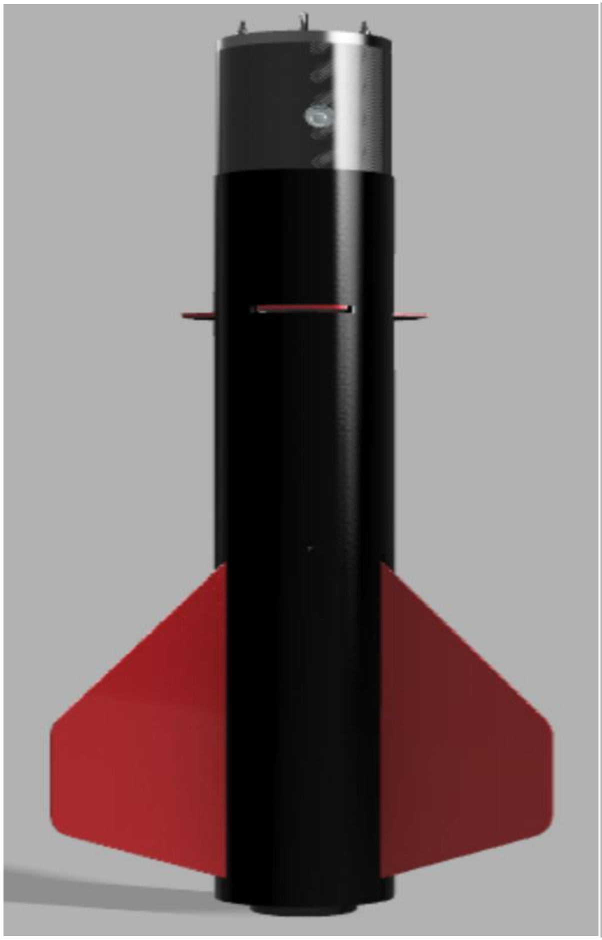


Figure 24: BEDS Canister Assembly with Booster Bay

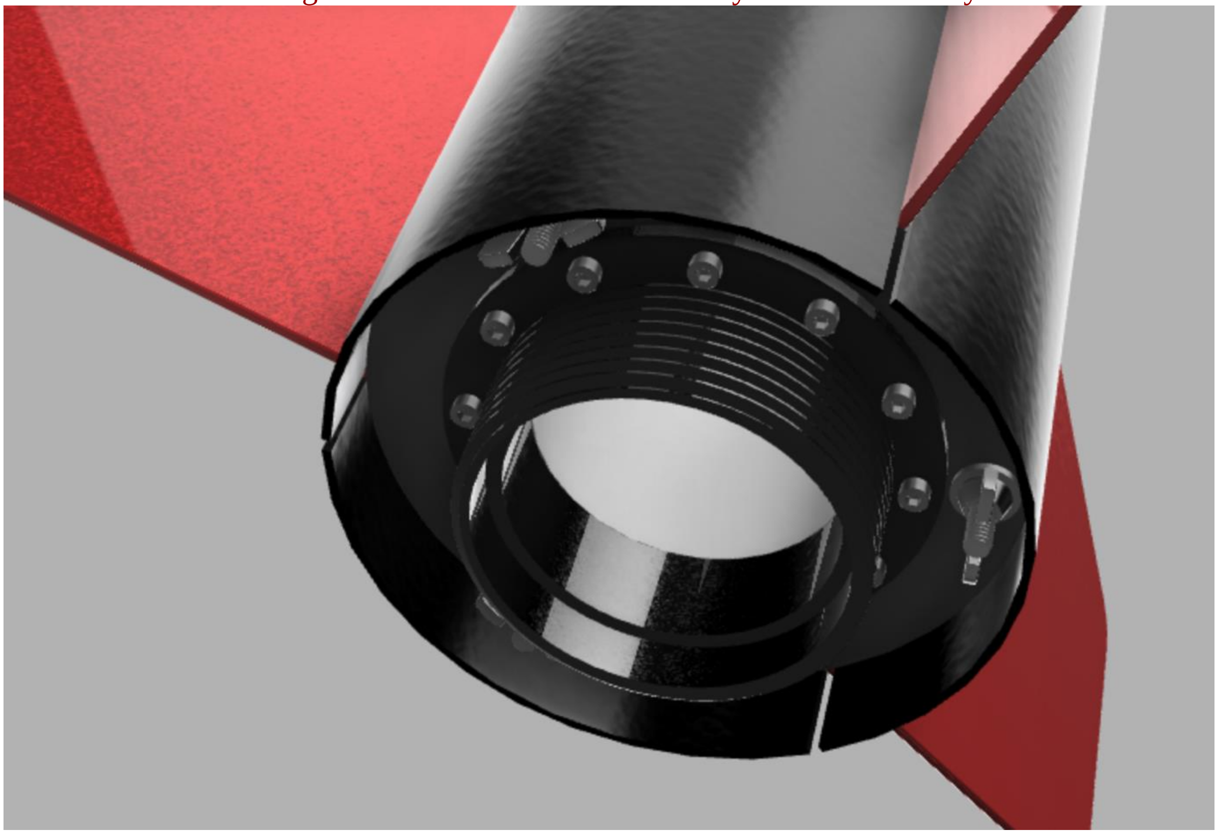

Figure 25: Motor Retainer & Centering Ring Assembly with Booster Bay

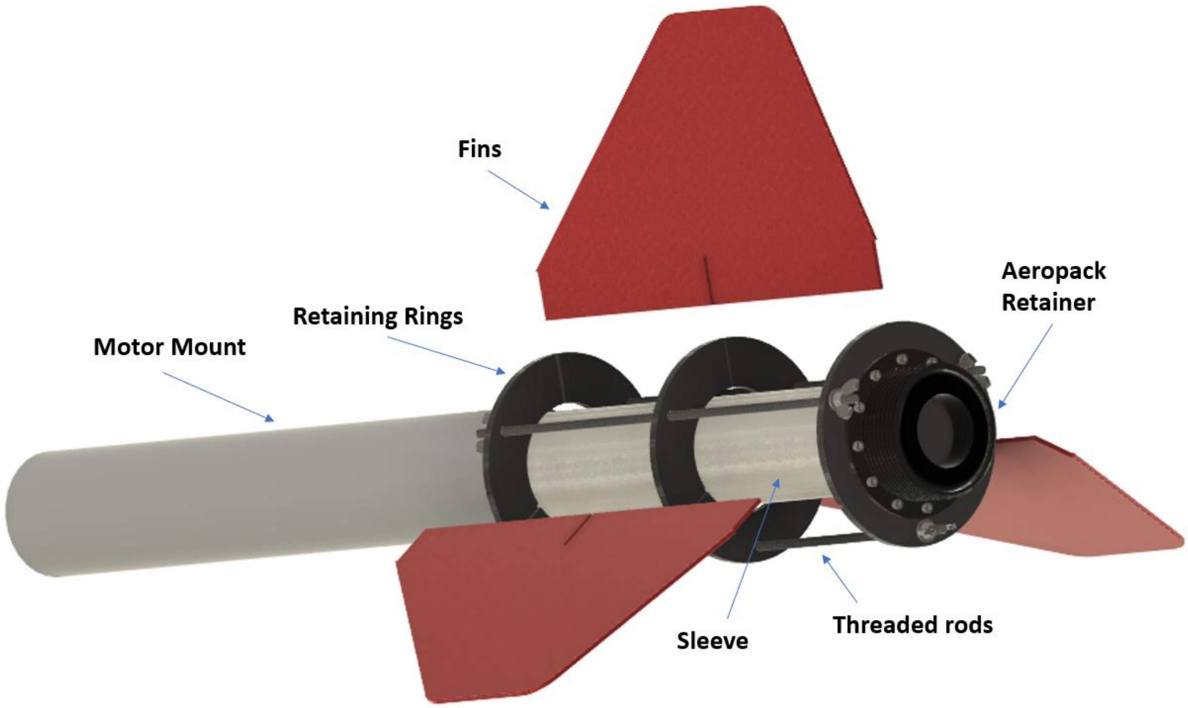

Figure 26: Exploded Fin Can

3.4.10 Overall System Summary

With the complete assembly, the final system weighs 49.3 lbs and is 104.6 inches long. The section views of the fore and aft section of the vehicle can be seen below:

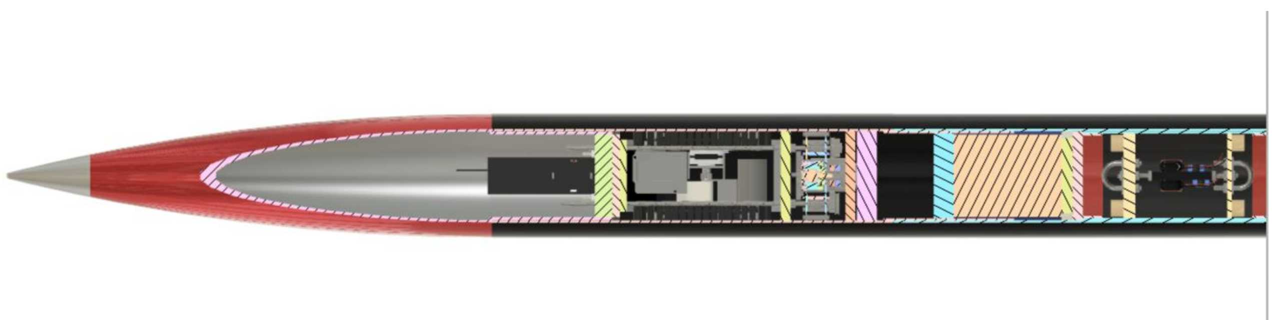

Figure 27: Section View of Fore Section of Total Assembly

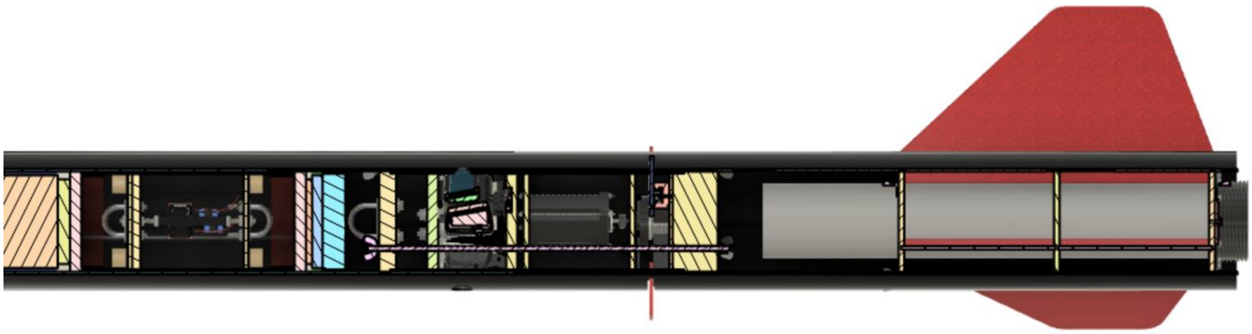

Figure 28: Section View of Aft Section of Total Assembly

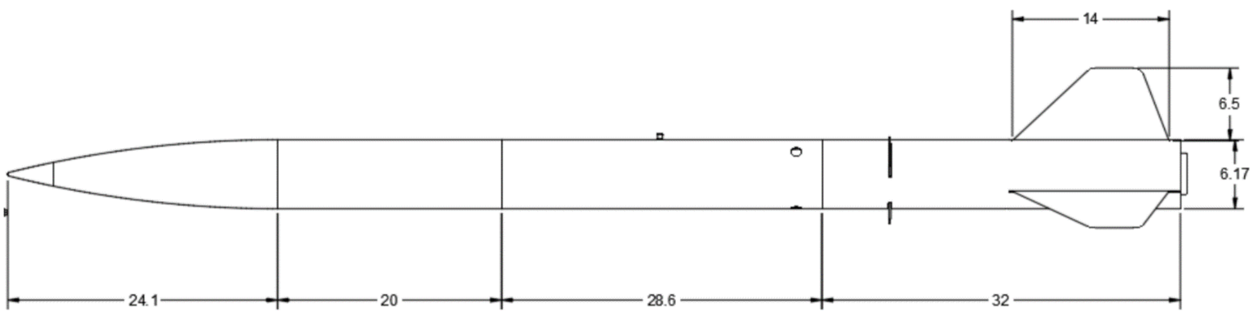

Figure 29: CAD drawing of the overall airframe

Figure 30: Exploded view of nose cone and payload

Table 21: Total Vehicle Weight Summary

Vehicle Component	Weight (lb)
Nose Cone and Telemetry Bay	5.26
Payload Bay	11.6
Avionics Bay	9.92
Booster Bay (Unloaded)	12.4

Total Vehicle (Unloaded)	39.2
Total Vehicle (Loaded)	49.3

3.5 Motor Selection

The motor selection process involved selecting different motors and vetting them against each other based on the important constraints such as apogee. The chosen motor is able to perform as intended with a projected apogee of 4824 ft while the target apogee is 4500 ft. Since OpenRocket is known to overshoot on the apogee and the VDS is expected to reduce the target height by roughly 200 ft, the selected motor will approximate propel the rocket to 4500 ft. The selection matrix is shown below:

Table 22: Motor Selection Matrix

Motor	Manufacturer	Apogee (ft)	Max Velocity (ft/s)	Max Acceleration (ft/s^2)
L850W	**Aerotech**	**3449**	**432**	**152**
L1500T-P	**Aerotech**	**3710**	**502**	**360**
L1520T-P	**Aerotech**	**3812**	**514**	**233**
L1420R-P	**Aerotech**	**4824**	**585**	**218**
L1365M-P	**Aerotech**	**4979**	**586**	**205**
L2375-WT	**CTI**	**5474**	**679**	**368**
L2200G	**Aerotech**	**5653**	**675**	**433**

The specifications of the selected motor is as follows:

Table 23: Selected Motor Specs

Aerotech L1420R-P Specs	
Total Impulse:	1035 lbf-sec
Burn Time:	3.2 sec
Peak Thrust:	407.8 lb
Average Thrust	319.9 lb
Mass Beore & After Burn	10.05/4.47 lb
Motor Retention Method	Screw On Retainer

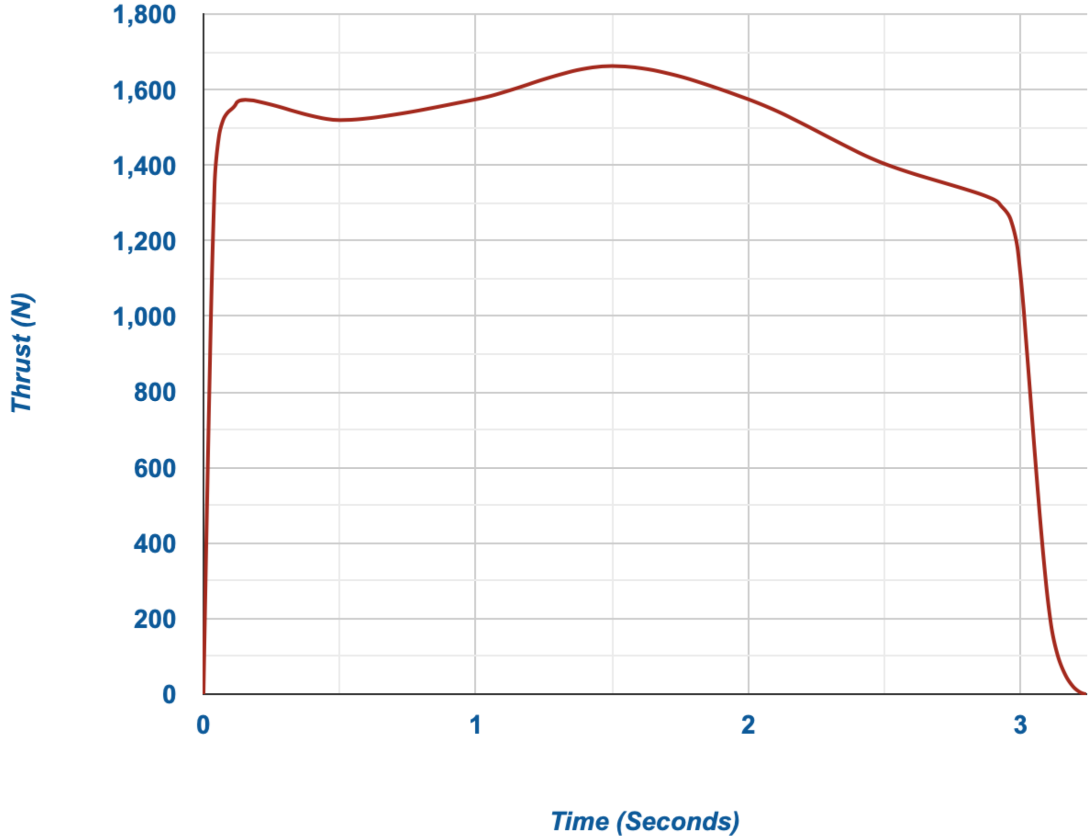

Figure 31: L1420R-P Motor Thrust Curve

3.6 Mission Performance Predictions

3.6.1 Target Altitude

The launch vehicle will be designed such that it reaches an apogee of 4500 ft above ground level.

3.6.2 Flight Profile Simulations

OpenRocket and RockSim were simultaneously used in order to simulate the flight profile of the vehicle. The complete OpenRocket model of the vehicle is shown below:

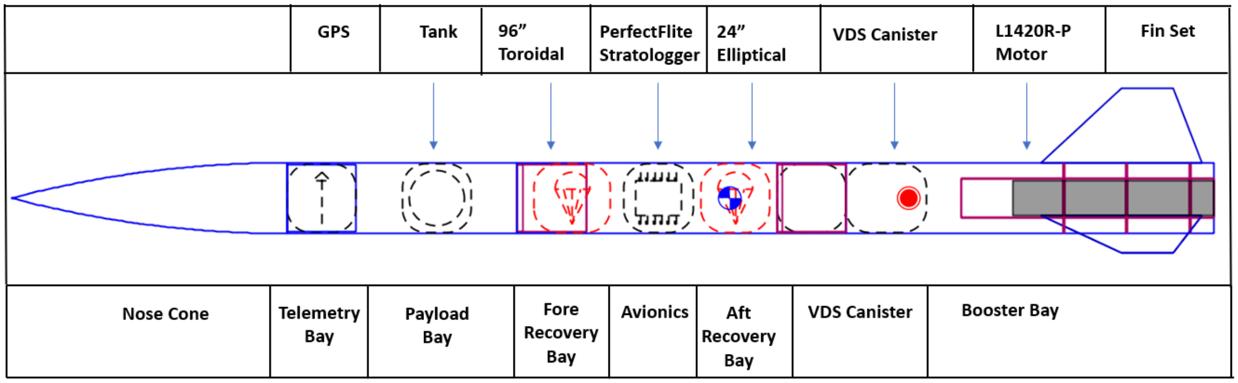

Figure 32: OpenRocket Model

The projected apogee at various crosswind speeds were simulated which would allow the team to get a reasonable idea of what the launch day apogee could be. During launch day a 12-foot rail will be utilized. However, based on the location of the fore rail button, the effective length of the rail gets lowered as shown below. The approximate location of the fore rail button from the base of the vehicle is 42 inches. Therefore the effective length of the rail becomes 102 inches.

$$L_{eff} = L_{rail} - L_{button}$$

The simulated profile without any cross wind is as follows:

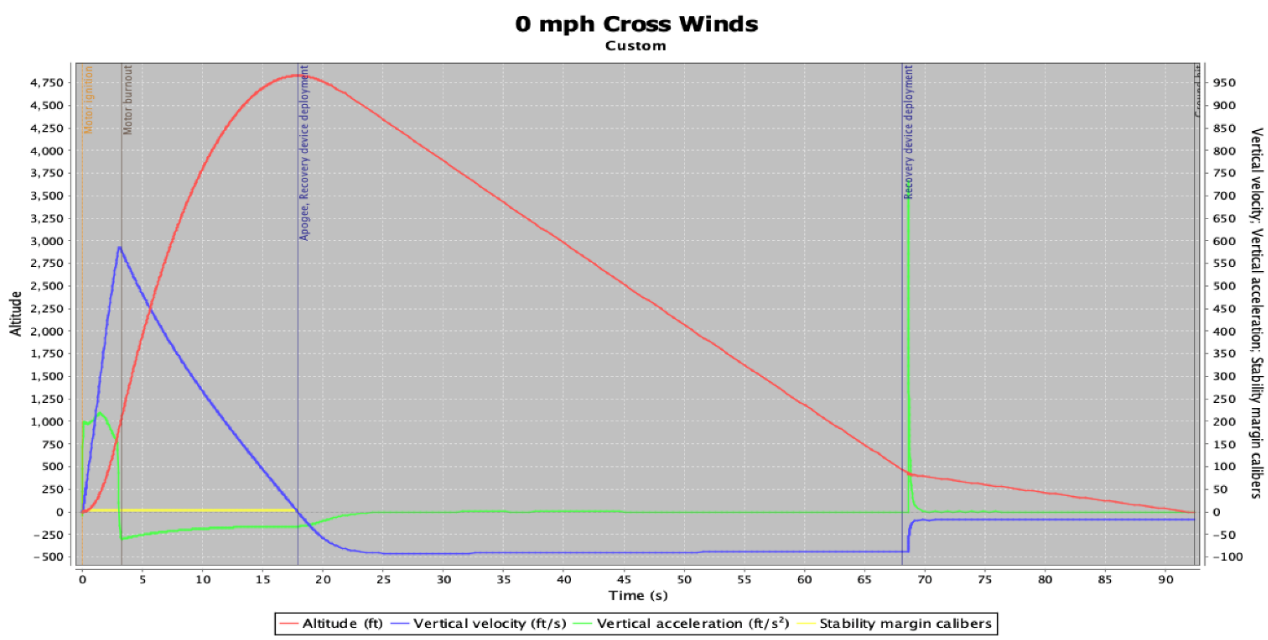

Figure 33: Launch Profile for 0 mph cross-winds

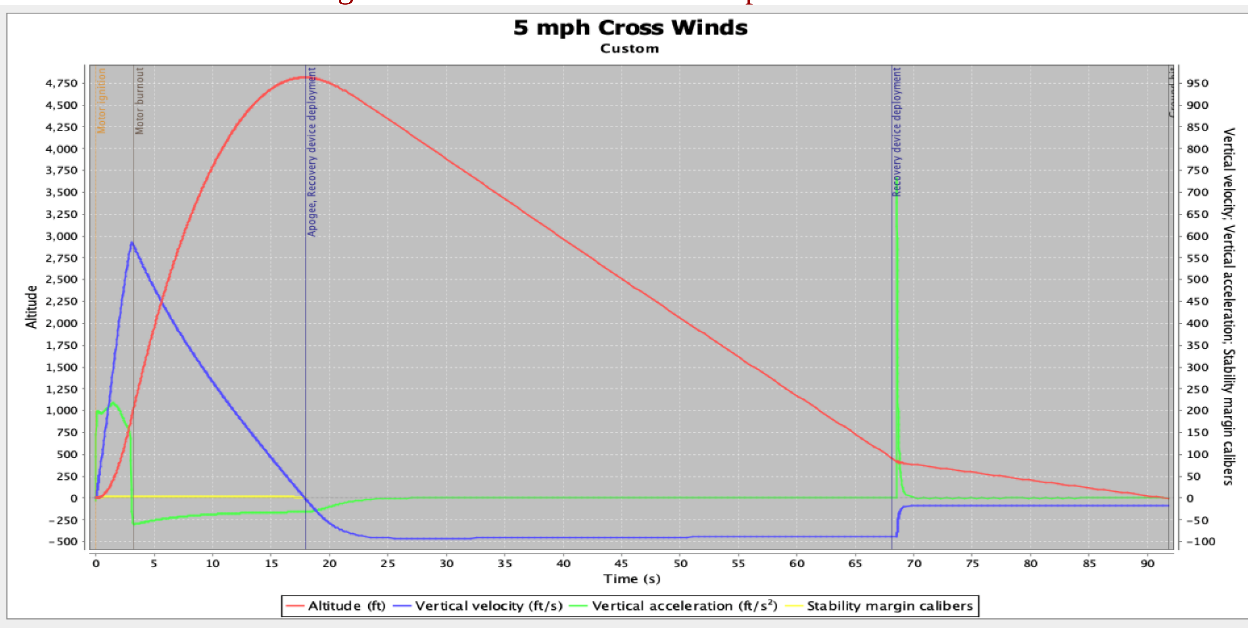

Figure 34: Launch Profile for 5 mph cross-winds

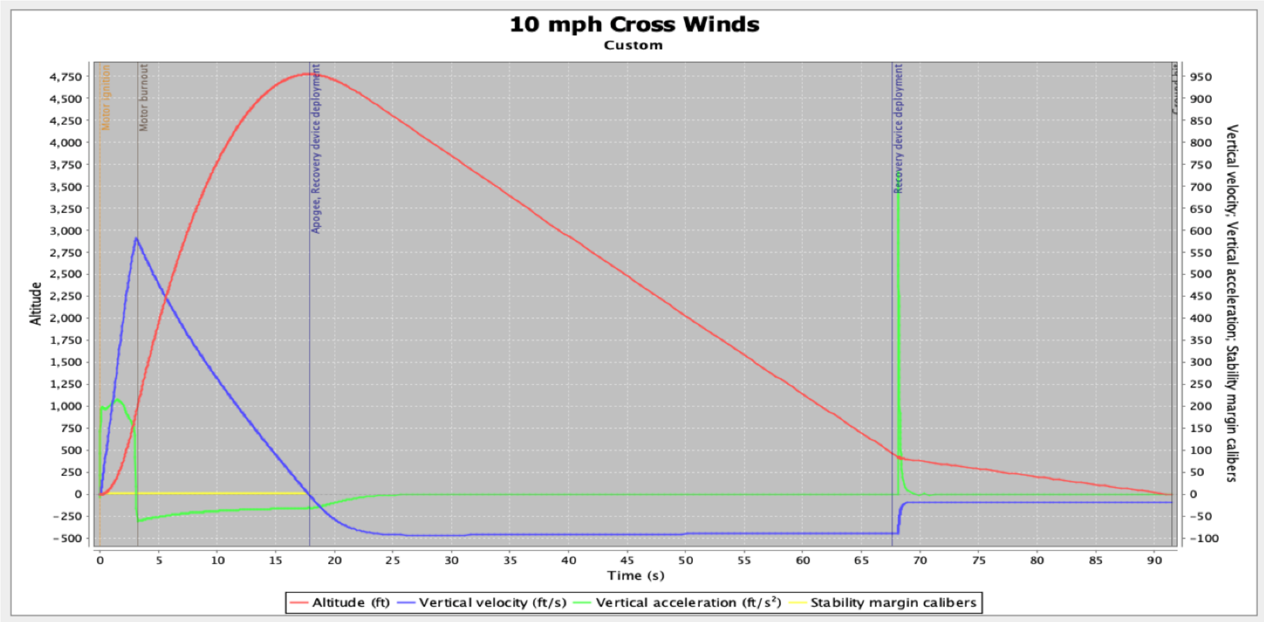

Figure 35: Launch Profile for 10 mph cross-winds

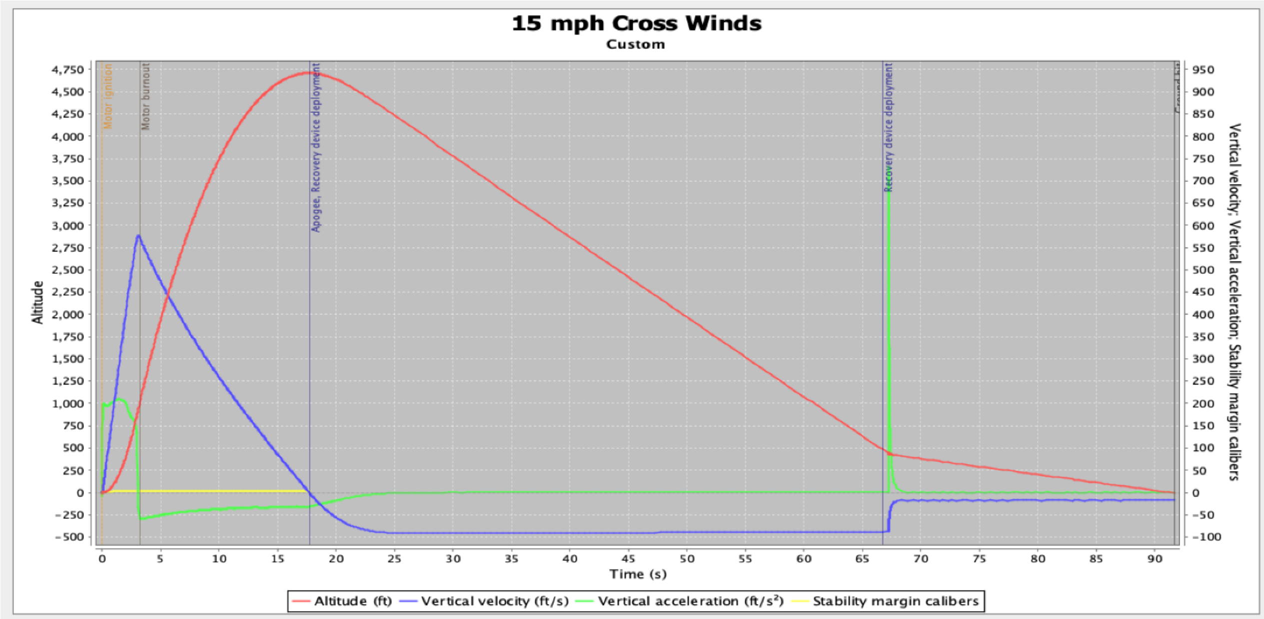

Figure 36: Launch Profile for 15 mph cross-winds

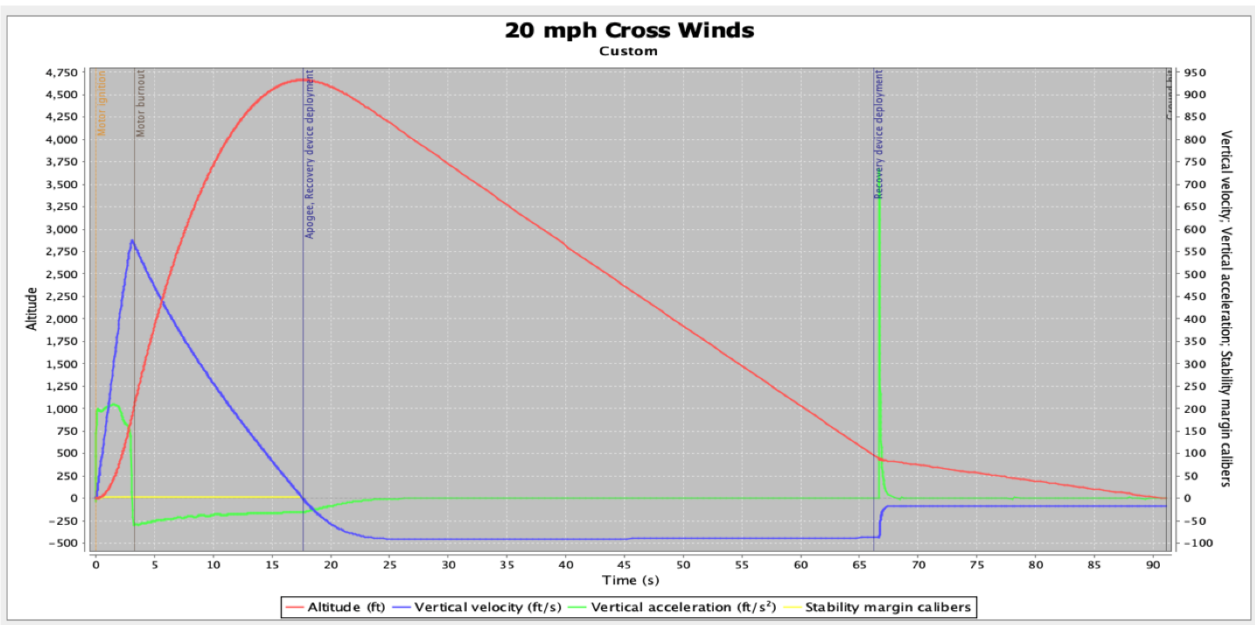

Figure 37: Launch Profile for 20 mph cross-winds

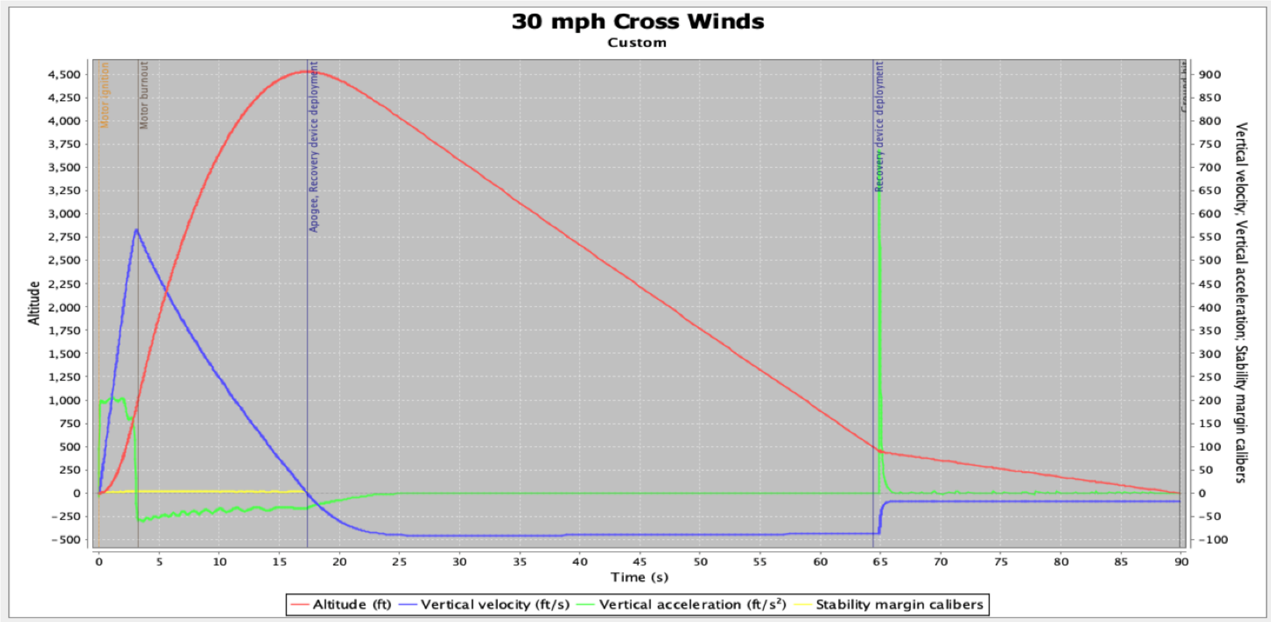

Figure 38: Launch Profile for 30 mph cross-winds

Table 24: Projected Apogee against Various Cross-Wind Speeds

	Apogee (ft)	Velocity off Rod (ft/s)	Time to Apogee (s)	Flight Time (s)	Ground Hit Velocity (ft/s)	Descent Time (s)
0 mph	4829	58.7	17.9	92.4	17.8	74.5
5 mph	4815	58.7	17.9	91.8	17.8	73.9
10 mph	4775	58.7	17.9	91.5	17.8	73.6
15 mph	4709	58.7	17.7	91.3	17.8	73.4
20 mph	4663	58.7	17.6	91.1	17.8	73.2
30 mph	4530	58.7	17.3	89.9	17.8	72.0

Table 25: Ascent Analysis

Maximum Velocity (ft/s)	585
Max Mach Number	0.53
Max Acceleration (ft/s^2)	218
Target Apogee (ft)	4500
Projected Apogee from sim (ft)	4824

3.6.3 Stability Margin, Center of Pressure, Center of Gravity

Table 26: Table of Stability Margin, CP and CG

Stability Margin (on pad)	2.52 cal
Static Stability Margin (at rail exit)	2.625
Location of CP from Nose Cone Tip	78.073 in

Location of CG from Nose Cone Tip	62.497 in
Rail Exit Velocity (ft/s)	58.7 lbs
Thrust to Weight Ratio	6.49

3.6.4 Data from Alternate Calculation Methods

Different forms of analytical methods can also be utilized in order to understand the propulsion system more closely which is essentially governed by Newton's laws of motion.

$$F = ma$$

The difference in pressure caused by the gasses exiting the rocket's motor nozzle leads to the improved equation:

$$Thrust = \dot{m}u_e + A_e(P_2 - P_3)$$

Once thrust is known, the total impulse can be calculated using the equation:

$$I = \int_0^t T dt = T_{avg} t_{burn}$$

Specific impulse on the other hand is useful for determining how efficient the motor is and follows the equation:

$$I_{sp} = \frac{I}{mg_0} = \frac{V_{eq}}{g_0} = \frac{V_e + \frac{A_e(P_e - P_0)}{\dot{m}}}{g_0}$$

The Rocket Equation, or Tsiolkovsky's equation helps to determine the overall change in velocity of the rocket by relating it to the effective exhaust velocity. This equation is used by computer simulations along with some other parameters to determine trajectory of flight and apogee.

$$\Delta V_{mod} = I_{sp} g_0 \ln\left(\frac{m_f}{m_f}\right) - \ gravity\ penalty - drag\ pentalty$$

Hand calculations are important for the purpose of double checking the Open Rocket software so that all of our theoretical values for apogee and drift and the like are not all dependent upon a single computer program that may have some flaw. In order to calculate the peak altitude of the rocket some variables must be found. Firstly the average mass of the vehicle before burnout can be found using the equation:

$$m_a = m_r + m_e - \frac{m_p}{2}$$

where m_r is the mass of the rocket, m_e is the mass of the motor, and m_p is the propellant mass. The aerodynamic drag coefficient can then be calculated using the equation

$$k = \frac{1}{2}\rho C_D A$$

where ρ is air density (1.22kg/m3), C_D is the drag coefficient, and A is the vehicle's cross-sectional area (m2). Then, the burnout velocity coefficient is found using

$$q_1 = \sqrt{\frac{T - m_a g}{k}}$$

where T is the motor thrust and g is the gravitational constant (9.81 m/s^2). Next, the burnout velocity delay coefficient is found using

$$x_1 = \frac{2kq_1}{m_a}$$

and the burnout velocity is calculated using

$$v_1 = q_1 \frac{1 - e^{-x_1 t}}{1 + e^{-x_1 t}}$$

where t is the motor burnout time. The rocket's altitude at motor burnout can then be calculated by using

$$y_1 = \frac{-m_a}{2k} \ln\left(\frac{T - m_a g - kv_1^2}{T - m_a g}\right)$$

After burnout the coasting distance must be calculated using the coasting mass which can be gotten using

$$m_c = m_r + m_e - m_p$$

and the coasting distance using

$$y_c = \frac{m_c}{2k} \ln\left(\frac{m_c g + kv_c^2}{m_c g}\right)$$

Finally, the peak altitude can be gotten using the equation

$$PA = y_1 + y_c$$

The only issue with this method is that the drag coefficient C_D is hard to calculate accurately without doing test flights leading to an inaccurate peak altitude. Additionally this method assumes a constant thrust force which is not entirely accurate as thrust varies over the course of the burn time which further increases the inaccuracy. Lastly this method models the density of air as constant which is actually not true either, with the density decreasing with elevation. This fact would affect the drag on the rocket and would cause the calculation to err on the side of lower apogee as a result. All of this being said, the calculated apogee using this method is only about 4300ft. This is a 10.4% difference from the Open Rocket approximation.

After knowing the weights and station data of the components of the rocket, the center of gravity was also calculated by hand using the equations below:

$$\overline{X_{CG}} W_{CG} = \Sigma(W_i \overline{X_\iota})$$

The weights of the individual components allowed for the calculation of the center of gravity to be 44.26 inch from the base of the rocket which differs from 5.13%. Similarly the center of pressure was also analytically calculated and a value of 25.23 inches from the base of the rocket was derived. This deviates from the simulated value by 4.9%.

3.7 Recovery Subsystem

3.7.1 Parachute Selection and Descent Configuration

A main parachute deployment height of 600ft was chosen to ensure the deployment is above the minimum deployment bound of 500ft, while being low enough to where the drift would be minimized as much as possible. The drogue chute will be deployed at the apogee point of 4700ft in order to control the descent of the rocket enough to minimize the drift of the rocket.

3.7.2 Main Parachute

The main parachute will be deployed several thousand feet after the drogue chute to minimize descent time and drift, while still being as controlled as possible. The main parachute is primarily used to allow safe descent of the rocket as it returns to the ground.

Properties and parameters of the main parachute were found through using mathematical models utilizing both dynamics and fluid mechanics. This allows estimations for parachutes parameters and nominal diameter. One important equation used for this process is the equation for terminal velocity, which is written as:

$$v_{term} = \sqrt{\frac{2KE}{m}}$$

In which,

v_{term}: Terminal Velocity

KE: Kinetic Energy

m: Mass

It is required that each independent section of the rocket have a maximum kinetic energy of no more than 75 ft-lbf.

With the terminal velocity now being known, it is simple to calculate the drag force using the following equation.

$$F_d = \left(\frac{1}{2}\right)\rho {v_{term}}^2 C_d n A_o$$

For which:

F_d: Drag Force

ρ: Fluid Density (of air is 0.0023769 $slug/ft^3$)

C_d: Drag Coefficient

n: Number of Parachutes

A_o: Canopy Surface Area

Since the shape of the parachute can be modeled as a circle, the canopy surface area can be replaced by the equation for area of a circle seen below.

$$A_o = \pi {d_o}^2/4$$

Where:

d_o: Nominal Diameter

This diameter is unknown and needs to be found in order to meet the minimum kinetic energy requirement. To find this value, we can equate the drag force and the force due to gravity and solve for the diameter if several assumptions are made. These include constant air density and that only drag on main parachute is accounted for. The equation is as follows:

$$d_o = \sqrt{\frac{8mg}{\rho {v_{term}}^2 C_d n}}$$

In this case:

g: Acceleration Due to Gravity ($32.2\ ft/s^2$)

From this equation, solving for the nominal diameter of the parachute is relatively simple as long as the mass of the rocket is known, as well as the parameters of the parachute. These parameters can be seen in the following table.

Many of the parameters in these equations have values which come from individual parachutes. Numerous parachute considerations, for both the drogue and main parachutes, can be seen in the following table:

Table 27: Parachute Shape Parameters

Parachute	Measure Type	Cd	Stability	Use	Cost (approx.)
Annular or Toroidal	Frontal area is protected (circle shape)	Usually around 2.2	Good at a low speed	Main Parachute	$250+
Elliptical	Frontal area is protected (circle shape)	Usually around 1.6	Medium to good from high to low	Main or Drogue Chute	Around $200
Panel Style	Across top panels	Around 1.1	Vertical stability is very good, can rotate	Main Parachute	Around $200
Flat Sheet	Across chute	Around 0.7	Alright at lower speeds, bad at high speed	Main or Drogue Chute	Less than $200
Cruciform	Across chute	Around 0.7	Good at most speeds	Main or Drogue Chute	Around $200

From here, it was simple to narrow down the desired parachutes. A higher drag coefficient was desired, in addition to higher stability, which made the annular and elliptical types the most desirable. A comparison of these two types can be seen in the table below.

Table 28: Selected Parachute Shapes

Parachute	C_D	D_O (ft)	D_C (in)	Cost (USD)
Annular/Toroid	2.2	7.45	120	433
Elliptical	1.6	7.446652	84	200

By comparing these parachute types, it was possible to get a good idea of what was needed for the recovery system to function properly. In the end, the annular parachute known as Iris Ultra 96'' Standard Parachute was selected as the main parachute for the rocket. This is because while being more expensive that it's elliptical counterpart by a significant margin, it has a notably higher drag coefficient and is also more stable. Therefore, it appears to be a more reliable parachute.

3.7.3 Drogue Parachute

The drogue parachute will be deployed at an apogee of 4,700 ft. By extension, it is vital to have a reliable parachute to function as the drogue. The chosen parachute is the 24'' Elliptical Parachute because it is cost efficient while allowing for stability. In addition, the drag coefficient will be lower than that of an annular drogue, and thus it will allow for the descent to be faster while still controlled.

3.7.4 Descent Velocity and Drift

The kinetic energy of any independent rocket section can be found via the classical formula for kinetic energy.

$$KE = .5mv^2$$

In addition, the terminal velocity of each section can be found by combining previously derived formulas, as seen below.

$$v_{term} = \sqrt{2mg/(\rho C_d n \left(\frac{\pi}{4}\right) d_c^2)}$$

From this equation and noting that the maximum kinetic energy of any independent section of the rocket can be found by using the kinetic energy formula with terminal velocity, it is possible to compare these values for each section.

Table 29: Rocket Section Mass, Velocity, and Kinetic Energy Data

Section	Mass (slugs)	Terminal Velocity (ft/s)	Maximum Kinetic Energy (ft-lb)
Payload	0.26708	9.4856	12.1054
Avionics	0.12473	6.4823	2.6206
Booster Bay	0.52391	13.2853	46.2347
Nosecone	0.22618	8.7291	8.6171

It is also required to calculate the rockets rate of decent. This will be done by using both an open rocket simulation as well as a numerical calculation via Fourth Order Runge-Kutta (RK4). The

RK4 calculation for descent rate will be set up by solving for the net acceleration in the following way.

$$y''(t) = -32.2 + \frac{\rho y'(t)^2 C_d (\frac{\pi}{4}) d_{parachute}^2}{2m_{total}}$$

Where the diameter of the parachute is equal to that of the drogue chute above and at an altitude of 600ft, and equal to that of the main parachute below it's deployment altitude of 600 ft. In addition, the boundary conditions for the descent are set at y(0) is equal to the apogee height and y'(0) equals zero due to simple kinematics. From here, it is possible to calculate the descent time using RK4. The total descent time was numerically calculated to be 76.4 seconds. The value obtained by the OpenRocket Simulation was 74.1s, which agrees with the numeric value within a small degree of error.

Drift Calculations

To calculate the drift experienced by the rocket, the following formula was used.

Drift(t) = tV

t = time

V = wind speed

Using the previously discussed simulated descent time of [enter here] it is possible to attain the following vales.

Table 30: Descent Drift

Wind Speed (mph)	Wind Speed (ft/s)	Drift (ft)
20	29.33	2173.4
15	22	1630.2
10	14.67	1087.0
5	7.33	543.2
0	0	0

3.8 Shear Pins and Ejection Charges

3.8.1 Shear Pins

Shear pin selection is closely tied to the process of selecting the appropriate ejection charges. First, the force that is imparted onto the rocket during flight must be calculated. The shear pins must be thin enough to break when the black powder charges ignite and they should be thick enough to not cause the rocket to separate due to the pressure difference between the inside and outside of the rocket. This pressure difference comes into play while the rocket is launched as the altitude causes a decrease in the external pressure while the internal pressure remains constant. Our design will use 2-56 X 1/4" long Round Slotted Machine Screw Nylon shear pins as they can withstand the initial launch forces but can easily shear off during ejection charge ignition. These pins were also selected as they are relatively cheap and multiple ground tests will be performed to determine a more accurate amount of ejection charge mass in addition to our theoretical calculations the ones we selected require 21.413 lbf/pin to shear

Figure 39: Shear Pins

The primary concerns are that the charges cause irreversible damage to a component outside the shear pins or that not enough is used to properly deploy the parachutes, ejection tests will be conducted to confirm the amount of black powder selected separates the parachutes while not damaging any of the rocket sections. This test will also confirm the electronics are configured correctly.

3.8.2 Black Powder

The quantity of shear pins used as well as the volume of the parachute bays allow for calculations of the ejection charges mass. First, the required pressure to break apart the shear pins needs to be calculated, which by using basic physics can be done with the equation below.

$$P = \frac{4F}{\pi D^2}$$

For which

F: Required shear force in pound-force

D: diameter of parachute bay in inches

P: Pressure required to break pins

The volume of the parachute bay can be seen below.

$$V = (\frac{\pi}{4})D^2L$$

Where

L: length of the parachute bay in inches

V: volume of parachute ay

The formula for cross-sectional area of the parachute bay can be found using the circular area formula.

$$A = (\frac{\pi}{4})D^2$$

A: cross-sectional area of parachute bay

As for calculating the actual mass of the black powder required in the ejection charge, it cam be found with the ideal gas law, which is presented below.

$$m = (PV)/(RT)$$

m: mass of black powder (lbm)

R: gas constant $[in \frac{lbf}{lbm}]$

T: temperature in degrees Rankine

It is important to note that the standard mass unit used for ejection chargers is in grams, so it is necessary to use a conversion factor of $454\ g/lbf$ in order to convert into grams. By plugging this and the previous formula for pressure into the ideal gas law, the new formula is as follows.

$$m = (454FL)/(RT)$$

To make the formula even more simple to use, the ideal gas constant can be assumed to be $266\ in\ lbf/lbm$ and temperature to be at 3307 degrees Rankine. Using these values results in the simplified formula below.

$$m = 0.000516FL$$

There are four shear pins being used that require 84.44lbf to break on average. The length of the parachute bays is 9.309" and 4.132" for the main and drogue respectively. From here, the required black powder mass can be calculated, which is 0.4056g and 0.1800g for the main and drogue respectively.

These calculations are just a simple estimation of the mass of black powder that will need to be purchased for the rocket to function as desired. The value will be found more accurately upon preforming ground tests and with advice from our project mentor and faculty advisors.

3.9 Parachute Deployment

3.9.1 Pistons

Pistons are included in order to help push the parachutes out of the parachute bay after the ejection charges are ignited and also protect the recovery system by physically separating them from the hot gases. They must be made of a sturdy material which will be able to push out the parachutes after the ejection charges have been ignited. They must also have a hole in them to allow for the passage of the shock cord.

Figure 40: Piston Design

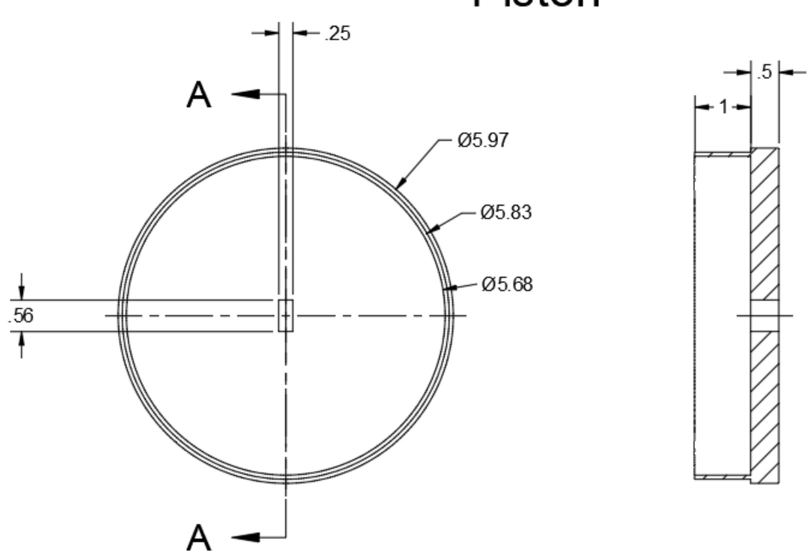

Figure 41: Piston Dimensioned Drawing

The current piston design is made of a cylindrical slab of MIL-P-6070 plywood. The piston is about 1.5 inches long in total with a hollowed outside that also has a smaller diameter such that the piston can be rested against the avionics bay tube. A transition tight fit for the smaller diameter side is likely the best fit for this purpose since it can be assembled and disassembled by hand and allows for piston movement without being too loose. The larger diameter side of the piston should have a close running fit so it can slide quickly within the airframe to push out the parachutes.

3.9.2 Recovery Harness

The recovery harness is a cord that connects to the parachutes and allows for their deployment. It also keeps the sections of the rocket together upon parachute deployment so that parts of the rocket will all land together. As such, it must be strong enough to withstand flight forces and resist corrosion due to high heat.

For this reason, a two 7/16" wide Kevlar cords were chosen over nylon ones as the former is both very strong and resistant to high temperatures, whereas nylon is known to be flammable and would require additional protection that Kevlar Harnesses do not require. The drogue harness it 10 feet long while the main harness is 20 feet long for a total length of 30 feet of cord.

3.9.3 Parachute Protection

The parachutes selected are made of nylon, which can burn in high temperatures. Thusly, the parachutes require protection. Two methods of parachute protection were considered. Deployment bags surround the parachute and ensure they inflate properly, keeping the suspension lines of the parachute straight. The other method is using a parachute blanket made of Nomex, which is highly fire and heat resistant material. The Nomex blanket was chosen to shield both parachutes from the hot gases as it is important to keep the parachutes safe, the deployment bags will not be required if the parachutes are folded properly, and the length of the deployment bags causes the rocket as a whole to be longer than desired.

3.9.4 Avionics Bay

The avionics bay houses and protects the electronics required for altitude determination and parachute ejection during flight. The electronics required for the avionics bay of a Dual Event Recovery System include altimeters, batteries, electric matches, and a switch. The physical objects required for the avionics bay to function correctly are an avionics sled, ejection charge wells, an avionics tube/coupler, end plates, pistons, and fittings to hold the avionics bay together.

The avionics sled retains the altimeters, as well as their power supplies. Since two parachutes have to be deployed, and the recovery system must be fully redundant, there must be two altimeters, each with their own battery, connected to the ejection charges. Thus, the avionics sled must be capable of containing both of the altimeters and their power supplies.

The avionics tube must fit inside of the airframe and sequester as well as protect the electronics from ejection gases and electromagnetic interference from other rocket sections. This tube must be strong enough to withstand impact of the rocket upon the ground as per the 75 lb·ft kinetic energy limit of landing.

3.9.5 End Plates

The end plates of the avionics bay house the ejection charge wells and shock cord mounts. They are also responsible for sealing the electronics away from the hot ejection gases required for parachute deployment. The end plates themselves must be able to withstand these gases and resist corrosion.

3.9.6 Recovery Harness Mounts

The recovery harnesses must attach to the end plates with the help of these fixtures. They must be able to withstand the hot ejection gases, be strong enough to withstand the force of parachute deployment, and resist corrosion.

3.9.7 Ejection System

The ejection system of the parachutes consists of several different components, including charge wells. The charge wells will contain black powder which will be ignited with electric matches, as per Requirement 3.1.3. The amount of black powder required to eject the parachutes depends on the lengths of the parachute bays as well as cross-sectional area of the airframe. The charge wells are sized based on those calculations.

3.9.8 Altimeters

Altimeters must be able to send electronic signals such that parachutes may be launched at altitudes of 5500 feet or less, to connect to two black powder charge canisters, and to operate using commercially available batteries. The altimeters also need to be set up in a redundant system so if one charge or one altimeter fails, another can be triggered to complete parachute deployment procedures.

The altimeter that was chosen was the PerfectFlite StratologgerCF. This altimeter: may deploy parachutes from 100-9999 feet AGL, record maximum velocity, store data for 16 flights of 18 minutes each, has an accuracy of ± (0.1% altitude reading + 1 foot), may be powered by 4-16V batteries, is very easy to use and assemble, weighs 0.38oz, may perform dual deployment, is resistant to false trigger, has brownout protection and will tolerate 2 second power loss in flight, and has selectable apogee delay for dual altimeter setups that prevents overpressure from simultaneous charge firing. As such, it meets all of our requirements for an altimeter.

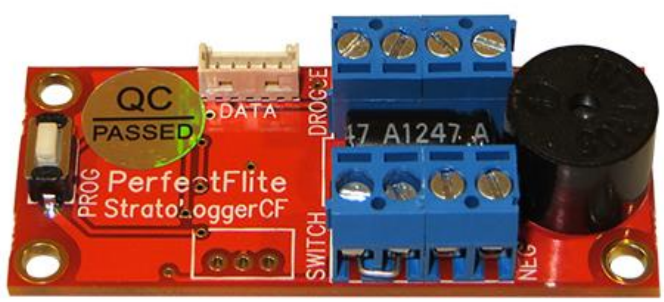

Figure 42: PerfectFlite StratoLoggerCF Altimeter

3.10 Avionics and Electronics

3.10.1 Altimeter Circuit Configuration

The altimeter electrical circuit must be fully redundant as per Requirement 3.4, must have their own commercially available batteries according to Requirement 3.5, and must not be connected to electrical circuits of other sections as per Requirement 3.8. Therefore, each altimeter is connected to its own battery and two charge canisters, one main and one drogue canister. The electrical circuit will be arranged as shown below:

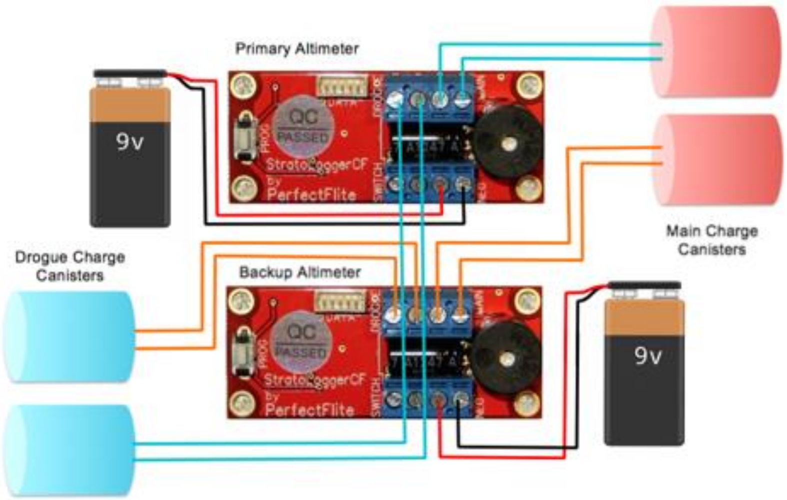

Figure 43: Avionics Circuit Configuration

The batteries required must be commercially available, so 9V batteries and LiPo batteries were considered. While LiPo batteries are often lighter, take up less space, and are rechargeable, 9V batteries were selected for the avionics bay power supplies since they require less maintenance, are far less expensive and hence easily replaceable, less dangerous (as LiPo batteries can melt or otherwise be damaged if overcharged), and are recommended for use with many commonly used altimeters.

3.10.2 Arming Switch

The avionics bay must be able to be turned on from the outside of the airframe and must be able to stay on despite flight forces as per Requirements 3.6 and 3.7. There were two types of arming switches considered: a keylock switch and a rotary switch. A keylock switch requires a key to turn and activate while a rotary switch does not require one, only needed pressure applied in a circular motion by something hard, sharp, and or thin. The rotary switch was selected as keys can be misplaced, and the rotary switch can be turned on easily by a person with a fingernail or a screwdriver, but not by flight forces.

Figure 44: Rotary Switch

3.10.3 E-Matches

Electric matches ignite the black powder charges for the purpose of parachute deployment. In order to ignite the matches and thus the powder charges, some kind of chemical dip is required. For our purposes, we have chosen an e-match starter kit with extra wires and pyrogen dip. This can be assembled without licenses or the need for hazmat shipping. As this chemical is dangerous however, it is necessary to read the dip's safety data sheet.

3.10.4 Fittings

The fittings holding the avionics bay together must be strong enough to resist ejection charge forces and be able to handle vibration during flight, staying locked in place. Fittings on the outside of the end plates should also be corrosion resistant.

3.11 Electronics Concept Designs

3.11.1 Avionics Bay Concepts

Avionics Bay Concept Design 1

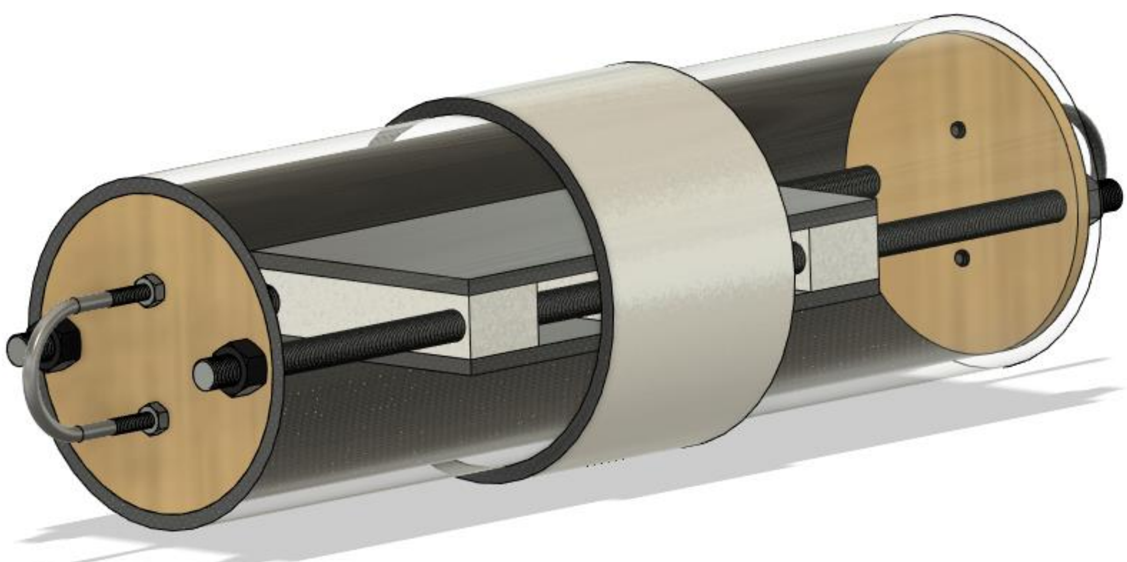

Figure 45: Avionics Bay Concept Design 1

The first concept design of the avionics bay is 12” long and has its electronics surrounded by a long fiberglass coupler with a 3” collar epoxied onto it that is made out of the same material as the airframe. The endplates are made out of aircraft-grade plywood, MIL-P-6070 plywood, and fit into the ends of the coupler. The avionic sled consists of two thin plates of fiberglass connected by three fiberglass spacers with holes drilled in two spots for the placement of threaded rods. The altimeters are affixed to the board with screws as needed via holes drilled/machined in the board. The charge wells were selected to be 8 gram aluminum cylinders to be screwed on to the end plates. Threaded rods pass through the end plates and the avionic sled, the recovery harness mounts are U-bolts, and high strength hex nuts are put in place on the inside of the endplates to secure the harness mounts as well as on the outside of the end plates to hold the threaded rods in place. The fittings are all Zinc-plated steel and have ½” diameters.

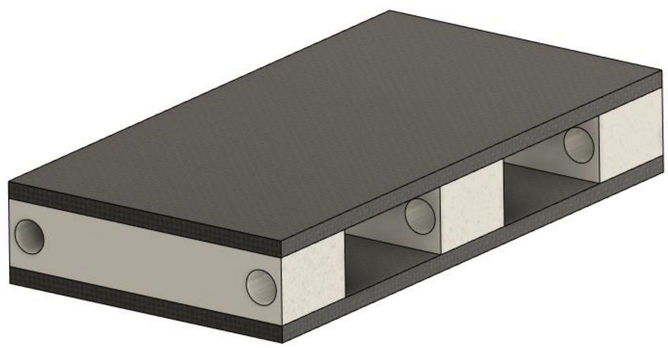

Figure 46: Avionic Sled Concept Design 1

Pros:

- The coupler is corrosion resistant and bending.
- The end plates are rather light and strong since aircraft grade plywood has high strength and low density.
- U-bolts spread out force over a larger area than eyebolts, which are known to bend during flight if they are not forged or welded properly.
- Zinc-plated steel is corrosion resistant and strong.
- The aluminum charge wells are corrosion resistant and durable with low density in comparison to steel. They also have a high enough capacity to hold any amount of black powder required.
- Once all the parts are made, this design would be easy to assemble.

Cons:

- The end plates are wood, and thus will likely not resist corrosion by the hot ejection gases very well.

- The fittings have too large of a diameter. While being strong, they will also be very heavy.
- Fiberglass is difficult to machine, and thus, it would be difficult to fabricate the avionics sled.
- There are no hex nuts keeping the avionic sled from moving along the threaded rods.
- The avionic sled is made up of a lot of material and would be heavy since it is made of fiberglass instead of plywood or lightweight plastic.
- This design violates the rule that any coupler region will have a length of at least one rocket body diameter, as the coupler is 12" long in total, but has a collar region of 3", while the diameter of the rocket is 6".

Avionics Bay Concept Design 2

The second concept design of the avionics bay is 13" long and has its electronics surrounded by a long fiberglass coupler with a 1" collar epoxied onto it that is made out of the same material as the airframe. The endplates are made out of fiberglass are recessed several inches into the coupler. The avionics sled is also made of fiberglass, but it is a single, short slab instead of a long one with multiple sections. Thusly, electronics would have to be mounted on both sides of the sled. There are holes for threaded rods directly through the slab on either side. There are also slots through the board so that zip ties can be used to secure batteries. The charge wells were selected to be 3 gram aluminum cylinders to be screwed on to the end plates as preliminary calculations revealed that less than 3 grams of black powder were required to deploy the parachutes. Threaded rods pass through the end plates and the avionic sled, the recovery harness mounts are U-bolts complete with mounting plates, and high strength locknuts are put in place on the inside and outside of the endplates to secure the harness mounts as well as hold the threaded rods in place. Locknuts are also placed on either side of the avionic sled to stop it from moving along the threaded rod. The fittings are all Zinc-plated steel and have ¼" diameters.

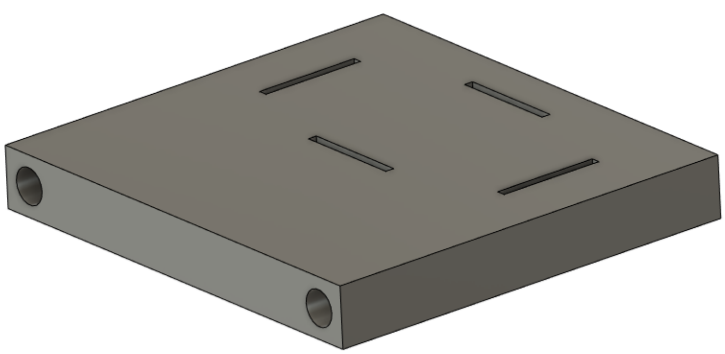

Figure 47: Avionics Sled Concept Design 2

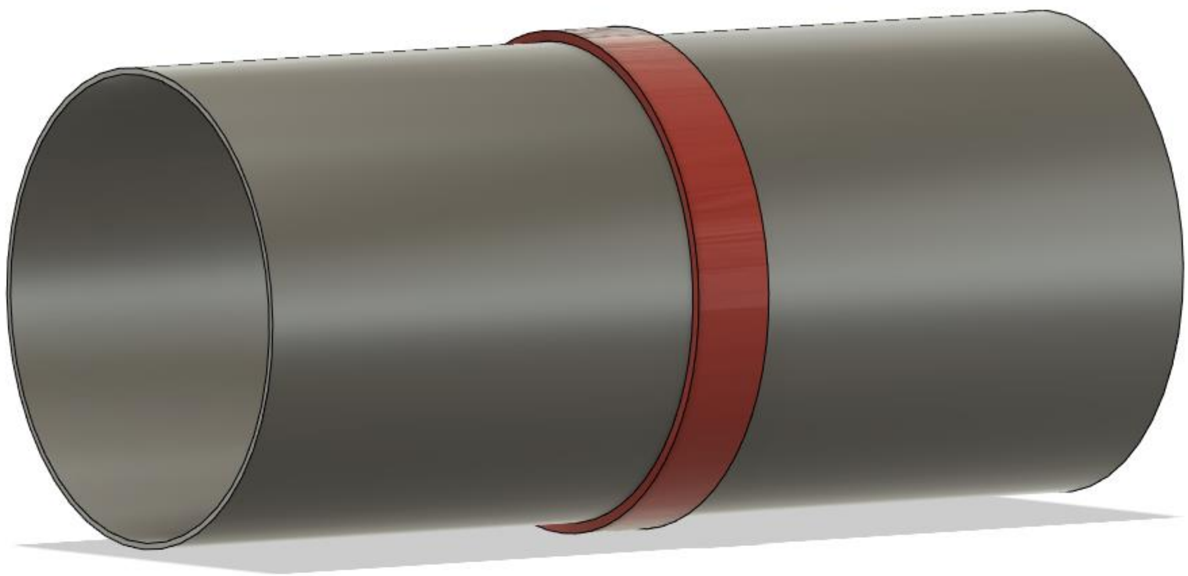

Figure 48: Avionics Bay Concept Design 2 Outside View

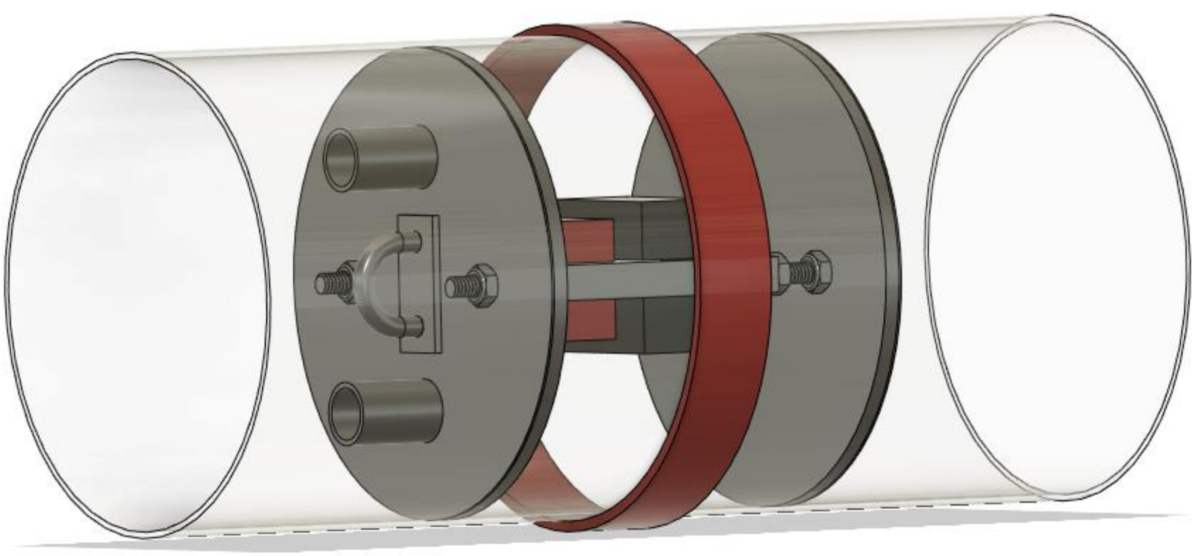

Figure 49: Avionics Bay Concept Design 2 Inside View

Pros:

- The coupler is corrosion resistant and bending.
- Avionics sled can remain stable on the threaded rods and is made out of less material, reducing the weight of the bay.
- The fiberglass end plates are strong, have resistance to bending, and are corrosion resistant.
- The recessed end plates allow for the saving of space in the rocket.
- U-bolts spread out force over a larger area than eyebolts.

- The mounting plates for the U-bolts will better distribute the force of ejection.
- Zinc-plated steel is corrosion resistant and strong.
- The aluminum charge wells are corrosion resistant and durable with low density in comparison to steel. They are lighter comparatively than 8 gram charge wells.
- This design does not violate the rule that any coupler region will have a length of at least one rocket body diameter, as the coupler is 13” long in total, and has a collar region of 1”, while the diameter of the rocket is 6”.
- The fittings are much lighter comparatively and still have a tensile strength of 150,000 psi.
- Locknuts have better grip on bolts to resist loosening without damaging threads.

Cons:

- The end plates are fiberglass would be about twice the weight of plywood end plates of the same size.
- Fiberglass is difficult to machine, and thus, it would be difficult to fabricate the avionics sled and end plates, but less so than design 1.
- It would be more difficult to successfully assemble and access the bay when the end plates are recessed so far into the coupler.
- While zip ties can be used to secure the batteries to the avionic sled, vibration could cause the batteries to come loose since they are only constrained to a flat plane.
- The end plates are not fitted to the ends of the coupler which requires other methods for the attachment of the sled assembly to the tube.

Avionics Bay Concept Design 3

The third concept design of the avionics bay is 9.375” long and has its electronics surrounded by a blue tube. The end plates consist of an aircraft grade plywood with a thin layer of fiberglass on the outside. The end plates are recessed slightly into the tube. The avionics sled is a single, short slab made out of ABS plastic, which is capable of being 3D printed. It also includes indentations for the batteries and altimeters. The sled has holes in it for the threaded rods to go through. Thusly, electronics would have to be mounted on both sides of the sled. There are holes for threaded rods directly through the slab on either side. There are also slots through the board so that zip ties can be used to secure batteries. The charge wells were selected to be 2 gram capacity PVC cylinders to be screwed on to the end plates as preliminary calculations revealed that less than 2 grams of black powder were required to deploy the parachutes. Threaded rods pass through the end plates and the avionic sled, the recovery harness mounts are U-bolts complete with mounting plates, and high strength locknuts are put in place on the inside and outside of the endplates to secure the harness mounts as well as hold the threaded rods in place. Locknuts are also placed on either side of the avionic sled to stop it from moving along the threaded rod. The fittings are all Zinc-plated steel and have ¼” diameters. For retention in the tube, there is an added bulk plate attached to one of the end plates that will be epoxied onto the inside of the tube. The epoxied bulk plate will be attached to the endplate closest to the end plate closest to the main parachute bay.

Figure 50: Avionics Bay Design Concept 3 Outside View

<u>Pros:</u>

- The blue tube is strong and dense enough to absorb the impact of landing.
- Avionics sled can remain stable on the threaded rods and is made out of less material, reducing the weight of the bay.
- The avionics sled is easily 3D printable, and the ABS plastic is strong, flexible, machinable, and has high temperature resistance.
- The indentations in the avionics sled constrain the electronics which helps with the stability of the parts in conjunction with the zip ties.
- The plywood end plates are strong and the outer fiberglass layers add the benefit of corrosion resistance.
- The recessed end plates allow for the saving of space in the rocket.
- U-bolts spread out force over a larger area than eyebolts.
- The mounting plates for the U-bolts will better distribute the force of ejection.
- Zinc-plated steel is corrosion resistant and strong.
- The PVC charge wells can resist corrosion like aluminum and are lighter in comparison to the 3 gram aluminum charge canisters.
- This design of the bay is not a coupler region and does not have to abide by the body length diameter requirement. Just as well, the end plate assembly is more accessible since the end plates are not recessed far into the tube.

- The fittings are light and the threaded rods still have a tensile strength of 150,000 psi.
- Locknuts have better grip on bolts to resist loosening without damaging threads.
- The epoxied bulk plate allows for the retention of the avionics sled assembly within the coupler.

Cons:

- The end plates are not fitted to the ends of the coupler which requires other methods like the epoxied bulk plate for the attachment of the sled assembly to the tube.
- The PVC charge wells are more brittle than aluminum charge wells.
- Blue tube is strong, but not as resistant to bending as fiberglass and likewise does not have as much heat resistance.

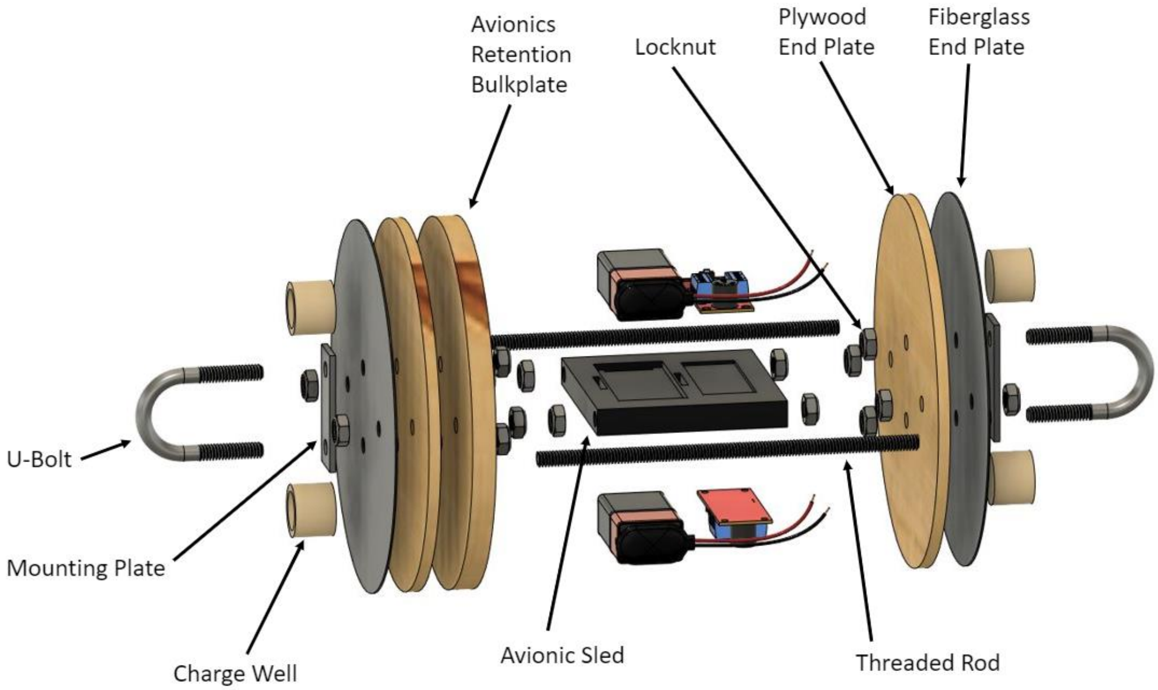

Figure 51: Avionics Bay Design Concept 3 Inside View

The leading design of the avionics bay was chosen with the following decision matrix. Weights of 1-4 were assigned to the design requirements and ratings chosen proceed from 1-10.

Table 31: Avionics Bay Concept Design Decision Matrix

Design Concepts		Design Concept 1		Design Concept 2		Design Concept 3	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Usage of Space	3	2	6	8	24	9	27
Weight	4	5	20	7	28	8	32
Parachute Deployment	4	3	12	9	36	10	40
Mounting of Electronics	2	2	4	5	10	7	20
Ease of Manufacturing	3	5	15	4	12	7	21
Ease of Assembly	3	9	24	7	21	8	24
Cost	1	5	5	7	7	8	8
Durability	4	8	32	9	36	9	36
Accessibility	2	10	20	8	16	9	18
Total		**138/260**		**190/260**		**226/260**	

Therefore, the selected avionics bay design is design concept #3. The dimensioned drawings are depicted below.

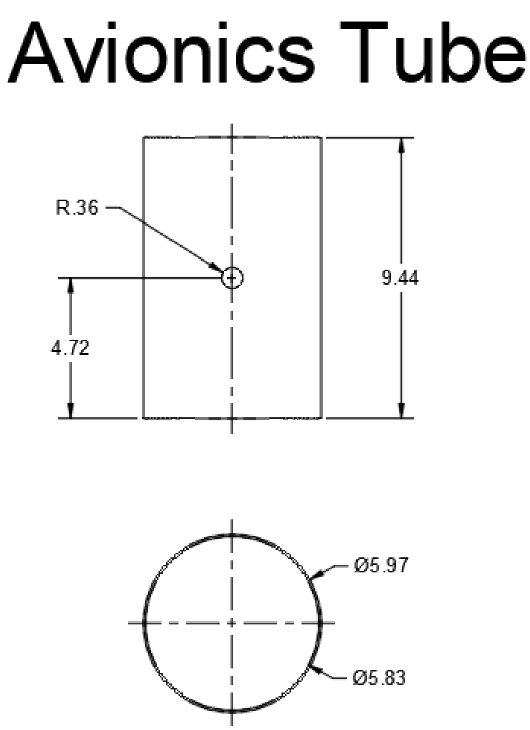

Figure 52: Avionics Tube Dimensioned Drawing

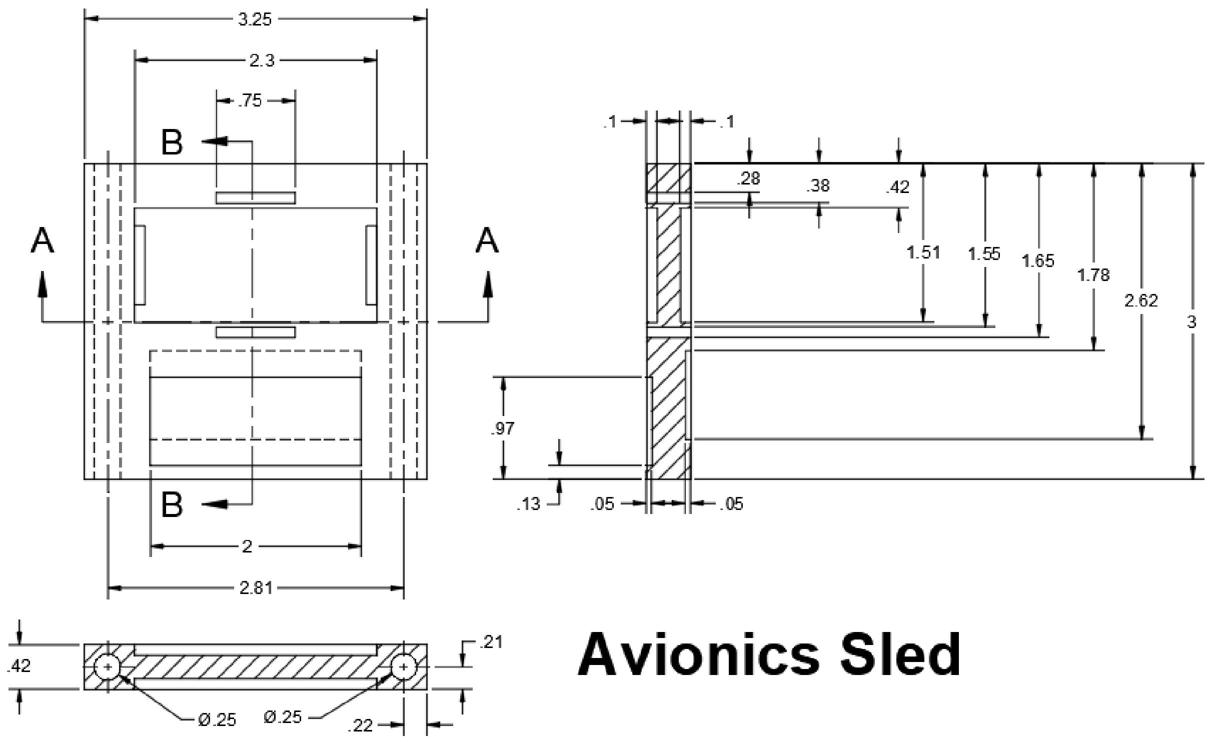

Figure 53: Avionic Sled Dimensioned Drawing

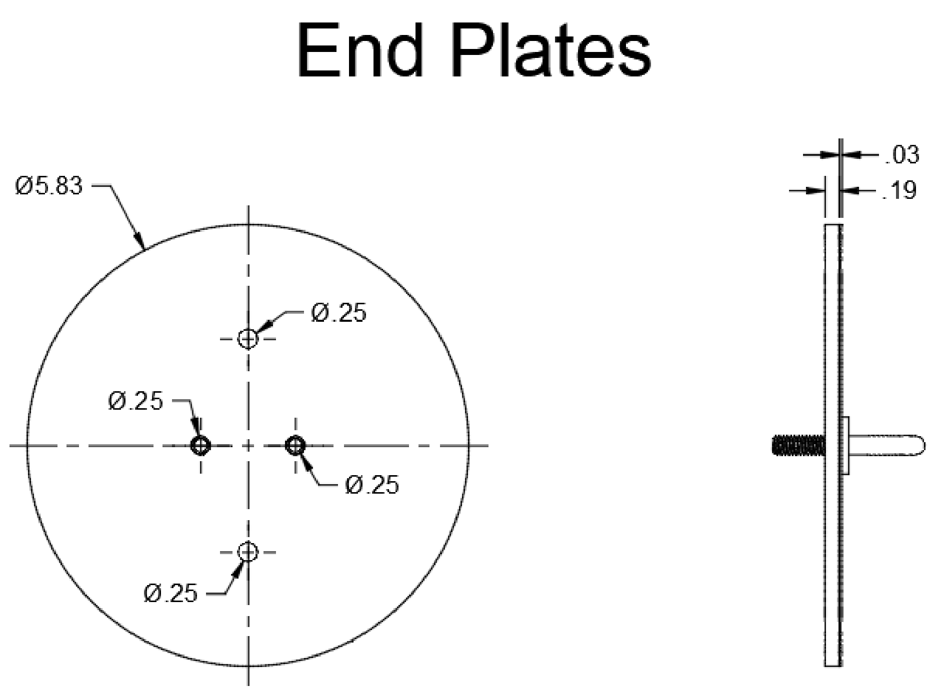

Figure 54: End Plates Dimensioned Drawing

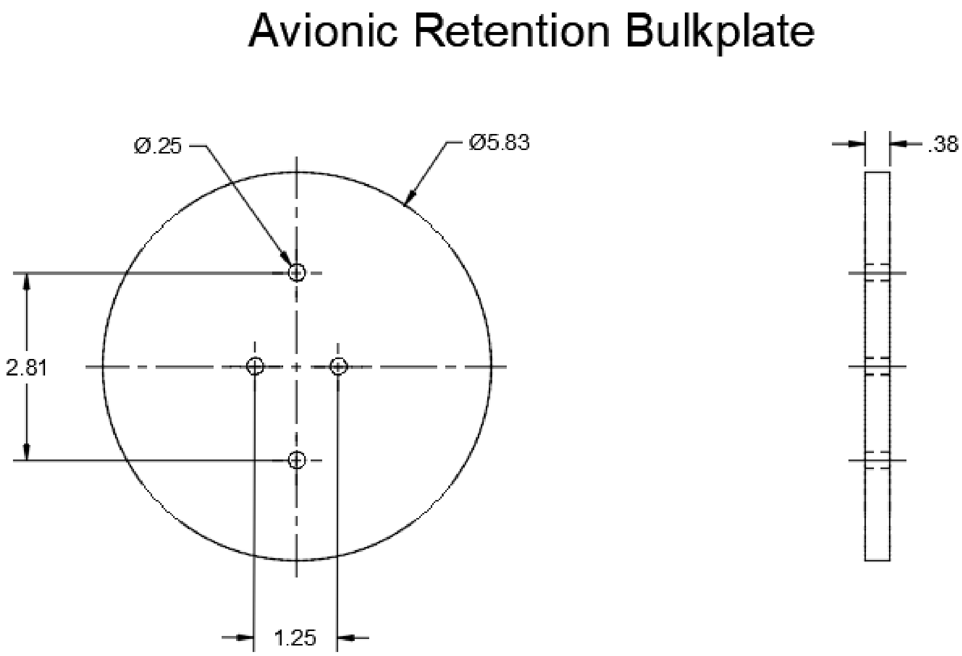

Figure 55: Avionic Retention Bulkplate Dimensioned Drawing

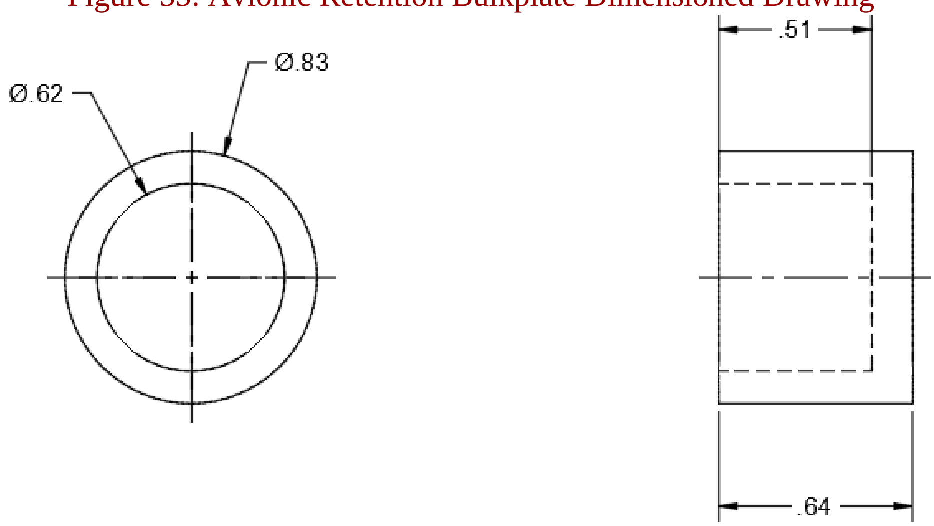

Figure 56: Charge Wells Dimensioned Drawing

3.11.2 Telemetry Bay Concepts

The telemetry bay houses and protects the GPS tracking electronics. This bay must be located near the front of the rocket either in or near the nosecone and must not interfere with other sections. The bay cannot be surrounded by metal which will block signals of the GPS transmitter. The tracking device(s) must be able to transmit position from a far distance that at least covers the recovery area of 2500 ft radius. There must be a tracking device for each rocket section that lands untethered from the rest of the vehicle. They must be powered by commercially available power supplies.

The selected GPS tracking device selected for recovery is the BRB900 GPS Telemetry System. This type of device was chosen because it does not require a HAM license, which provides more convenience. It has a range of 6 miles, which is more than enough as the landing area is only 2,500 feet in diameter. The transmitter can also store 2.5 hours of data before recording stops, so the rocket may be found even if it must remain on the launch pad for awhile. The BRB900 also includes a handheld receiver (with an LCD option) that is paired with the transmitter to ensure data is not received from the wrong device. Additionally, it includes a 3.7V battery for the transmitter and USB Interface / battery charger, with an added option that prevents overcharge which could result in the melting of the battery. It can be operated by programs such as Hyperterm or TeraTerm after it is plugged in by USB. It also makes use of a wire-whip antenna, which has a reduced chance of breaking in the nosecone than a “rubber duck” antenna. Lastly, it is quite small with a length of 2.85” and a width of 1.25”, a size that may easily fit inside the nosecone.

Figure 57: BRB900 GPS Telemetry System

Telemetry Bay Concept Design 1

The first design consisted of a two bulkplates of ½” height, the top one made of plywood and the bottom made of aluminum. The top plate has a slot through it to allow an ABS plastic telemetry sled to pass through so the latter can be housed in the nosecone as well as a rectangular indentation to allow the sled to be mounted to the plate. An aluminum mounting plate would then be used to cover the sled bottom so the top plate's underside would be flush with the bottom plate. The bottom plate is just a simple aluminum plate with holes for No. 8-32 threaded rods so the bottom plate, top plate, and sled can all be attached together as one object. Aluminum hex nuts and threaded rods would be used to hold the bay together. The sled itself is shaped so that the it can fit through the top plate opening and be able to hold the GPS tracking device, which would have to be mounted using bolts or screws. The base of the sled is wider and has holes in it to permit the passage of these fittings.

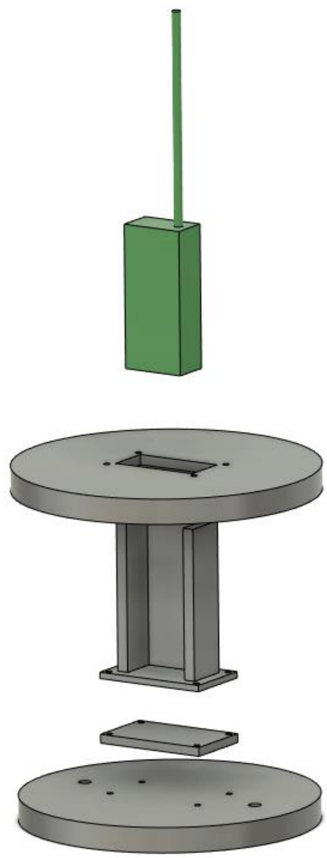

Figure 58: Telemetry Bay Concept Design 1

Pros:

- The aluminum bottom plate is strong, corrosion resistant, and lighter than steel.
- The telemetry bay does not interfere with the payload bay as the only protruding parts from the underside of the bay are the fittings.
- The sled can be safely secured to the top plate.
- Aluminum, plywood, and ABS plastic are easy to machine.
- The ABS plastic sled can be easily 3D printed, is flexible, strong, and heat resistant.
- Aluminum is non-magnetic, which reduces the chances of interference with the GPS device.

Cons:

- The aluminum bottom plate is not as hard as steel and could be worn down if harder materials are used and come into contact with it. Although aluminum is lighter, it is still somewhat heavy in comparison to the other parts due to its thickness.
- The telemetry sled is simple and may not allow for the security of the GPS tracker's power supply.
- The telemetry sled slots into the top plate, which might be more difficult to assemble. Just as well, after the top plate is epoxied, the configuration cannot be changed easily.
- While the telemetry bay does not interfere with the payload bay for the most part, it would be better if the fittings were flush with the bottom plate.

Telemetry Bay Concept Design 2

The second design is similar to the first design with a few changes. The bottom aluminum plate is now 0.3475" in height and has counterbores so the fittings on the underside can remain flush with the underside. It also has a rectangular indentation in the top so the telemetry sled can be attached there instead of the top plate. So, the aluminum mounting plate was discarded. The sled is longer now and has a top section for the GPS device as well as a bottom section for the battery. The shelf below the GPS device has a rectangular cutout so the battery connection can be made easier. The battery itself is housed in the bottom slot of the sled, where there are four openings such that cable ties may be used to further secure the power supply. Cutout channels were added to the back of the telemetry sled so the cable ties do not prevent the sled from passing through the slot in the top plate.

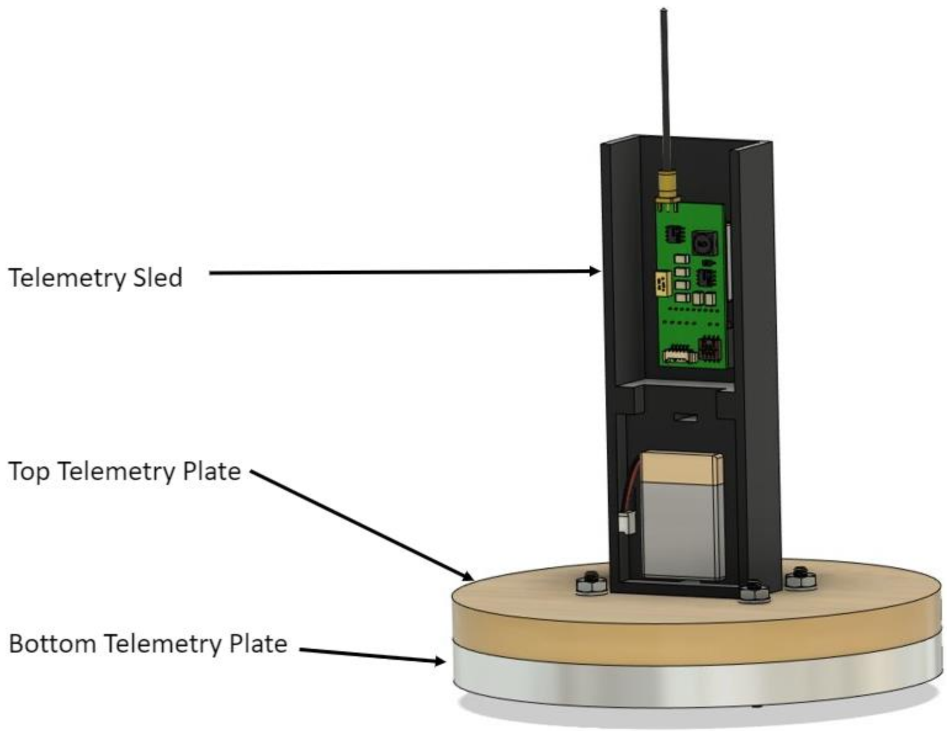

Figure 59: Telemetry Bay Design 2

Pros:

- The aluminum bottom plate is strong, corrosion resistant, and lighter than steel, and its reduced thickness also reduces the weight of the rocket.
- The telemetry bay does not interfere with the payload bay as no parts protrude from the underside.
- The sled can be safely secured to the bottom plate and hold both the GPS device and its power supply more securely.
- Aluminum, plywood, and ABS plastic are easy to machine.
- The ABS plastic sled can be easily 3D printed, is flexible, strong, and heat resistant.
- Aluminum is non-magnetic, which reduces the chances of interference with the GPS device.

Cons:

- The aluminum bottom plate is not as hard as steel and could be worn down if harder materials are used and come into contact with it.
- After the top plate is epoxied, the configuration cannot be changed easily; the fittings would have to be installed to the top plate prior to epoxy application.

The leading design of the telemetry bay was chosen with the following decision matrix. Weights of 1-4 were assigned to the design requirements and ratings chosen proceed from 1-10.

Table 32: Telemetry Bay Design Concept Decision Matrix

Design Concepts		**Design Concept 1**		**Design Concept 2**	
Requirement	Weight	Rating	Score	Rating	Score
Weight	4	5	20	7	28
Mounting of Electronics	3	6	18	9	27
Ease of Manufacturing	3	6	18	6	18
Ease of Assembly	3	7	21	7	21
Cost	1	6	6	6	6
Durability	4	8	32	8	32
Total		**115/180**		**132/180**	

Therefore, telemetry bay design #2 is the better design choice and is the current version.

Telemetry Bay Power Supply

Although avionics power supplies are often 9V batteries, telemetry power supplies are usually LiPo batteries. Just as well, the BRB900 GPS device is packaged with a LiPo battery that has built-in protection from being overcharged. Thus, the original disadvantages of the LiPo battery are mitigated, and a LiPo battery has been selected for the telemetry bay's power supply as a result.

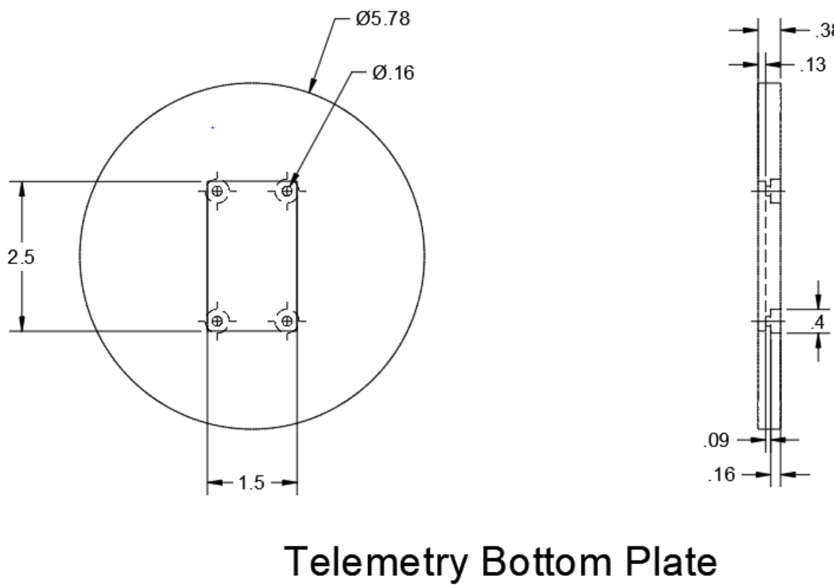

Figure 60: Telemetry Bay Bottom Plate Dimensioned Drawing

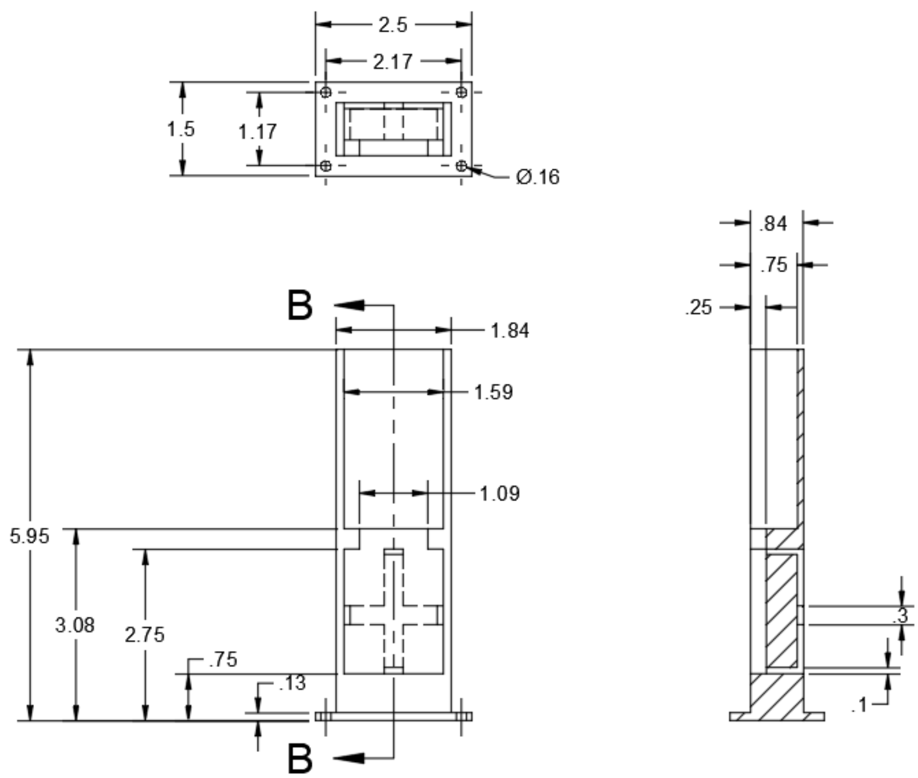

Figure 61: Telemetry Sled Dimensioned Drawing

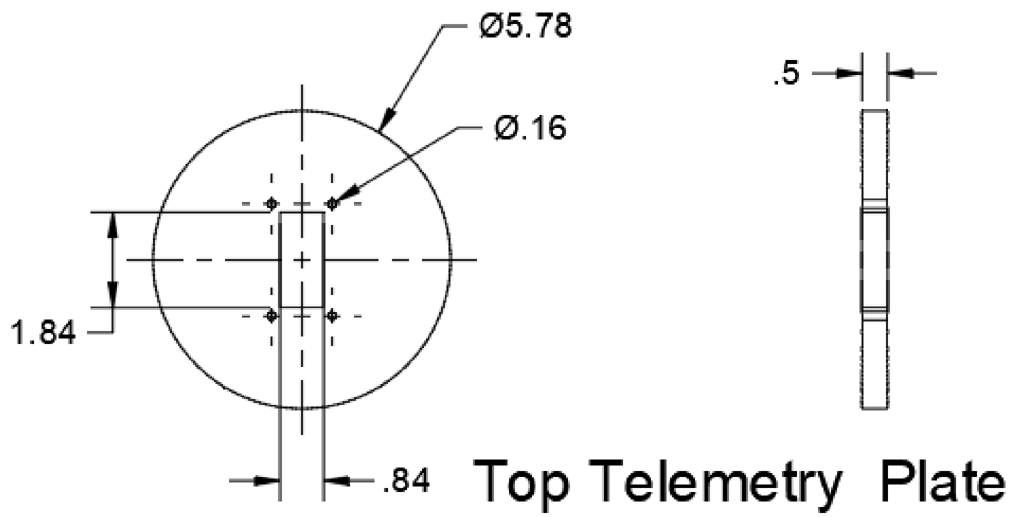

Figure 62: Top Telemetry Bay Plate Dimensioned Drawing

4 Payload Criteria

4.1 Payload Mission Objective

The payload mission objective is to deploy a rover from the launch vehicle that will travel to sample recovery site, recover at minimum 10 ml of a simulated lunar ice sample, and transport the stored sample 10 linear feet away from the recovery site. The payload will be retained within the launch vehicle using a mechanical retention system. Once the launch vehicle is safely on the ground the payload will reorient and exit the launch vehicle.

4.1.1 Mission Success Criteria

The payload mission will be considered a success if the following criteria are met:

1. Payload is safe and intact after the launch vehicle has landed
2. The rover reorients and exits the payload bay.
3. The rover travels to the sample recovery area.
4. 10 ml of sample material is collected and stored.
5. All of the stored sample is transported 10 ft away from the recovery area.

4.2 Payload Mechanical Design

4.2.1 Chassis Shape

Triangular prism shape. This shape allows for the lateral mounting (both sets of wheels are oriented in line with the rocket airframe axis) of the payload in the rocket airframe. Thus, it is by far the most space efficient chassis design leaving the most volume for useful mass. However, this design has poor ground clearance and stability. When width of the rover exceeds its length, it introduces a potential risk of getting stuck in rough terrain which will jeopardize the entire payload mission.

Cuboid shape. This is the simplest chassis shape to manufacture. Equipment mounting inside the rover body is extremely easy to accomplish with this chassis design since all the faces are planes. While cuboid shape chassis can be mounted laterally in the rocket airframe as was previously mentioned in the Concept 1, it will introduce all the downsides associated with ground clearance in the triangular design while having no corresponding upsides. When mounted axially a lot of the volume will be taken by the wheels and thus it is not the most space efficient design. Another problem with this chassis design is the mounting of the rover itself. Since all the faces of cuboid are straight lines there is no natural way to hold the payload midflight. Some sort of retention system would unnecessarily complicate the overall design, lower reliability, and increase cost.

Octagonal prism shape. This chassis design is a compromise between the two previous designs. Octagonal design inherently allows for more volume than cuboid given the same surface area. This chassis shape also has better terrain traversal given the same ground clearance when compared to other designs, as there is no possibility of catching the ground with the chassis corner. It is relatively easy to manufacture since all faces of octagonal prism are planes that could be bolted or epoxied together. Octagonal shape has also a very natural way to be mounted to the airframe. Having two plates with the opposite contour on either side of the rover will hold geometrically in place. This design however has the same problem as Concept 2 when mounted axially. The wheels on both sides of the chassis take up a lot of space that could be otherwise be used to carry equipment.

Table 33: Chassis Shape Decision Matrix

Design		**Triangular Prism**		**Cuboid**		**Octagonal Prism**	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Manufacturability	1	9	9	8	8	7	7
Ground Clearance	4	3	12	5	20	7	28
Stability	3	3	9	8	24	8	24
Volume	2	10	20	6	12	8	16
Total		**50**		**64**		**75**	

The leading chassis design that the team will proceed with is octagonal prism body. Octagonal prism shape for the chassis is a perfect combination of space efficiency and ground clearance, which are the two most important design parameters. The octagonal chassis has a natural shape on the front and back giving a good ground clearance and allowing for easy mounting within the airframe. Compared to the triangular design it has a very good stability while not compromising too much of the volume. The leading chassis design is shown in Figure 64.

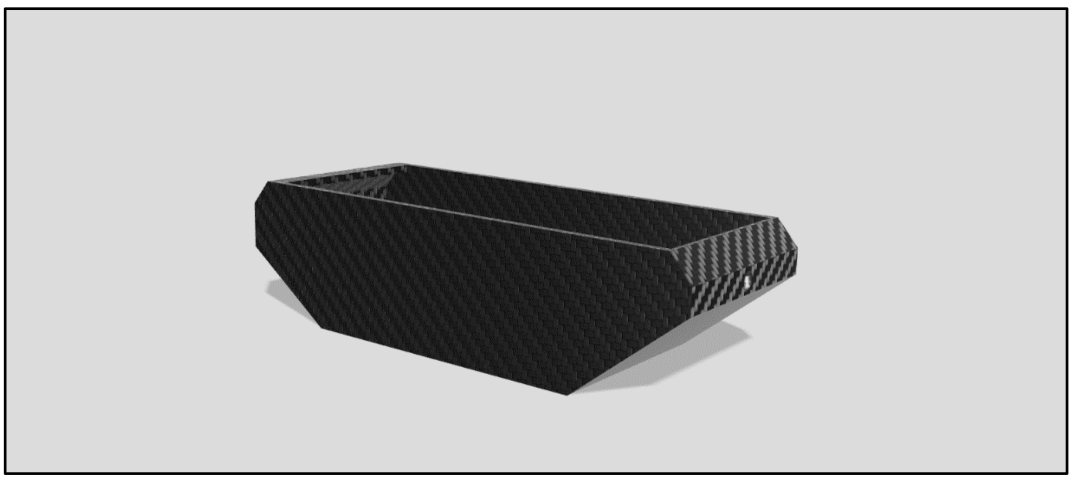

Figure 63: Payload chassis shape

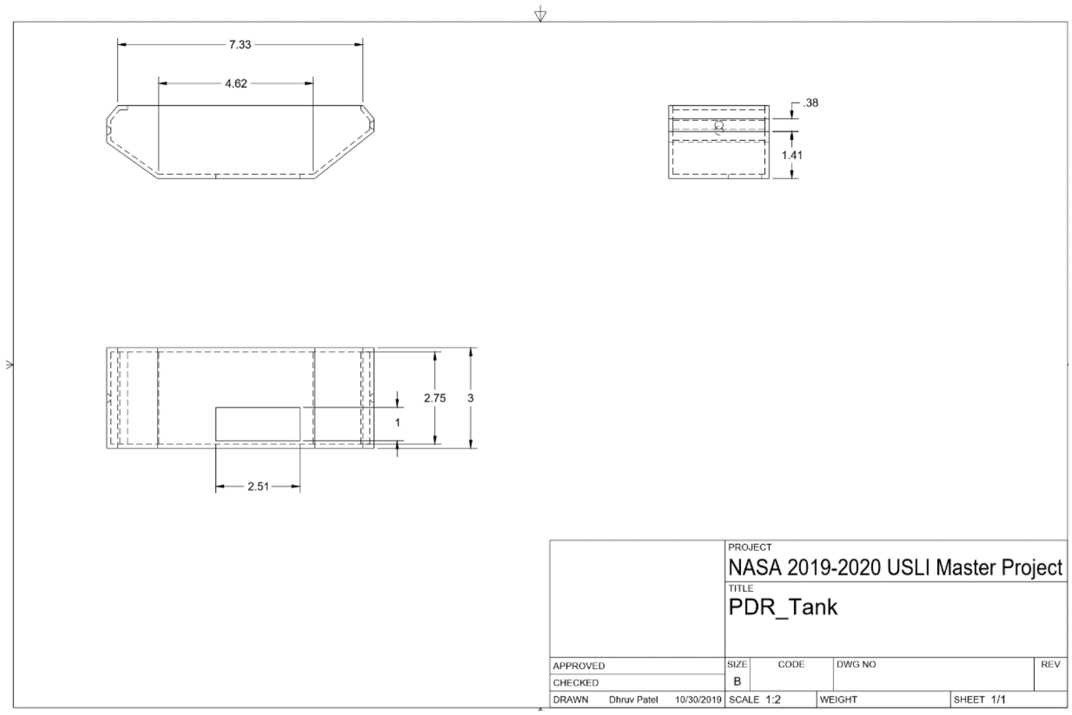

Figure 64: Payload chassis drawing

4.2.2 Drive Train

Swerve drivetrain. This is a very agile drivetrain design, the benefits of which are apparent when exiting the rocket airframe. Where other drivetrain designs would have potential problems turning between two retention plates, swerve drive can simply reorient its wheels to run sideways. However, this design has many flaws for our application. First major flaw is that the wheels tend to not provide as much traction on an uneven terrain. To combat with lack of traction it would be necessary to increase wheel diameter thus taking up a lot of space in the payload section. And lastly, the swerve drive train is very complicated to design and program especially when space is limited.

Tank drivetrain. Tank drivetrain combined with tank treads is incredibly good at traversing rough terrain due to high pushing force and independent left and right motors. The agility is not as good as in swerve drivetrain, but it is still decent due to having zero turn radius. It is very simple to build and program, thus increasing its reliability. Tank drivetrain combined with treads are smaller in size for the given traction value since diameter of wheels could be much smaller compared to swerve drivetrain.

Table 34: Drive Train Decision Matrix

Design		Swerve drivetrain		Tank drivetrain	
Requirement	Weight	Rating	Score	Rating	Score
Simplicity	2	2	4	9	18
Size	3	5	15	7	21
Terrain Traversal	5	3	15	9	45
Total		**34**		**84**	

The leading drive train design that the team will proceed with is tank drivetrain due to its simplicity and terrain traversal. It is much simpler than the swerve drivetrain which would require multiple motors for individual wheel where a tank drivetrain could be as simple as one motor on each side. For our application where space is paramount, it would be better to choose a simpler design that saves space but loses some of the agility. Moreover, the tank drivetrain is a perfect in combination with tank treads. Knowing that the terrain is going to be very uneven and rough it is important to make sure that the rover could actually get to its destination. This is where tank design seems to be an obvious choice of a drivetrain. The tank tread design for the drive train is shown below.

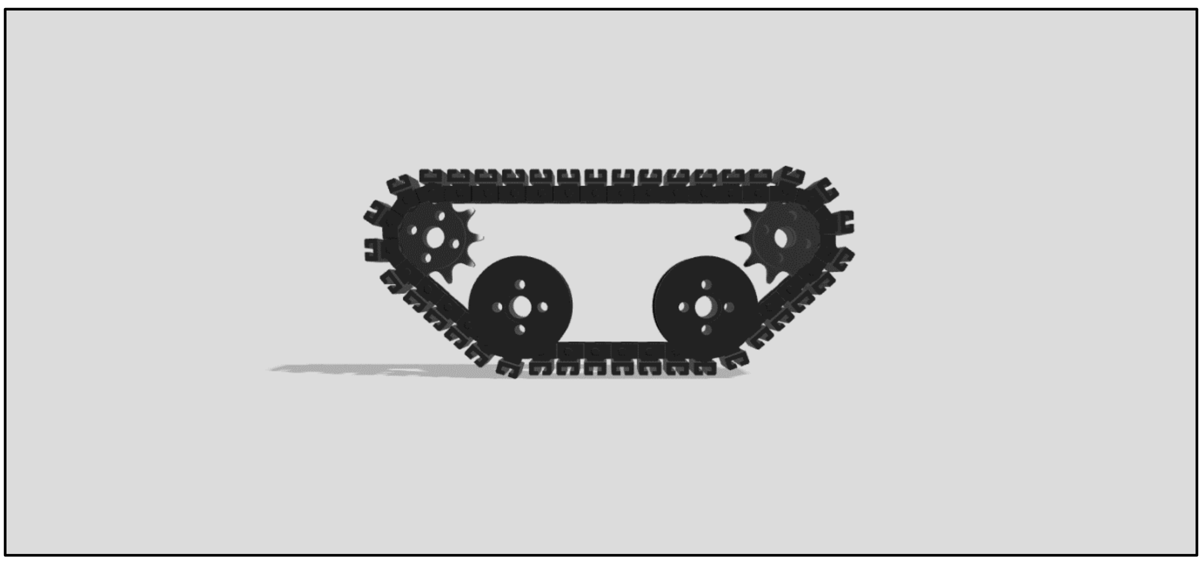

Figure 65: Tank treads for drivetrain

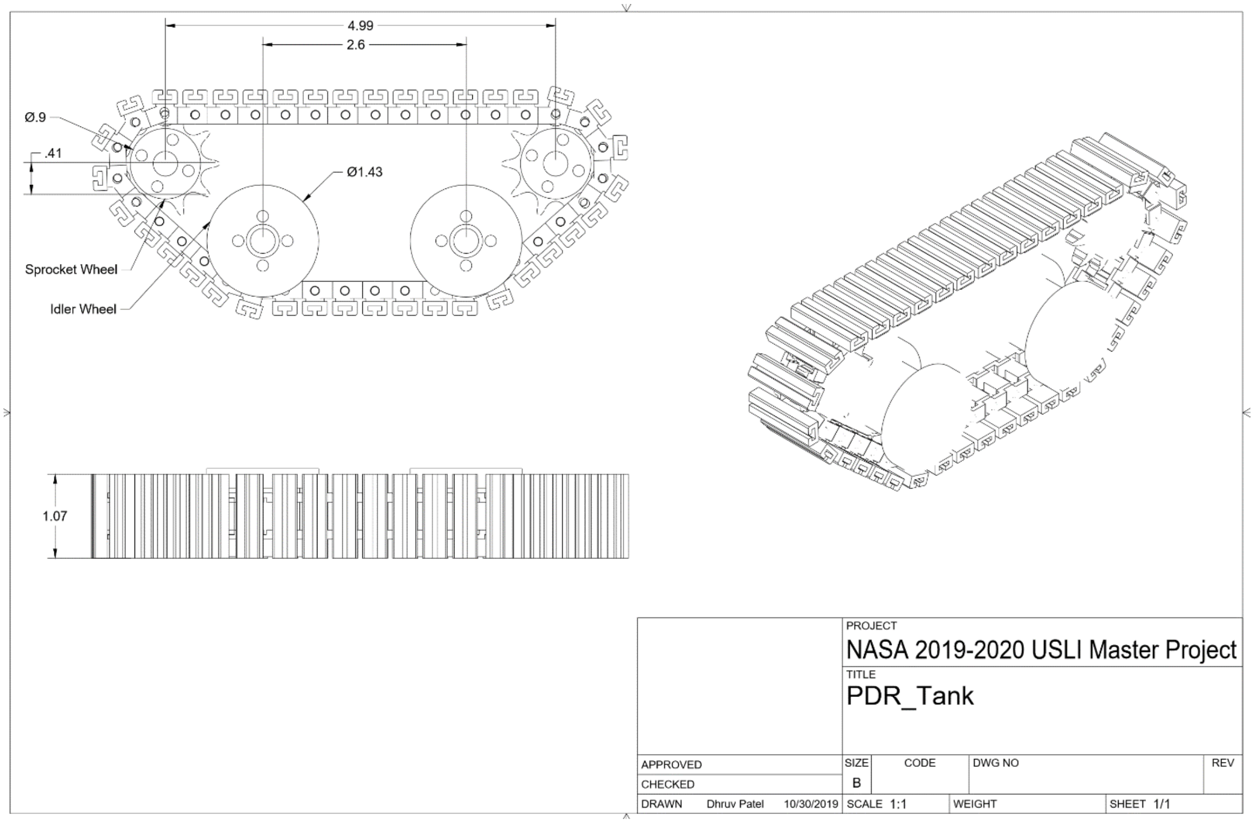

Figure 66: Tank treads drawing

4.2.3 Lunar Ice Sample Collector

Auger drill collector. The main advantage of this design is the ability to collect hard material by drilling into the sample and using auger to gather it. However, it is very complicated to manufacture and assemble. The size and weight of the auger drill with all of its motors makes it unsuitable for our application. The simulated lunar ice will be easily separated granular material, thus there is no reason to use this design since its biggest advantage is not going to be utilized with granular sample material.

Front mounted scoop. Knowing that the sample is granular material, scoop design is an obvious next choice. Scoop design requires only 1 motor to operate and very easy to fit in a narrow rover chassis. However, mounting the scoop in front of the rover would interfere with rover retention plates. While mounting the scoop below the retention mechanism would decrease rover's ground clearance. To combat these downsides the following scoop design was developed.

Mid mounted scoop. By mounting the scoop in the middle of the rover, it will not interfere with retention plates. To maximize ground clearance, it is also beneficial to recess scoop inside the rover body which would come out only during sampling. Thus, mid mounted scoop has all the benefits of the front mounted design while optimizing ground clearance.

Table 35: Lunar Ice Sample Collector Decision Matrix

Design		**Auger Drill**		**Front mounted scoop**		**Mid mounted scoop**	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Manufacturability	4	1	4	8	32	8	32
Mounting Difficulty	3	10	30	7	21	10	30
Weight and Size	3	3	9	9	27	9	27
Total		**43**		**80**		**89**	

The leading sample collection design that the team will proceed with is mid mounted scoop. Given that the simulated material will be granular there is no reason to choose auger drill with all its complexities and little upsides. Front and mid mounted scoops are both great choice and are identical in all parameters except mounting difficulty. The front design would introduce unnecessary complications since that space is utilized by retention plates. The mid mounted scoop alleviates these problems while keeping all the upsides. The leading scoop design and its implementation with the chassis is shown in the figures below.

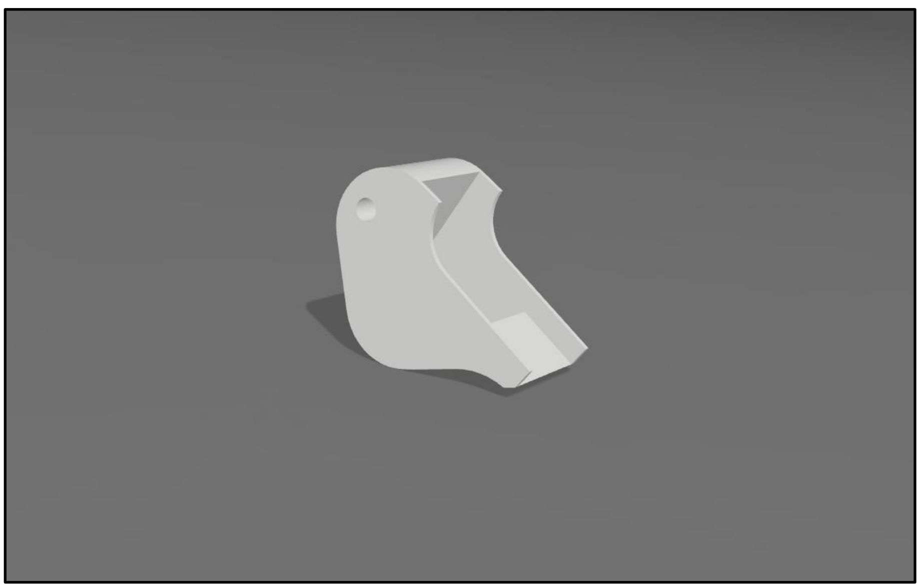

Figure 67: Leading scoop design

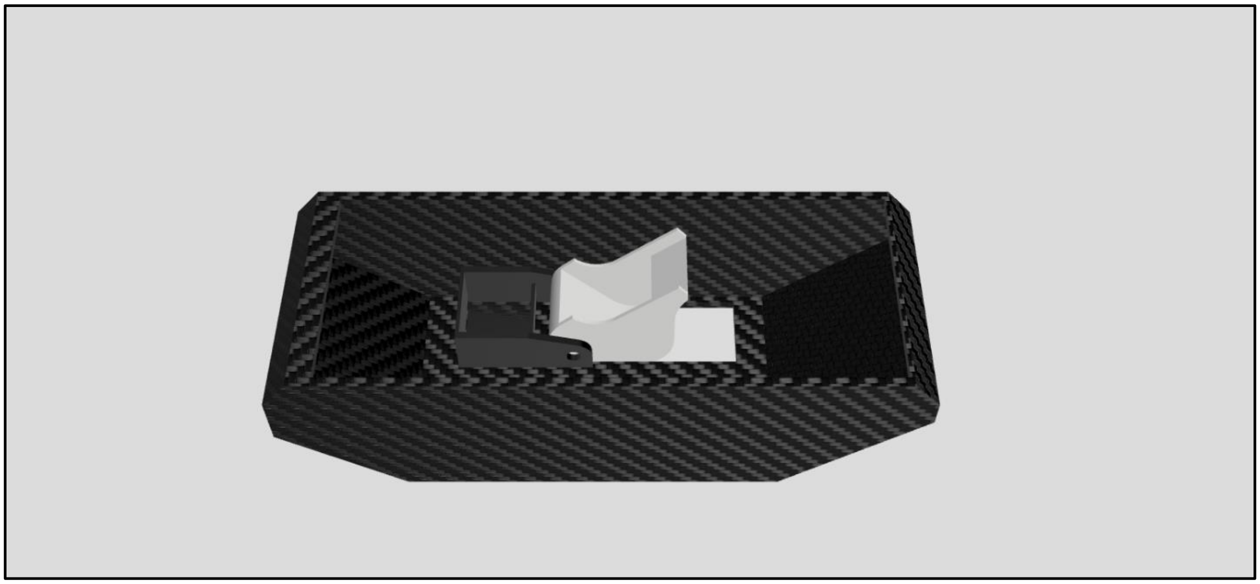

Figure 68: Mid mounted scoop with scoop container

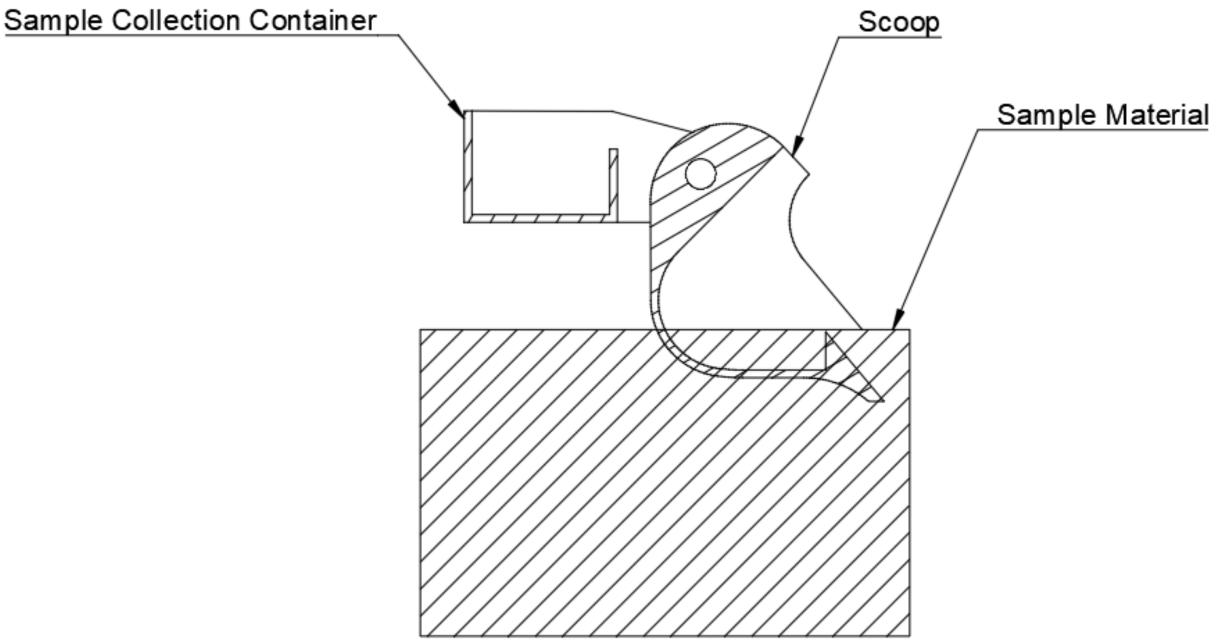

Figure 69: Section view of scoop collecting sample material

4.2.4 Chassis Material

Aluminum Alloy (such as 2024, 6061, 6063, etc.). These alloys have a high strength to weight ratio, high machinability, and can be welded. Aircraft grade aluminum allows us to manufacture chassis components ourselves and is competitively priced.

Carbon fiber: Carbon fiber has one of the highest strength to weight ratio of all materials, allowing the chassis to be considerably lighter and stronger. Although carbon fiber is very expensive and more difficult to machine. We would need to use our University's waterjet or specialized machining tools to manufacture the chassis components. Since carbon fiber cannot be welded, components will need to be epoxied or bolted together.

3D printed plastics: 3D printed plastics using 3D printer at Stony Brook University. Material will be either Acrylonitrile Butadiene Styrene, High Impact Polystyrene, or a Polycarbonate. These are the materials compatible with our University's 3D printer. These options are the least expensive and easiest to manufacture but are the weakest and may not be suitable for aerospace applications.

Table 36: Chassis Material Decision Matrix

Design		**Aluminum Alloy**		**Carbon Fiber**		**3D printed plastics**	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Cost	2	8	16	4	8	8	16
Weight	4	6	24	10	40	8	32
Strength	4	8	32	9	36	1	4
Total		**72**		**84**		**52**	

The leading chassis material that the team will proceed with is carbon fiber. Our chassis components are not extremely large and the benefit from increased cost is advantageous use of our budget. A lighter chassis that is stronger than using traditional materials allows us to increase our weight budget for other parameters and components such as motor power, drivetrain system, more feedback systems, etc.

4.2.5 Treads Material

Acetal (polyoxymethylene) Thermoplastic: Acetal has high strength and low friction properties. It has high wear resistance and several manufacturers have tread kits for hobbyists made of this material. The low friction properties allow for less wear on tread links but do not provide very much surface friction for the ground and may not be adequate for off road terrain.

Acetal (polyoxymethylene) Thermoplastic with rubber track inserts: This is a desirable concept because the Acetal links can easily fit any required length and are relatively strong, and the rubber track inserts allow for higher friction to mantle difficult obstacles and terrain. This is a relatively low cost solution that will work for many different specifications if our design is iterated in the future.

Rubber: A pure rubber tread would have the highest coefficient of static and sliding friction. Having no links between treads also reduces the likelihood of failure due to tread link breakage. This is a robust solution but isn't very customizable. Rubber's strength will significantly drop or be unusable if spliced to fit new required lengths. Therefore we may have to use thermoplastic treads during prototyping and then when the design is completely finalized, order a rubber tread specific to our final dimensions. Also, with a classic tank drivetrain with driven wheels, the clearance must be high enough to allow for the elasticity of the rubber treads to be advantageous in acting as suspension.

Table 37: Tread Material Decision Matrix

Design		Acetal		Acetal with rubber insert		Rubber treads	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score
Customizability	1	9	9	9	9	4	4
Weight	4	8	32	7	28	5	20
Traction	3	5	15	8	24	9	27
Reliability	2	7	14	7	14	8	16
Total		**70**		**75**		**67**	

The leading tread material that the team will proceed with is acetal with rubber track inserts. The material is highly customizable and can be implemented even if our exact design specifications vary throughout the design and manufacturing periods. The main qualm with a purely thermoplastic tread material was the lack of traction. Implementation of rubber track inserts into the acetal treads will give us a compromise between traction, weight, customizability, and cost.

4.2.6 Lunar Ice Sample Collector Material

The simulated lunar ice sample collector shown in Figure 70 will be 3D printed. Because of the shape and required performance parameters of the scoop, 3D printing will suffice for our design. It would be impractical to machine a scoop or order one custom built and is not necessary. Therefore, we will 3D print the scoop using ABS.

4.2.7 Summary of Leading Tank Design

Combining all the preferred designs of the individual parts the final tank design is shown below. The rover is going to be an octagonal prism shaped body made out of carbon fiber to increase rigidity and strength of the rover. Tank drivetrain with tank treads spans the entire body length of the rover to maximize traction and its desirable terrain traversal properties. A 3D printed scoop is mounted to the middle of the tank to allow for greater ground clearance and weight optimization.

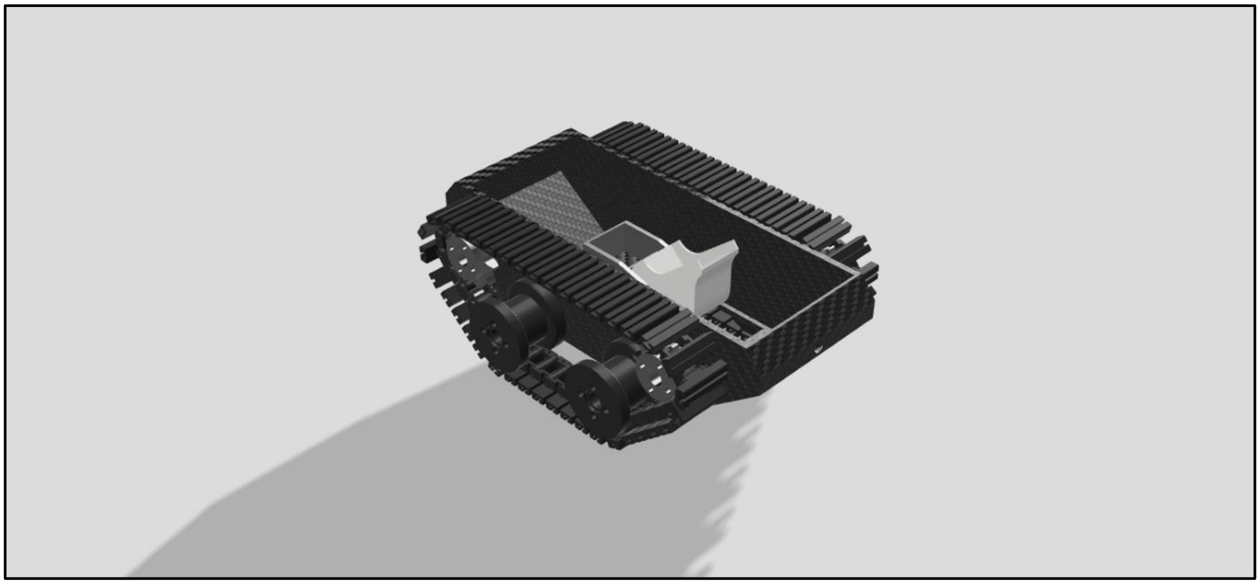

Figure 70: Final tank assembly

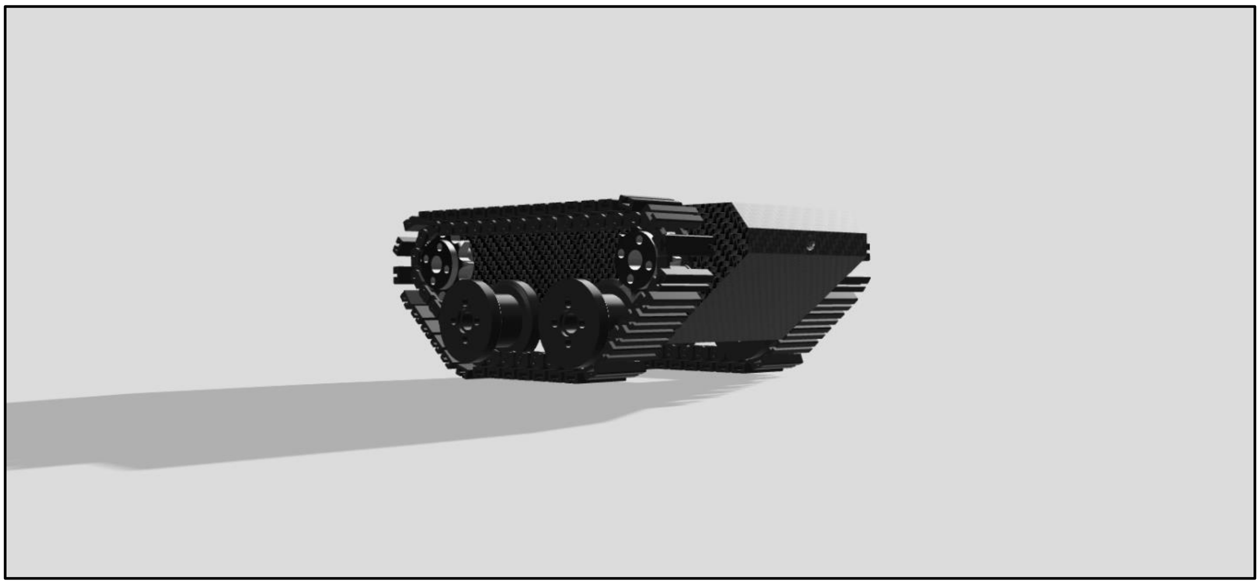

Figure 71: Final tank ground level view

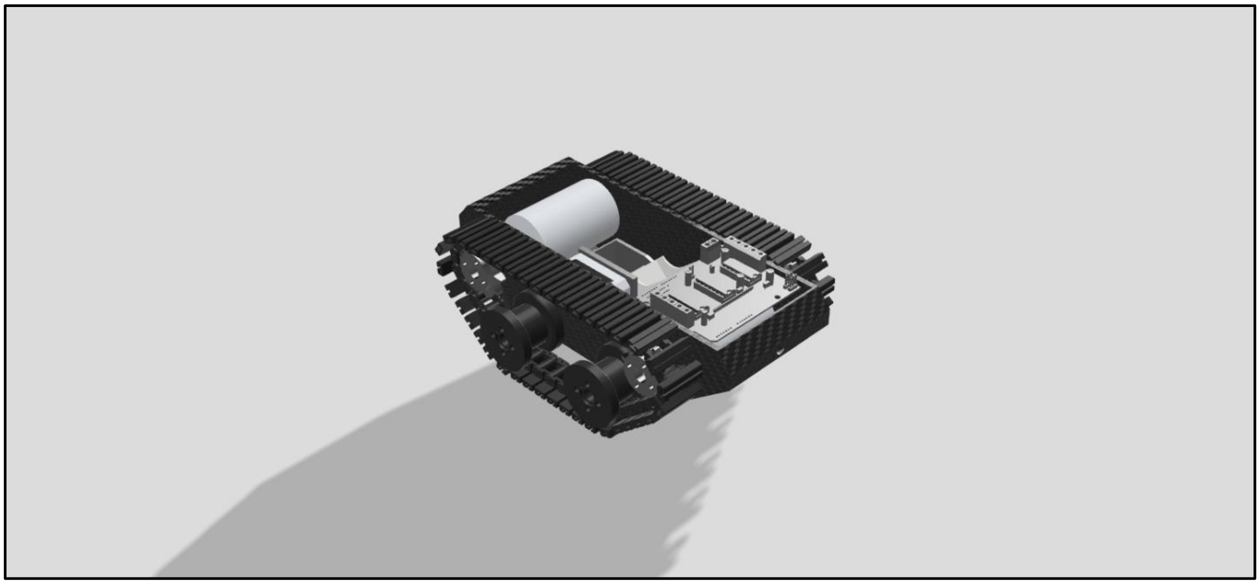

Figure 72: Final tank assembly with proposed electronics

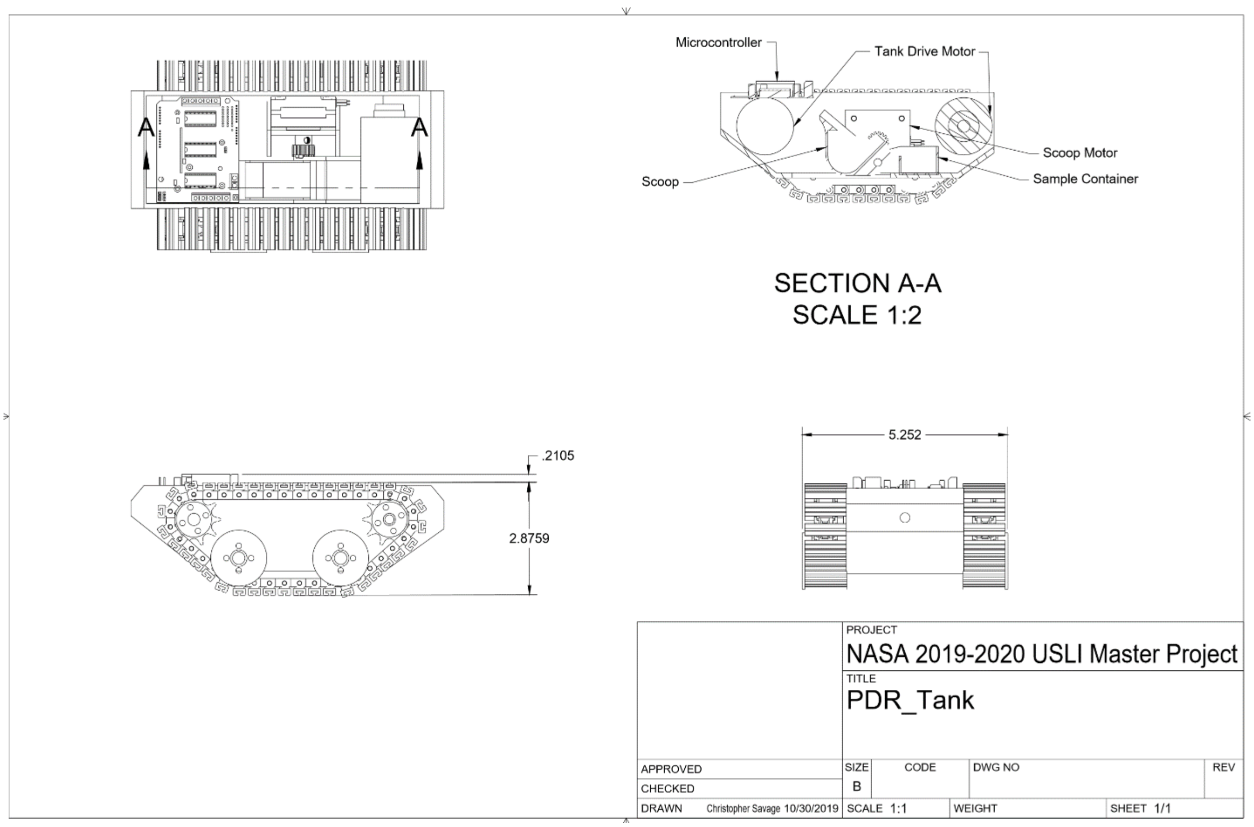

Figure 73: Final tank design drawing.

4.3 Tank Exiting and Reorienting System

The mission objective requires the payload to be retained within the launch vehicle until deployment. During deployment the payload has to reorient and exit the payload bay of the launch vehicle. In order to meet these requirements, different designs were considered for the retention, reorientation, and exiting method of the payload. The pros and cons of each design are considered below. A decision matrix was used to select the leading design of the TEARS.

4.3.1 Retention Method

The retention method has to secure the payload during flight and while the payload is being ejected. A few important requirements were considered during the design process for retention. Primarily, the designed system has to be able to secure the payload in all directions and orientations until deployment. This is a major concern, since the launch vehicle will experience rotation around the roll axis while in flight, thereby disturbing the payload. The retention system must have high strength. This requirement is necessary since the payload bay will be subject to high forces during flight. The payload bay will also experience some shock during the parachute deployment stage and landing. The retention system should be easily integrated into the payload bay of the rocket. This serves importance since having higher complexity in the retention design could lead to more modes of failure during the mission. The following designs were considered with considerations to the factors mentioned above.

Flat plate retention:

This design involves mounting the payload on a flat plate and securing the payload in place by (placement of cylindrical pins or lowering a housing from the top). The design provides a strong secure retention of the payload with minimal chance of the payload releasing from its mount during flight. Servo or stepper motors will be used to secure the fastening mechanism onto the payload plate. The plate mount will be simple to manufacture and assemble. Although this design offers a simple mounting mechanism for the payload, it does add a significant amount of weight to the payload bay. The mounting plate for the rover will need to be of a high strength material, such as aluminum in order to prevent failure during flight. Given the material weight for the mounting plate and the added weight of the motors required for the fastening mechanism, this method of payload retention will be heavy.

Chassis Shape Retention Mount:

The second design involves the use of cylindrical plates with two retention mounts holding onto the payload from the front and the back. The front cylindrical plate is mounted on to the nose cone shoulder. The shape of the retention mounts will match the front and rear end profile of the payload. When the payload bay is closed the two retention mounts fasten the payload by a geometric tight fit. The cylindrical plates will travel out of the payload bay during the exiting process in conjunction. The benefit of this design is that it simple to integrate into the payload bay. Multiple motors are not required to hold the payload in place since the cylindrical plates are geometrically constraining the payload. The cylindrical plates could be purchased and easily machined down to the necessary dimensions. The manufacturing of the retention mount could be complicated, since the dimensions and the shape of the front and rear end of the rover will need to be replicated.

Chassis Shape Retention mount with spherical nubs:

This design was an iteration of the second design discussed above. The retention mount now involves spherical nub extruding from the center that will enter a hole of the same diameter in the front and rear plates of the payload chassis. This design has all the benefits of the second design with an improved method of holding the payload in flight. Having the spherical nubs attached to the chassis from the retention mount will help prevent any lateral movement of the payload during flight. The nubs don't require extraneous motors to fasten the payload as the first design alternative required and offers fewer modes of failure while being comparable in reliability.

The three designs were compared using a decision matrix on weight, reliability of retention, and ease of integration into the payload bay. The results are shown in Table 38.

Table 38: Retention Method Decision Matrix

Design		**Flat Plate**		**Chassis Shape**		**Chassis Shape with spherical nubs.**	
Requirement	Scoring Weight	Rating	Score	Rating	Score	Rating	Score
Weight	2	3	6	8	16	8	16
Reliability	6	8	48	6	36	8	48
Integration	2	5	10	7	14	7	14
Total		**64**		**66**		**78**	

After considering weight, reliability, and integration of each retention design choice, the leading design choice was the chassis shape retention mount with pins. This design proves to be the most reliable without additional weight and complexity. This design is shown in Figure 74.

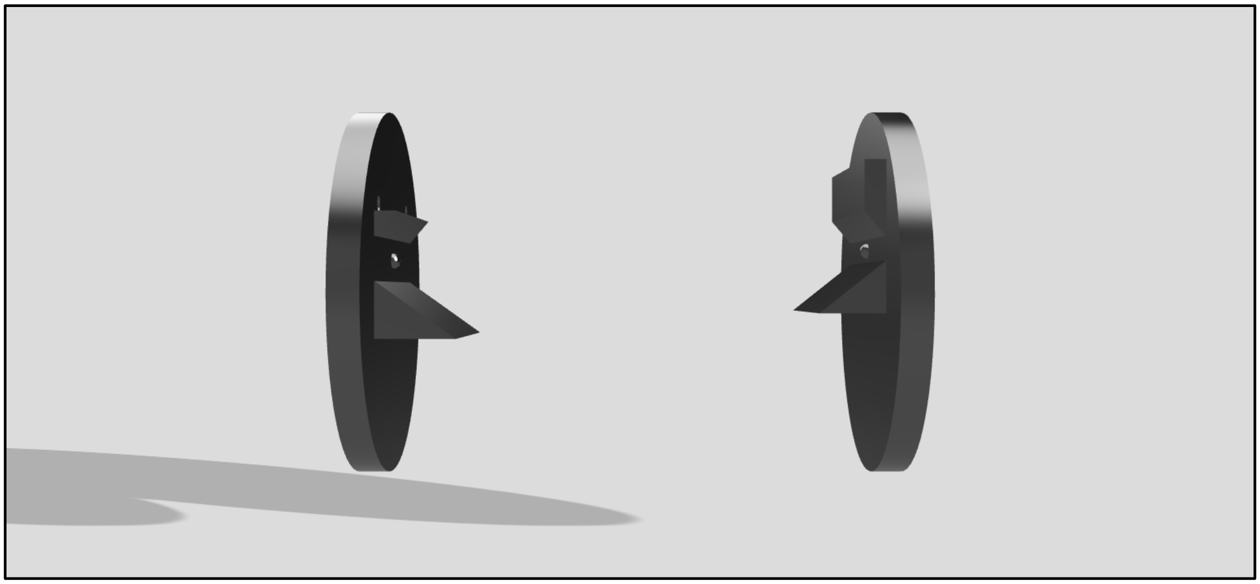

Figure 74: Leading design for retention mounts

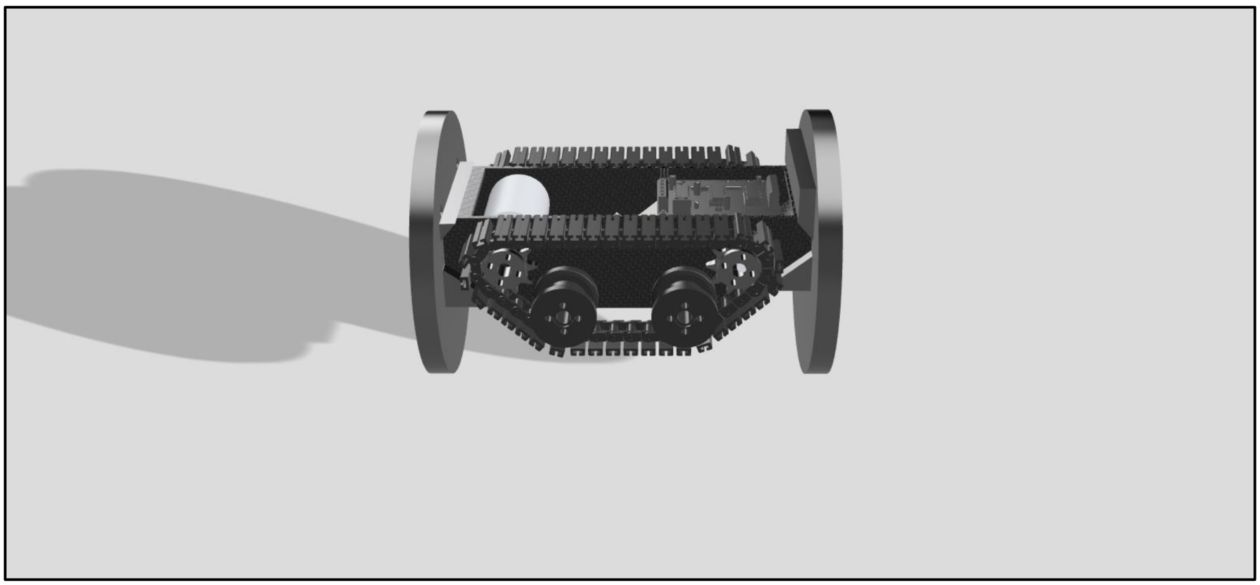

Figure 75: Tank mounted on the retention mounts.

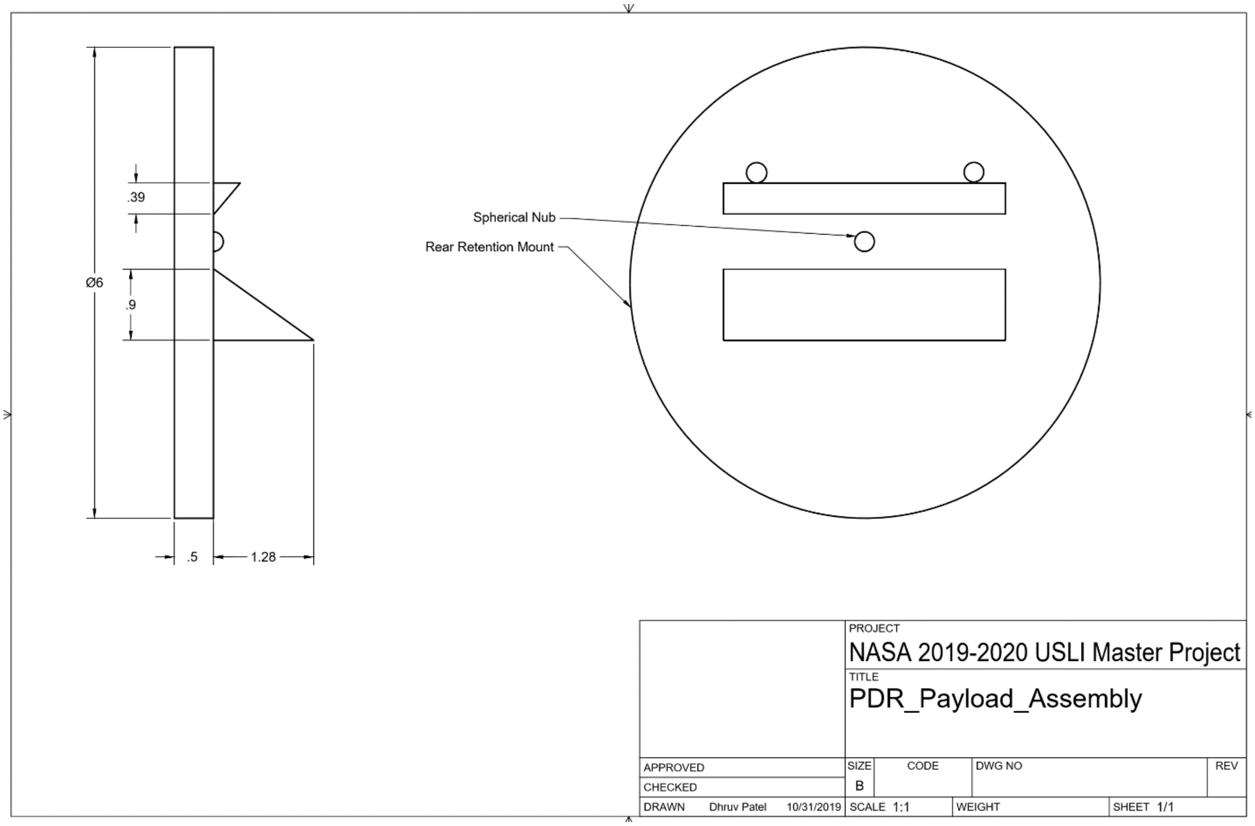

Figure 76: Retention mount drawing.

4.3.2 Reorientation Method

One of the mission success criteria is that the payload rover has to reorient itself. This mechanism is necessary because the leading design choice for the payload does not have the ability to self-right itself. The payload bay will land on the ground in an undetermined orientation, and a reorientation system will adjust the payload into the correct orientation. A couple of designs were considered for this mechanism and the primary requirement that was considered was the reliability of the system.

Counterweight Orientation:

This design uses a counterweight attached to cylindrical rotating plates that are at each end of the payload retention and exiting system. The rotating plates are held in place until reorientation needs to occur. Once the retention and exiting system needs to reorient, the rotating plates are released and the counterweights rotate till they are at the bottom due to gravity, thereby causing the whole system to rotate with it. This design offers a simple solution to ensure proper orientation of the payload. A set of motors will be required to actuate the mechanism that fixes and releases the rotating plates. The motor requirement alongside the added weight of the counterweights could lead to a huge weight addition within the payload bay. This form of reorientation provides minimum control and would lead to failure of the payload mission due to the smallest of errors.

The possibility of the lock and release mechanism breaking during flight must also be considered, as this would lead to a freely rotating payload system mid-flight.

Direct Drive Reorientation:

The second design that was considered uses one cylindrical plate attached to the rear end of the payload bay. This plate will attach to the retention mount and exiting system but will stay fixed while the payload exits. A motor will be directly mounted to this plate and will actuate the reorientation process. A thrust ball bearing will be used to reduce friction during reorientation. This design requires a strong motor to handle the weight of payload, retention mounts, and exiting system. The material for the reorientation plate needs to have high strength in order to prevent failure. This design offers precise control during reorientation phase. The motors ability to handle the stresses imposed on it during reorientation is the primary concern with this design.

Gear train Reorientation:

The third design uses a similar concept to the second design, but the motor now rotates with the reorientation plate. In this design a square head axle is driven through the bulkhead and through washers and thrust bearings to the reorientation plate. The square head axle passes through the center of the reorientation plate. The reorientation motor is mounted on the reorientation plate and the shaft has a pinion gear attached to it. This smaller pinion meshes with a larger gear that is extending from the center of the reorientation plate. Once the motor is turned on, the reorientation plate and everything mounted to it turns around the larger pinion gear. This design will be a bit heavier than the second design concept but will reduce motor torque requirements. This is a more compact design than the direct drive reorientation mechanism. This design was deemed the most reliable of the three design alternatives.

The three designs were compared on weight, reliability, and ease of integration using a decision matrix and their results are shown in Table 39.

Table 39: Reorientation Method Decision Matrix

Design		**Counterweight**		**Direct Drive Reorientation**		**Square Key Rotation**	
Requirement	Scoring Weight	Rating	Score	Rating	Score	Rating	Score
Weight	2	6	12	5	10	5	10
Reliability	6	5	30	7	42	8	48
Integration	2	8	16	6	12	6	12
Total		**58**		**66**		**70**	

After considering each design using the decision matrix, the square key reorientation system was picked as the leading design. Since the mission will be a complete failure if the payload is not able to reorient itself, a reliable design is very important. Although this design will be heavy, it proves to be the most reliable. The leading reorientation system is shown in Figure 77.

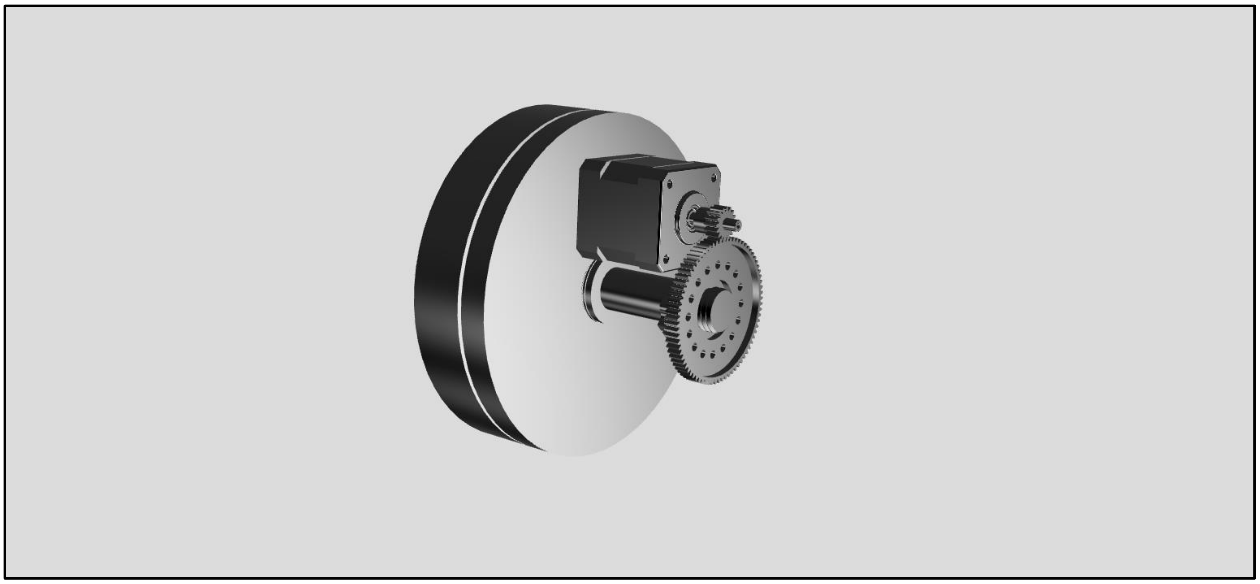

Figure 77: Leading design for reorientation

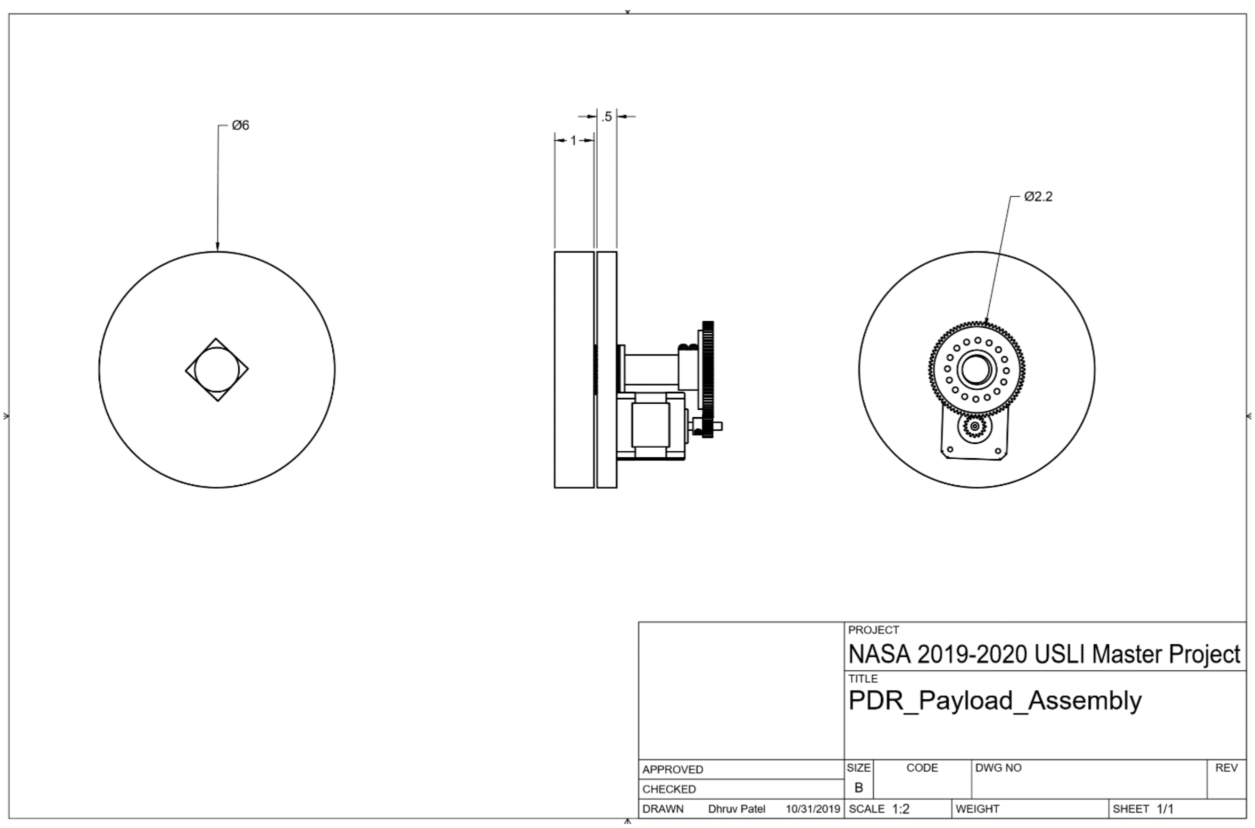

Figure 78: Reorientation design drawing

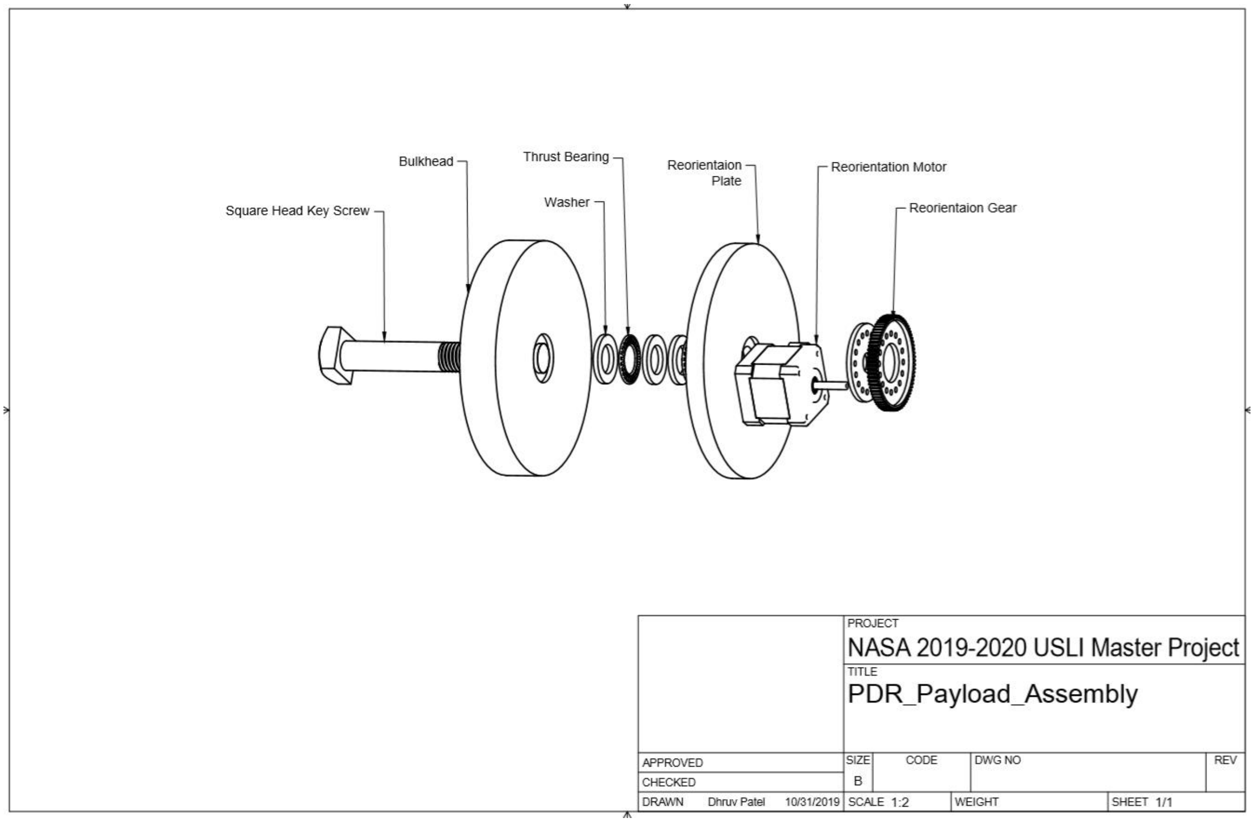

Figure 79: Exploded view of reorientation system

4.3.3 Exiting Method

Upon the landing of the payload bay the payload will need to deploy out of the body tube. The use of black powder and other similar energetics is prohibited for payloads performing ground deployment. Since our payload is being deployed on the ground a mechanical exiting system is necessary. The strength of the exiting mechanism as well as the simplicity of the system were the primary factors that were considered during the design process.

Single Lead Screw:

The first design that was considered involved the use of a single lead screw from the reorientation plate to the nose cone. The retention mount will be embedded with a lead nut that will travel along the lead screw when the lead screw is actuated by a motor. This design has minimal complexity. The motor controlling the lead screw will be remotely controlled. Once the payload is on the ground the system will be controlled by an operator and the entire payload assembly will travel out the payload bay. Although the design is simple, the single lead screw is carrying almost all of the weight of the payload bay on itself. This design is not structurally reliable since the single lead screw will be carrying a lot of weight and the system could experience torsion during reorientation. The motor shaft will experience a significant torque since it is directly attached to the lead screw, and to prevent failure a strong motor will be required. The need of a strong motor will make this design moderately heavy.

Dual Lead Screw with Pulleys:

This design uses one motor actuating two lead screws through a pulley system. The two lead screws have respective mounts attached to the reorientation plate, and the screws extend from there through the nose cone. The retention mounts are embedded with two lead nuts that travel along the lead screw. This design will be heavier than the single lead screw design since a pulley and two lead screws are used. The use of a pulley could reduce the amount of torque experienced by the motor shaft depending on the gear ratio utilized. The load due to the weight of the payload and its retention mounts is distributed across two lead screws which helps structural reliability. The design is complex to integrate into the payload bay but has fewer modes of failures and increases chances of mission success.

The two designs were compared on weight, design simplicity, and structural reliability using a decision matrix. The simplicity of the design was weighted the least since the payload mission will be a complete failure if the payload can't exit the payload bay. The results are shown in Table 40.

Table 40: Exiting Method Decision Matrix

Design		**Single Lead Screw**		**Dual Lead Screw with Pulley.**	
Requirement	Weight	Rating	Score	Rating	Score
Weight	2	7	14	4	8
Simplicity	1	9	9	4	4
Structural Reliability	7	5	35	8	56
Total		**58**		**68**	

The leading exiting method based on the decision matrix was the dual lead screw with a pulley. The single lead screw design offered a simpler solution that was lower in weight but structurally unreliable. Since structural reliability was of highest importance to mission success, the single lead screw design was inadequate. The details of the leading design for exiting is shown in Figure 80.

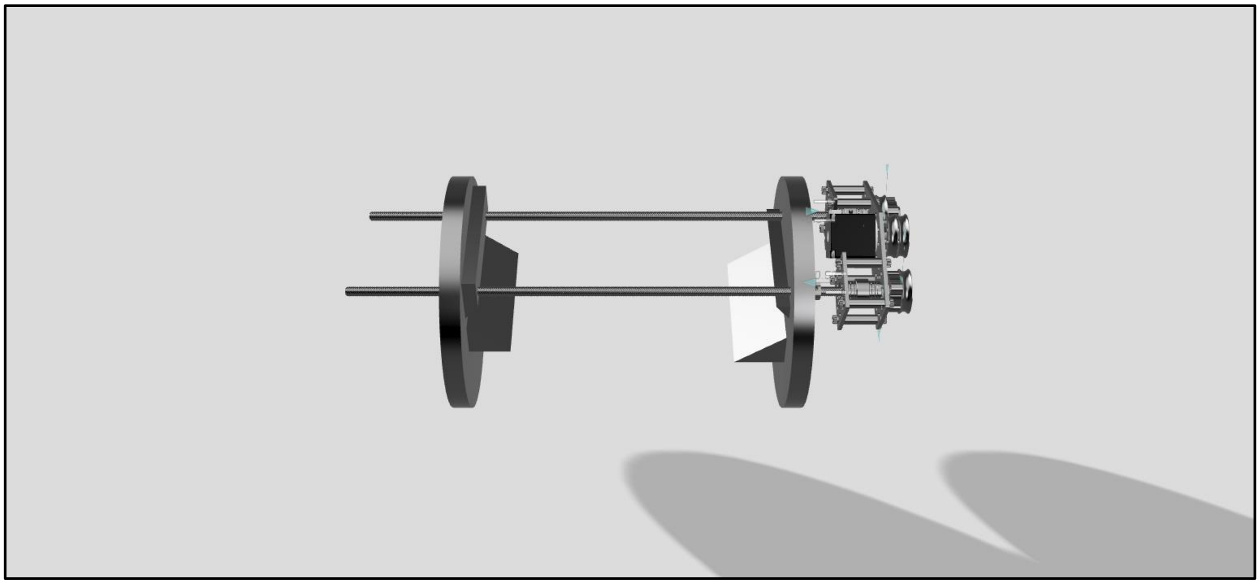

Figure 80: Exiting system attached to retention mounts.

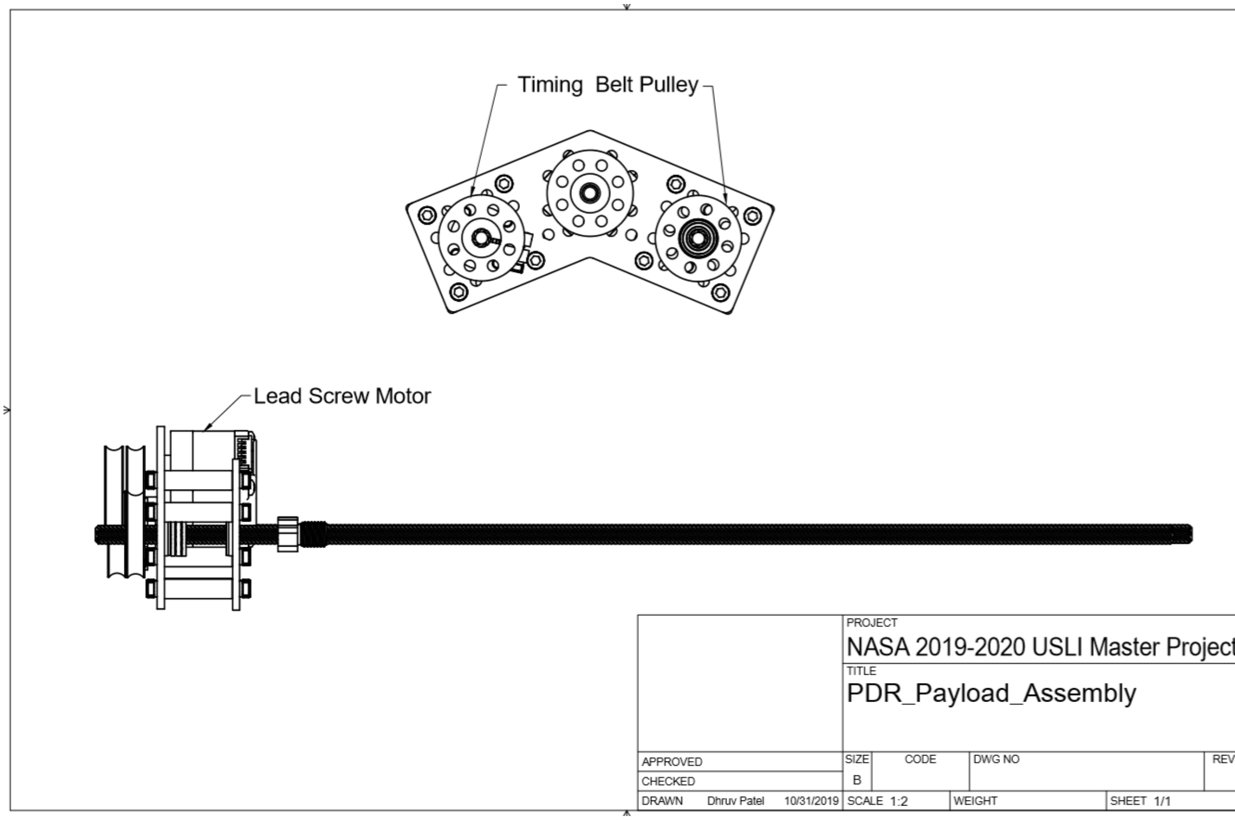

Figure 81: Exiting assembly diagram

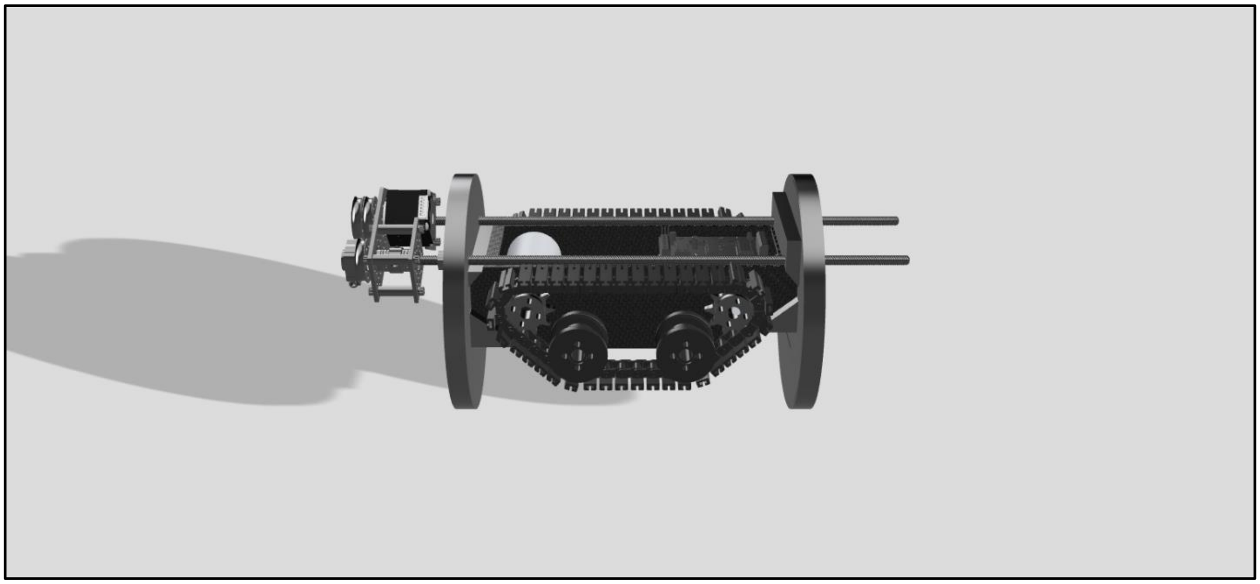

Figure 82: Exiting System with tank mounted

4.3.4 TEARS Materials

Once the leading design for the retention, reorientation, and exiting systems were picked, the materials for the necessary parts were considered. The necessary material strength requirements were considered for each part and then consideration was given to minimize weight. The materials for TEARS are discussed in the order they are assembled starting from the bulkhead at the avionics bay to the nose cone.

The bulkhead separating the payload and the avionics bay is attached to the reorientation plate of TEARS. The reorientation plate will be holding a lot of the electronics weight for the payload bay. Since there is a high load imposed on this plate, weaker materials such as 3D printed plastics won't structurally hold during flight. A highly dense metal alloy like steel would perform better in flight but will be significantly heavy. Given these considerations, the team decided on using aluminum as the material for the reorientation plate. Aluminum is weaker than steel but still sufficient in strength for our application, and it is considerably lighter than steel.

The mount for the lead screw is made from aluminum brackets and clamping collars. The lead screw mount setup can be purchased, and the material is strong enough to bear the weight of the lead screw and the payload without failing. The gears required to drive the lead screw from the motor will be made from aluminum since weaker materials such as plastics will fail under high torque and the meshing gear teeth could break. While conducting research for purchasing lead screws, the team found that aluminum and steel were the most common materials available for purchase. Steel was picked as the material of choice since the lead screw will be under a lot of load from the weight of the retention mounts and the payload.

The cylindrical plate for the rear retention mount will be made of fiberglass since it has a high strength to weight ratio and is light weight. The manufacturing with fiberglass should be simple since it is a cylindrical plate with no other defined features. Aluminum was picked as the material for the retention mounts. The mount will be custom made by the team and will require precise machining. The team has more experience with the machining with aluminum and this influenced the team's decision during material considerations for the retention mounts.

4.3.5 Summary of Final TEARS Design

The leading TEARS design can be seen in Figure 83. The deployment procedure for TEARS will follow the following steps after the payload bay has safely landed on the ground.

1. The exiting system is controlled by a remote controller until the nose cone shoulder is moved just outside the payload bay.
2. The reorientation system is then controlled, and the payload is rotated to its correct orientation.
3. The exiting system is controlled again until the forward retention mount is free from the lead screw.
4. The exiting system is controlled in the reverse orientation until the front end of the payload detaches from the forward retention plate and the front of the payload body hits the ground.
5. The payload controller is now turned on and used to drive the payload free from the rear retention mount and onto the sample recovery area.

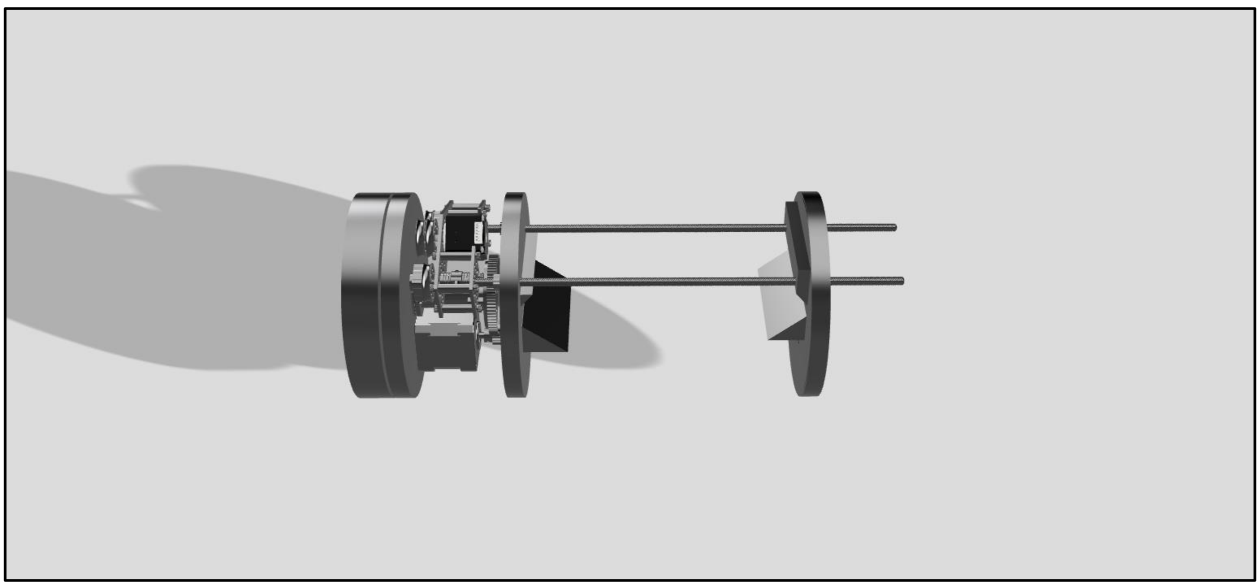

Figure 83: TEARS assembly

The final payload bay assembly after combining the leading alternatives for TEARS and the payload mechanical design can be seen in Figure 84.

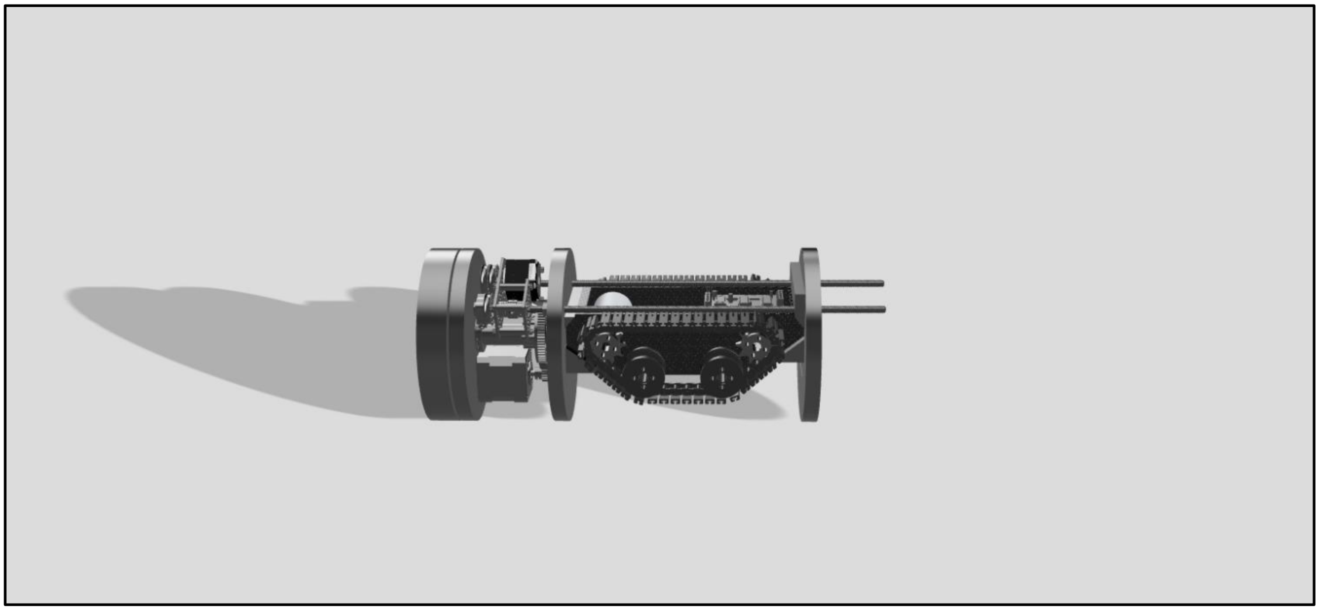

Figure 84: Leading design for payload mission

The payload in its deployed position is shown in Figure 85.

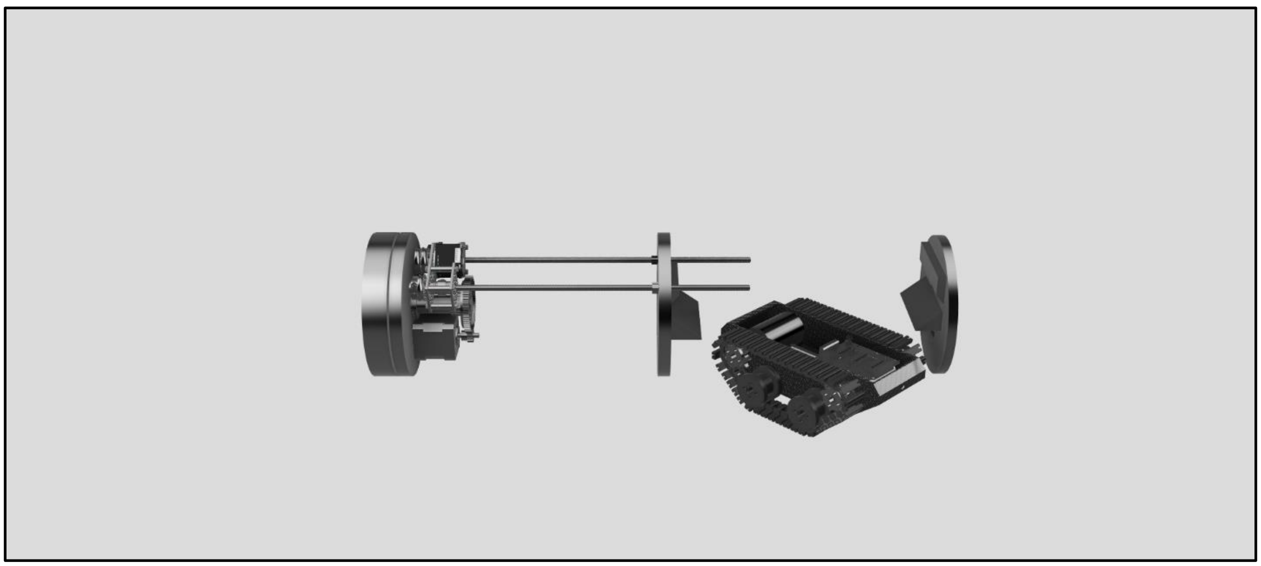

Figure 85: Payload in deployed position

4.4 Payload Electronics

4.4.1 Microcontroller Selection

The microcontrollers will be the hub of logic processing. We will need a microcontroller for the DICU, TEARS and the rover. On the DICU the microcontroller will function primarily as a means of transporting information to the rover and displaying information transported from the rover. Because the microcontroller for the DICU will not be on the rover, weight and size are not so important. However, technical specifications would be more important due to the video the microcontroller will be displaying through HDMI.

For the rover and TEARS, the microcontroller must be able to talk with the motor controller over I2R. The Rover microcontroller must have enough pin outputs to connect to the transceiver, FPV camera, and motor controller. Whereas the TEARS microcontroller must have enough pin outputs to connect to the Long Distance Receiver and Motor Controller. Size and weight are more important factors here since we need to fit within a small space and would like to reduce weight. During the building process of the rover, it is likely we will come across problems we must troubleshoot, often, these kinds of problems can be resolved using sensors. Therefore, excess pins would be preferable if such a case occurs.

Table 41: Microcontroller Decision Matrix

Design		**Raspberry Pi 3 B**		**Raspberry Pi Zero W**		**Arduino Nano**		**Arduino Uno Rev3**	
Requirement	Weight	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Weight	1	8	8	10	10	10	10	6	6
Size	2	6	12	10	20	10	20	8	16
Technical Specifications	3	10	30	8	24	5	15	6	18
Price	1	6	6	9	9	6	6	6	6
I/O Pin Capacity	2	10	20	10	20	4	8	8	16
Operating Load	1	3	3	3	3	6	6	6	6
Total		**79**		**86**		**65**		**68**	

The Raspberry Pi's score higher than the Arduino's overall, where the Raspberry Pi Zero W is the highest rated microcontroller, and the Raspberry Pi 3 B is the second highest rated microcontroller. The Raspberry Pi Zero W has higher or equal ratings than the Raspberry Pi 3 B for all requirements except technical specifications. Due to this, the Raspberry Pi 3 B is chosen for the DICU and a Raspberry Pi Zero W for the rover and TEARS.

4.4.2 Communications Equipment

For TEARS we use a 3000m RF Remote Control Switch. The switch was chosen for the fact that it can control relays from long distance and can receive signals through obstacles. Additionally, it is cheap and can control up to 14 relays switches. It not only meets our requirements, but surpasses them, we are using two stepper motors so we would only need four relay switches total. Once a relay switch provides input to the Raspberry Pi Zero W, it will tell the motor controller to start driving the associated motors. The device functions on a 315MHz frequency.

On the rover, we have two forms of RF communications with the DICU. The first is the XBee, it was chosen due to its simplicity, size, and long-range capability of up to 15 miles. While there are some alternatives to XBee, it is the most widely used and is arguably the best in terms of simplicity. The XBee operates at the 2.4GHz frequency. The second is the FPV Camera transmitter, there are many FPV cameras, but this specific design was chosen due to its antenna and small size. The antenna is a dipole brass antenna, it is cheap and will operate well at long range if in direct line of sight. The transmitter communicates with an FPV receiver on the DICU. These FPV units operate at 5.8GHz.

4.5 Electrical Schematics

Data Transmission between the rover and the DICU will be achieved via the XBee Transceiver Board, this board will receive data governing the motor control. The signals are then interpreted by the Raspberry Pi Zero W. As soon as a signal is received by the XBee, the Raspberry Pi will turn the FPV Transmitter and the FeatherWing Motor Controller on. The Raspberry Pi Zero W communicates with the FeatherWing Motor Controller over I2C by using the SCL and SDA pins. Once the FeatherWing Motor Controller translates these commands into MicroPython, it will regulate voltage to the DC Motors and the Stepper Motor. Signals will also be sent back to the DICU including data such as Stepper Motor angle, Motor Controller Status and FPV Transmitter Status.

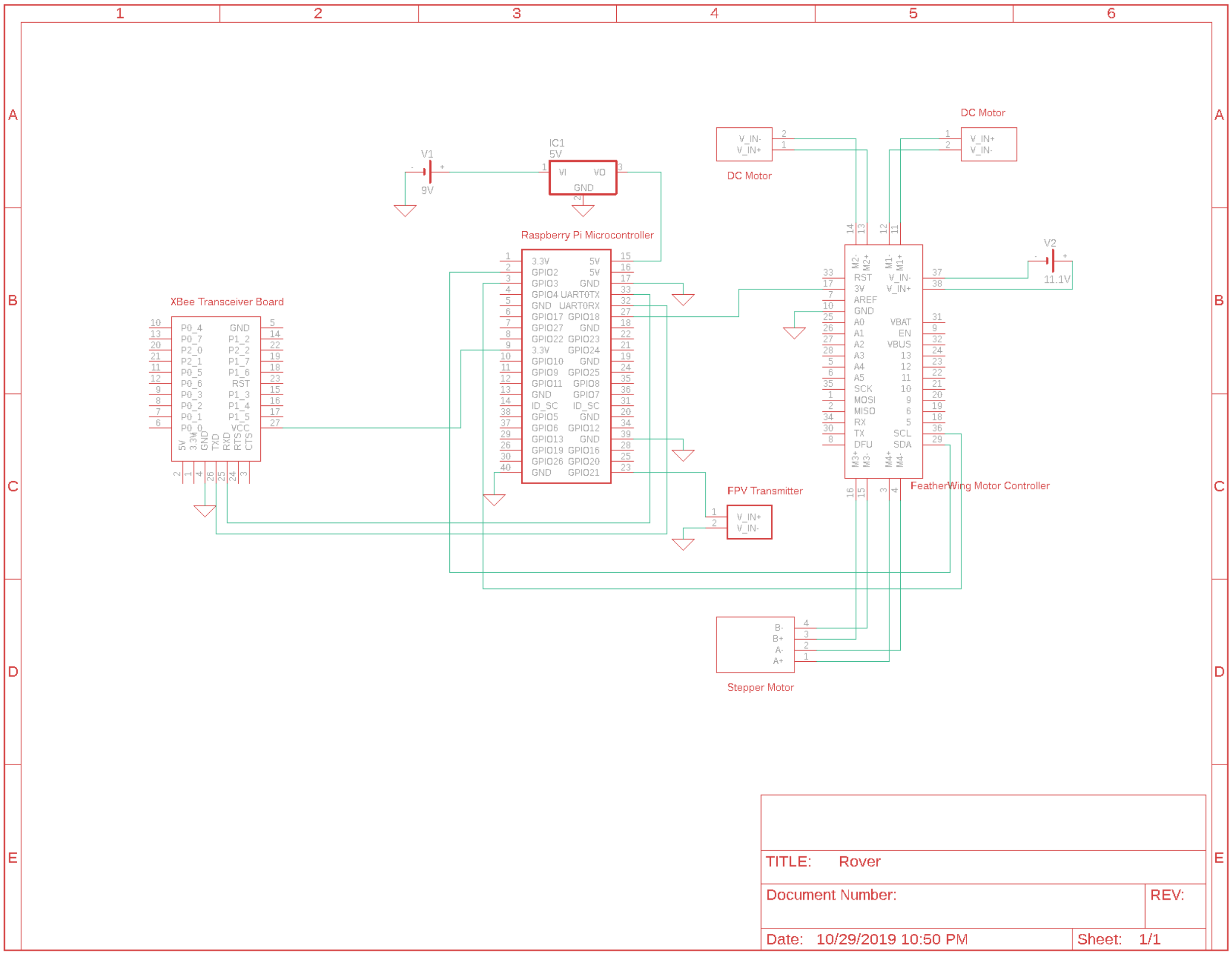

Figure 86: Rover Electrical Schematic

The DICU will have two sections. The first will simply receive signals from the FPV Transmitter, this will then be displayed on a 3.5" LCD Monitor. The second section will have a Raspberry Pi Model 3 B sending signals to the rover through the XBee Transceiver Board. These signals will control motors and will be input though a controller connected to the Raspberry Pi Model 3 B via USB. Data will also be sent from the rover to the DICU and displayed on an HDMI screen, powered through USB.

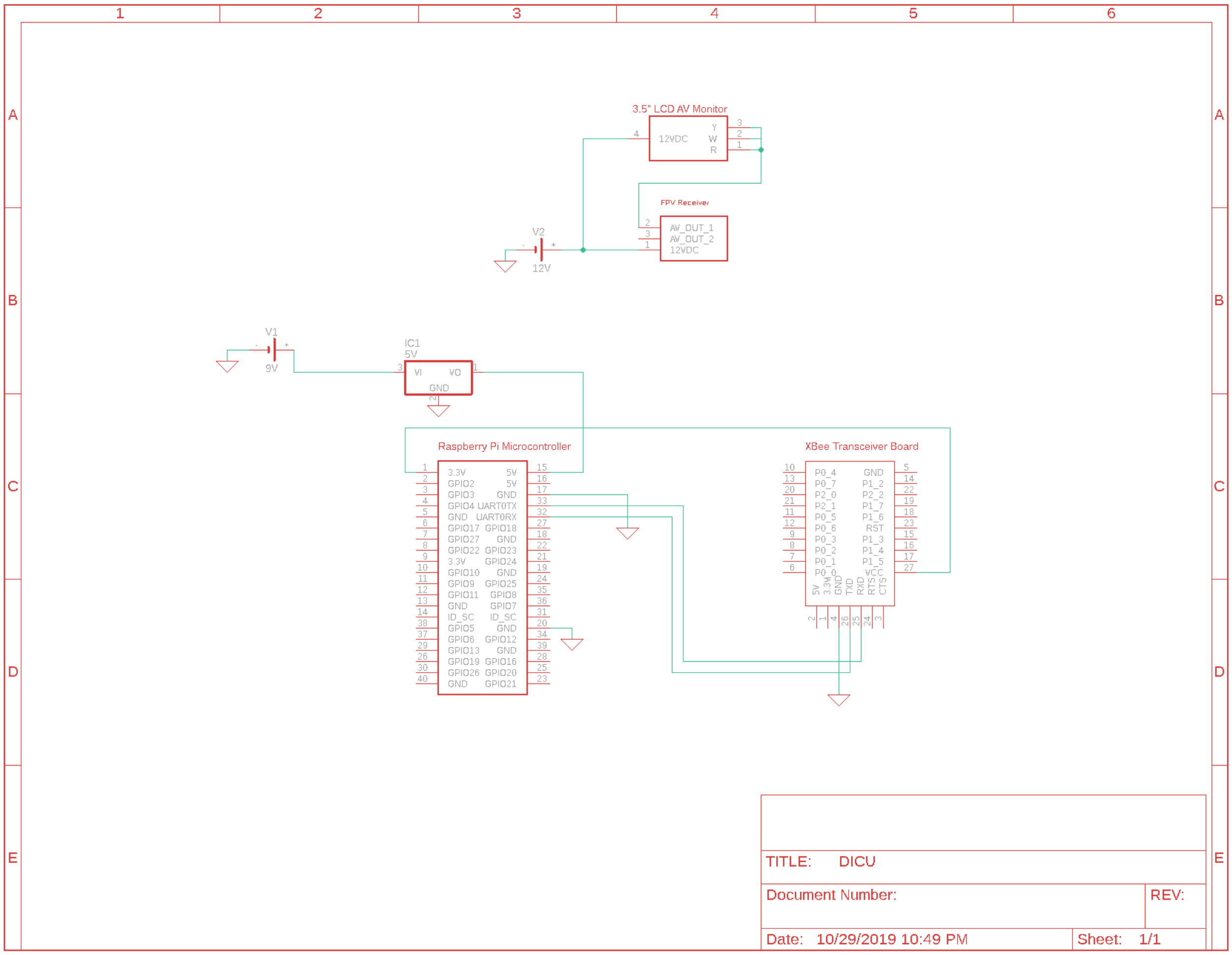

Figure 87: DICU Electrical Schematic

TEARS will function using a Long-Distance RF Receiver, controlled by an RF Transmission Controller. The receiver and the Raspberry Pi Zero W are both powered by the same power supply. The Long-Distance RF Receiver will send 3.3 Volts, via Normally-Open Relays, to the Raspberry Pi Zero W whenever the RF Transmitter specifies. When this signal is received in GPIO21, the Raspberry Pi Zero W will tell the FeatherWing Motor Controller it would like the first Stepper motor to engage. When this signal is received in GPIO20, it will tell the Motor Controller to engage the second Stepper Motor.

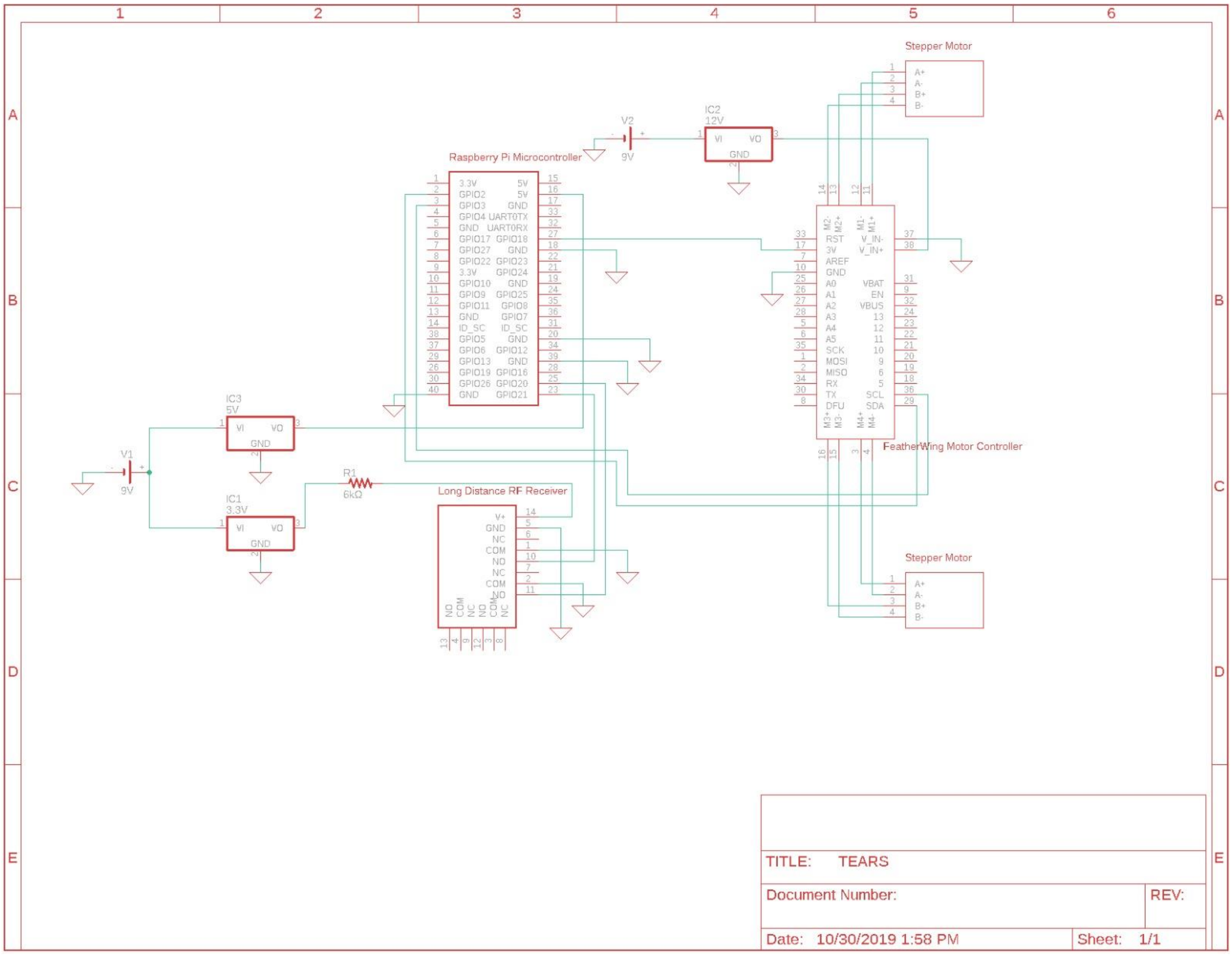

Figure 88: TEARS Electrical Schematic

4.6 Payload Mass Estimates

The total mass of the payload and TEARS was calculated using mass values obtained from datasheets for parts and electronics and the densities of materials for custom made components. The mass values are shown in Table 42 and Table 43.

Table 42: Tank Mass Totals

Tank Mass Totals			
Component	**Quantity**	**Unit Weight (oz)**	**Total Weight (oz)**
Lithium Polymer Battery	1	5.93	5.93
9V Alkaline Battery	1	2	2
Tank Drive Motor	2	7.4	14.8
Raspberry Pi Zero W	1	1.2	1.2
XBee	1	0.64	0.64
XBee Adapter	1	0.32	0.32
Prototyping Board	1	0.25	0.25

FeatherWing Motor Controller	1	0.16	0.16
Linear Voltage Regulator	1	0.13	0.13
Scoop Stepper Motor	1	2.12	2.12
Scoop	1	3	3
Chassis	1	13.25	13.25
Treads Links	60	0.705	4.23
Sprocket Wheels	4	1.32	5.28
Idler Wheels	4	2.29	9.16
Total Tank Weight			62.47
Total Tank Weight (lbs)			3.90

Table 43: TEARS Mass Totals

TEARS Mass Totals			
Component	**Quantity**	**Unit Weight (oz)**	**Total Weight (oz)**
Lead Screw	2	7.12	14.24
Lead Screw Clamping Collar	2	0.14	0.28
Lead Screw Keyhole Nut	4	0.18	0.72
Aluminum Hub Gear (48 T)	5	0.3	1.5
Pinion Gear	1	0.45	0.445
Dual Pattern Bracket	2	0.45	0.9
Single Patten Bracket	2	0.20	0.4
Raspberry Pi Zero W	1	1.2	1.2
FeatherWing Motor Controller	1	0.16	0.16
Prototyping Board	1	0.25	0.25
Reorientation Motor	1	4	4
Lead Screw Motor	1	7.76	7.76
Abytele Receiver	1	4	4
Linear Voltage Regulator	3	0.13	0.39
9V Alkaline Battery	2	2	4
Fiberglass Reorientation Plate	1	21.1	11.90
Retention Mount	2	5.57	11.14
Total TEARS Weight			63.285
Total TEARS Weight (lbs)			3.96

The total payload bay mass is shown in Table 44.

Table 44: Payload Bay Mass Total

Payload Section	**Mass (lbs)**
Tank Mass	3.90
Tears Mass	3.96
Total Mass	7.86

4.7 Payload and Launch Vehicle Interfaces

The payload and TEARS are part of the payload bay of the launch vehicle. The payload bay is located right after the nose cone of the launch vehicle. At the aft end of the payload bay a bulkhead separates the payload with the avionics bay. The bulkhead will have the base of a square head screw mounted within it that will extend to the reorientation plate of TEARS. The fore section of the payload bay will have the nose cone shoulder attached to a retention mount. The nose cone shoulder will have a lead nut with a clamping collar embedded in it that the lead screw will pass through. The GPS sled will be housed near the tip of the nose cone and the two open ends of the lead screw will be below the sled. After parachute deployment the payload bay will be connected via a shock cord to a parachute. Once the payload bay has landed on the ground and reorientation has commenced the lead screw will be actuated and the nose cone will travel off the free end of the lead screw and separate itself from the payload bay.

5 Safety

5.1 Launch Concerns and Operation Procedures

Safety risks must be addressed in all possible situations. There are safety risks associated with some materials during storage, manufacturing and transportation. Risks also exist within the operation of most systems and subsystems. These risks will be addressed directly with a corrective action to modify design, by identifying the hazard, the cause, and the effect of the hazard. This allows us to mitigate and control hazards through either design, guards/barriers/reinforcements, personal protective equipment (PPE), and procedures. Hazards caused by system or subsystem failure, human error, as well as environmental factors causing failures will be addressed in section 5.2.

5.1.1 Material Safety Data Sheet

Every chemical or material being used during any stage of manufacturing, testing, or launch from epoxy, super glue, fiberglass or black powder must have a Material Safety Data Sheet. This sheet will be different for different materials but all will require at least the following sections outlined based off of OSHA's required sections,

Identification, Hazard Identification, Composition information, First Aid Measures, Fire-Fighting Measures, Accidental Release Measures, Handling and Storing Measures, Exposure Control and PPE required, Stability and Reactivity (including possible hazards from chemical properties), Toxicological Information, Disposal requirements (if any), Transport requirements (if any) and others.

A copy of the organized collection of all MSDS will be created by both Safety Officers and an up to date copy must be held by each team during any stage of manufacturing, testing, or launching.

If a material does not have a manufacturer's comprehensive MSDS then one must be created. All relevant sections listed above must be included and completed. Below is an example of a MSDS for Rocket Epoxy that will be used in the imminent development of our subscale model as well as our full scale rocket in the future.

Table 45: MSDS of RocketPoxy

Health Hazard Data	Acute	Eyes: product is moderately irritating to the eyes.
		Skin: Product is moderately irritating to the skin and may cause skin sensitization.
		Inhalation: Because of its low volatility this product is unlikely to be an inhalation hazard.
		Ingestion: Product is designed to have a low order of acute oral toxicity.
	Chronic	Pre-existing eye, skin or lung disorders maybe aggravated by exposure to this product.
Emergency and First Aid Procedures	Eyes: Immediately flush eyes with large amounts of water for 15minutes. Get medical attention.	
	Skin: Wash affected area immediately with large amounts of soap and water. Remove and wash contaminated clothing before reuse. Contact a physician if irritation occurs.	
	Inhalation: Remove victim to fresh air and provide oxygen if breathing is difficult. Get medical attention.	
	Ingestion: Do not induce vomiting. Give large amounts of water. Calla physician immediately. Never give anything by mouth to an unconscious person.	
Reactivity Data	Stability: stable under normal storage conditions. Unstable at elevated temperatures.	
	Incompatibility: Strong oxidizing agents, strong lewis or mineral acids and strong mineral and organic bases/especially aliphatic amines.	
	Hazardous decomposition products: Phosphorus compounds, carbon oxides, aldehydes, acids, phenolics and other unknown compounds.	

Spills or Leaks Procedures	If material is spilled: Avid contact with material. Persons not wearing proper protective equipment (see below) should be excluded from the area until cleanup is complete. Dike area to prevent spill spreading and scoop up excess to recovery containers. Absorb remnant on noncombustible material such as clay and shovel into containers for disposal.
	Waste disposal method: Dispose of waste in accordance with federal, state and local regulations.
Personal Protection	Respiratory protection: Not normally necessary unless the material is being used in such a way as to produce dust, mist , vapor, fumes or smoke.

Similarly, when other chemical or hazardous materials are used, the MSDS's must be read by every team member involved. As of now, the other hazardous materials being worked with include pyrogen for the e-matches and the black powder for parachute ejection. This is to ensure personnel safety.

5.1.2 Safety Laws and Compliance

The Safety Officers will have in depth knowledge of NAR/TRA code for high power rocketry, NASA SL 2019 Safety Regulations, NFPA 1127 "Code for High Power Rocket Motors", Federal Aviation Regulations 14 CFR, Subchapter F, Part 101, Subpart C; "The handling and use of low explosives (Ammonium Perchlorate Solid Rocket Motors - APCP)", and the Code of Federal Regulation 27 Part 55: Commerce in Explosives; Fire Prevention. The Safety Officers must review the Material Safety Data Sheets (MSDS) to make sure local laws and safety procedures are followed when ordering, handling, and storing all hazardous materials and chemicals. The NAR Safety Code may be found below.

Table 46: NAR Safety Code Compliance

Item	NAR Code	Compliance
1	**Certification.** I will only fly high power rockets or possess high power rocket motors that are within the scope of my user certification and required licensing	Only the NAR mentor, George N. George, is permitted to purchase, store, and handle rocket motors.
2	**Materials.** I will use only lightweight materials such as paper, wood, rubber, plastic, fiberglass, or when necessary, ductile metal, for the construction of my rocket.	The SAP, R&N, and PAY teams are responsible for using suitable and appropriate materials on the rocketry system, to satisfy this requirement.

3	**Motors.** I will use only certified, commercially made rocket motors and will not tamper with these motors or use them for any purposes except those recommended by the manufacturer. I will not allow smoking, open flames, nor heat sources within 25 feet of these motors.	Only personnel with NAR/TRA level 2 certification will be allowed to purchase, store, and handle high-powered rocket motors.
4	**Ignition System.** I will launch my rockets with an electrical launch system, and with electrical motor igniters that are installed in the motor, only after my rocket is at the launch pad or in a designated prepping area. My launch system will have a safety interlock that is in series with the launch switch that is not installed until my rocket is ready for launch and will use a launch switch that returns to the "off" position when released. The function of onboard energetics and firing circuits will be inhibited except when my rocket is in the launching position.	The Range Safety Officer (RSO) will have the final say in determining all safety issues. The NAR mentor, team Safety Officers, and the Propulsion team will ensure that the motor igniters are properly installed and that all procedures are followed in compliance with the NAR Safety C.
5	**Misfires.** If my rocket does not launch when I press the button of my electrical launch system, I will remove the launcher's safety interlock or disconnect its battery and will wait 60 seconds after the last launch attempt before allowing anyone to approach the rocket.	All team members will be responsible for meeting this requirement and any further instructions given by the Range Safety Office during misfires. RSO will have the final say on all misfires.
6	**Launch Safety.** I will use a 5-second countdown before launch. I will ensure that a means is available to warn participants and spectators in the event of a problem. I will ensure that no person is closer to the launch pad than allowed by the accompanying Minimum Distance Table. When arming onboard energetics and firing circuits I will ensure that no person is at the pad except safety personnel and those required for arming and disarming operations. I will check the stability of my rocket	The team will not fly the rocket until the NAR mentor has reviewed the design, examined the build, and is satisfied with regards to established amateur rocketry design and safety guidelines. Members will also be responsible for meeting this requirement and any

	before flight and will not fly it if it cannot be determined to be stable. When conducting a simultaneous launch of more than one high power rocket I will observe the additional requirements of NFPA 1127.	further instructions given by the Range Safety Officer during launch. The team leaders will be accountable for determining the stability during launch.
7	**Launcher.** I will launch my rocket from a stable device that provides rigid guidance until the rocket has attained a speed that ensures a stable flight and that is pointed to within 20 degrees from vertical. If the wind speed exceeds 5 miles per hour, I will use a launcher length that permits the rocket to attain a safe velocity before separation from the launcher. I will use a blast deflector to prevent the motor's exhaust from hitting the ground. I will ensure that dry grass is cleared around each launch pad in accordance with the accompanying Minimum Distance table and will increase this distance by a factor of 1.5 and clear that area of all combustible material if the rocket motor being launched uses titanium sponge in the propellant.	All team members will be responsible for meeting this requirement and any further instructions given by the Range Safety Officer during launch. Rockets motors are not allowed to expel titanium sponges for the 2019 NASA Student Launch Competition.
8	**Size.** My rocket will not contain any combination of motors that total more than 40,960 N-sec (9208 pound-seconds) of total impulse. My rocket will not weigh more at liftoff than one-third of the certified average thrust of the high power rocket motor(s) intended to be ignited at launch.	SAP is responsible for meeting this requirement
9	**Flight Safety.** I will not launch my rocket at targets, into clouds, near airplanes, nor on trajectories that take it directly over the heads of spectators or beyond the boundaries of the launch site and will not put any flammable or explosive payload in my rocket. I will not launch my rockets if wind speeds exceed 20 miles per hour. I will comply with Federal Aviation Administration airspace regulations	All team members will be responsible for complying with this requirement. The Range Safety Officer will have the final say on wind speed and direction and rocket launch direction.

	when flying and will ensure that my rocket will not exceed any applicable altitude limit in effect at the launch site.	
10	**Launch Site.** I will launch my rocket outdoors, in an open area where trees, power lines, occupied buildings, and persons not involved in the launch do not present a hazard, and that is at least as large on its smallest dimension as one-half of the maximum altitude to which rockets are allowed to be flown at that site or 1500 feet, whichever is greater, or 1000 feet for rockets with a combined total impulse of less than 160 N-sec, a total liftoff weight of less than 1500 grams, and a maximum expected altitude of less than 610 meters (2000 feet).	Location of launch sites for flight testing will be determined in association with LIARS, in compliance with FAA/NAR/Local laws for test launches. The Range Safety Officer will have the final say in determining whether it is safe for launching. No other launch sites will be allowed
11	**Launcher Location.** My launcher will be 1500 feet from any occupied building or from any public highway on which traffic flow exceeds 10 vehicles per hour, not including traffic flow related to the launch. It will also be no closer than the appropriate Minimum Personnel Distance from the accompanying table from any boundary of the launch site.	Location of Launch sites for flight testing will be determined in association with LIARS, in compliance with FAA/NAR/Local laws for test launches. The Range Safety Officer will have the final say in determining whether it is safe for launching. No other launch sites will be allowed.
12	**Recovery System.** I will use a recovery system such as a parachute in my rocket so that all parts of my rocket return safely and undamaged and can be flown again, and I will use only flame-resistant or fireproof recovery system wadding in my rocket.	The NAR mentor, with the help of the R&N team, will be responsible for the safe flight and recovery of the launch vehicle. Safety checklists will be used by the R&N team during the integration of the recovery system to ensure compliance of safety code during launch day. The

		Range Safety Officer will have the final say.
13	**Recovery Safety.** I will not attempt to recover my rocket from power lines, tall trees, or other dangerous places, fly it under conditions where it is likely to recover in spectator areas or outside the launch site, nor attempt to catch it as it approaches the ground.	All team members will be responsible for meeting this requirement and any further instructions given by the Range Safety Officer during launch.

The Stony Brook University team will only conduct approved launches, in locations and in conditions that comply with local, state, and FAA regulations. Safety Officers are required to review, understand and brief the team on all regulations regarding unmanned rocket launches and motor handling, including Federal Aviation Regulations 14 CFR, Subchapter F, Part 101, Subpart C, Amateur Rockets, Code of Federal Regulation 27 Part 55: Commerce in Explosives; and fire prevention, and NFPA 1127 "Code for High Power Rocket Motors." Before launching or testing in an approved location both Safety Officers must approve of the weather conditions including but not limited to wind, visibility, humidity, lightning. An airbrake system with redundant avionics will be utilized to ensure the rocket does not surpass the maximum apogee altitude as agreed upon with NASA or any launch site host.

5.2 Vehicle Safety

For the purpose of vehicle safety, Failure Modes and Effects Analysis (FEMA) must be performed.

5.2.1 Failure Modes and Effects Analysis

All safety concerns must be analyzed and mitigated in a way that ensures safety with verifiable precautionary steps to either eliminate or minimize the risk. To do this our team will utilize the FEMA table shown below. Details on the Risk Assessment Code (Table 3-2), Risk Level Color Code (Table 3-3), Definitions of Severity (Table 3-4), and Definitions of Probability (3-5) are all explained in depth in our Proposal in the aforementioned locations. A separate FEMA is shown below for each team Navigation and Recovery, Structures/Aerodynamics/Propulsion, as well as Payload.

Table 47: Risk Assessment Code

Probability	Severity			
	1 – Catastrophic	**2 – Critical**	**3 – Marginal**	**4 – Negligible**
A – Frequent	1A	2A	3A	4A
B – Probable	1B	2B	3B	4B
C – Occasional	1C	2C	3C	4C
D – Remote	1D	2D	3D	4D
E – Improbable	1E	2E	3E	4E

Table 48: Risk Level Color Code Scheme

High Risk
Moderate Risk
Low Risk
Minimal Risk

Table 49: Definitions of Severity

Description	Personal Safety and Health	Facility/Equipment	Environmental
1- Catastrophic	Loss of life or a permanent disabling injury	Loss of facility, systems of associated hardware.	Irreversible severe environmental damage that violates law and regulation.
2- Critical	Severe injury of occupational related illness.	Major damage to facilities, systems, or equipment.	Reversible environmental damage causing a violation of law or regulation.
3- Marginal	Minor injury or occupational related illness.	Minor damage to facilities, systems, or equipment.	Mitigable environmental damage without violation of law or regulation where restoration activities can be accomplished.

4-Negligible	First aid injury or related occupational related illness.	Minimal damage to facilities, systems, or equipment.	Minimal environmental damage not violating law or regulation.

5.2.2 Structures, Aerodynamics & Propulsion FMEA

Failure	Causes	Effects	Pre-RAC	Mitigation	Verification Plan	Post-RAC
Drag system does not function properly during launch.	Drag system could be inaccurately adjusting roll, or fins may not be turning synchronously.	The vehicle's flight trajectory will be altered, and apogee may not be reached.	2A	Extensive testing of the launch vehicle avionics along with the VDS to ensure that the system functions as expected.	The drag system will only be used if there is a high success rate during full-scale testing.	2D
Drag system does not deploy properly during launch.	Malfunctions could occur in the electronical system or software programming.	The vehicle will overshoot the target apogee and flight trajectory might be altered.	3A	Extensive testing of the launch vehicle avionics along with the VDS to ensure that the system deploys as expected.	The drag system will only be deployed if there is a high success rate during full-scale testing.	3D
Motor mount fails to keep motor in place.	The motor could push upwards into the body of the rocket and damage internal components located above the moto	Upward thrust vector is off centered, trajectory path is compromise, apogee may not be reached, catastrophic failure possible.	1D	The motor mount is tested before flight to ensure it can withstand the forces during flight. It will also be inspected during assembly to determine whether it was installed correctly.	An assembly checklist will be followed, and full-scale testing will verify this.	1E
Fins fracture during flight due to normal in-flight forces.	Fins are sheared off due to incorrect epoxy choice or method of installation.	The vehicle trajectory will be drastically altered and become unstable.	2D	Fin fillets and adhesive attachment points are inspected for fractures before and after flight.	Simulations will verify the structural integrity of the fins before testing. Assembly checklist will include inspecting the fins.	2E
Airframe fails during launch and in-flight.	The forces during flight exceed those that can be handled by the airframe material.	The launch vehicle breaks apart during flight resulting in catastrophic failure.	1D	The vehicle will be designed with the appropriate materials to handle the stress in-flight.	Simulations along with full-scale test flights will verify that the airframe can withstand	1E

					launch and flight forces.	

5.2.3 Navigation & Recovery FMEA

Failure	Causes	Effects	Pre-RAC	Mitigation	Verification Plan	Post-RAC
Unignited ejection charges ignites pre-assembly.	Improper handling of black powder, such as storing in a container, allowing it to be vulnerable to static, storing in heated conditions, too much vibration during travel, etc	Explosion of ejection charges and possibly engine causing possible harm to surrounding people and damage to property.	1C	Allowing only NAR certified personnel to handle the motor and black powder, abiding by the safety agreement. Storage containers must not create static and be located in facilities at relatively low temperatures.	The NAR mentor will handle the purchase, sizing, storage, and installation of the motor and black powder charges. Regardless, all team members must read the MSDS of black powder.	1D
Premature separation due to drag forces	Incorrectly sized main and drogue shear pins are sheared due to larger drag forces generated by lower section of the vehicle relative to the upper section, causing separation after motor burn out.	Parachutes deployed before apogee will withstand excess forces while the rocket travels at high speed, ripping apart the body of the rocket and causing catastrophic failure.	1B	Shear pins must be placed and sized correctly for the drogue and main parachutes.	Simulations and calculations of the launch related to drag caused by fins and other such systems will be carried out in order to determine the forces the shear pins must be able to handle. Thus, the correct shear pin configuration can be ascertained. Ground and sub-scale tests will further verify this.	1C
Premature deployment due to unwanted altimeter triggering	RF signals from tracking electronics triggers altimeters.	Parachutes deployed before apogee will withstand excess forces while the rocket travels at high speed, ripping apart the body of the rocket and causing	1C	The avionics bay that houses the altimeters will be physically separated from the tracking electronics and	During ground tests, the system as a whole will be turned on in order to determine if the aluminum foil serves its purpose in blocking the RF signals that could trigger the altimeters.	1E

		catastrophic failure.		aluminum foil shall line the inside of the avionics tube to create a Faraday cage that will block RF signals that may trigger the altimeters.		
Premature separation due pressure differential	Incorrectly sized and distributed altimeter pressure portholes cause uneven pressure in the altimeter and trigger it prematurely.	Parachutes deployed before apogee will withstand excess forces while the rocket travels at high speed, ripping apart the body of the rocket and causing catastrophic failure.	1A	Pressure portholes for avionics bays will be researched for correct sizing and be spaced evenly in the avionics bay to minimize the pressure differential.	Air pressure relief holes will be checked for their size, and the sub-scale flight tests will be able to demonstrate if they are spaced and sized correctly.	1D
Vehicle is not tracked after certain altitude is reached.	The tracking electronics wiring comes loose due to launch vibrations, or RF signals are too weak for the ground receiver due to heavy cloud obstructions.	Vehicle cannot be found if GPS tracking fails, may drift too far, or take too long to land due to overshoot.	2C	The GPS tracking system circuit can be tied down with cable ties or other fasteners in order to prevent the wiring from coming loose.	The tracking electronics can be tested on the ground if the wiring will come loose with a mechanical shaker, which can simulate the vibrations of the rocket during flight.	2D

5.2.4 Payload FMEA

Failure	Causes	Effects	Pre-RAC	Mitigation	Verification Plan	Post-RAC
Payload becomes loose in payload bay.	Payload mounting system does not immobilize rover during flight.	Payload is damaged, not able to exit payload bay properly due to not utilizing TEARS correctly, and can disrupt projected flight path.	2D	Payload will be mounted in x,y and z direction using geometric fit, pins, and lead screws.	Rover mounting will be tested during Full scale test flight.	2E

TEARS or the payload breaks during landing.	Impact with the ground causes stress within the components of TEARS or the rover that cause them to fracture.	Rover and/or TEARS catastrophically fails and the mission cannot be completed.	1D	TEARS and the Rover will be reinforced with heavy duty mounting plates that will withstand projected impact forces.	Rover and TEARS strength and ability to withstand impact forces will be tested during full scale test flight.	1E
Wires controlling TEARS and the rover become disconnected during flight or lan ding.	Forces during flight or landing cause wires to become disconnected that control any aspect of TEARS or the rover including but not limited to the raspberry pi, transponder, receiver, or battery connections.	TEARS or the Rover are not damaged but not able to complete the mission, due to inability to either receive, send, process information or become disconnected from the power supply.	1C	All electronics will be soldered in place and encased in a heat shield. Electrical retention tape as an extra measure will also be applied before launch.	Ability of the electronic connections to stay wired correctly will be tested in the full scale test flight	1D

5.3 Environmental Concerns

Failure	Causes	Effects	Pre-RAC	Mitigation	Verification Plan	Post-RAC
Launch vehicle/ electronics become damaged due to rain/wet ground landings.	Water sensitive part of the vehicle like the airframe, motor and the electronics come in contact with water.	The payload or avionics electronics may be damaged and structural integrity of the airframe will be compromised due to epoxy, circuits, and the like being damaged due to water vulnerability.	2C	The mechanical packaging must be designed to adequately seal electronics from wet environments. In addition, epoxy must be used sparingly and in sequestered locations to reduce chance of exposure. Tests and launches will not be performed in heavy rain.	The packaging of the electronics will be tested on the ground and during launches. If such tests occur during light rain, the parts will be inspected for damage, and changes will be made to design if there are such signs.	2E
Unignited ejection charges ignites pre-assembly.	Improper handling of black powder, such as storing in a container, allowing it to be vulnerable to static,	Explosion of ejection charges and possibly engine causing fires, damage to property, launch fields, other	1C	Only NAR certified personnel will handle the motor and black powder, abiding by the safety agreement.	The NAR mentor will handle the purchase, sizing, storage, and installation of the motor and black powder charges. Regardless, all	1D

	storing in heated conditions, too much vibration during travel, etc	team's launch vehicles, etc.		Storage containers must not create static and be located in facilities at relatively low temperatures.	team members must read the MSDS of black powder.	

5.4 Overall Project Risk Assessment and Mitigation

Failure	Causes	Effects	Likelihood /Impact Before	Mitigation	Verification Plan	Likelihood/ Impact
Insufficient funding.	Not enough funding-raising conducted, or sponsorships acquired.	Design choices that decrease overall efficiency of our design.	High/ High	The Deputy Project Lead will spearhead fundraising efforts to increase funds available to the team.	A detailed budget list will be maintained.	Medium/ Medium
Falling behind on schedule.	Inability of members to meet schedule deadlines.	Inability to conduct necessary launches for the competition and risk of project failure.	High/ High	Weekly meetings are held with minutes taken to ensure all subsystems remain on task.	The tasks and minutes are recorded in documents available to everyone on the team.	Medium/ High
Conflicts between team members.	Disagreements can arise between design choices and direction of the vehicle.	Delays in the project timeline and risk of project failure.	Medium/ High	Team members will communicate with each other through electronic devices and during bi-weekly meetings to encourage constructive discussion. Mentors and such may also be contacted to provide insight in settling these discussions.	Discussions during meetings will be recorded in documents available to everyone on the team.	Low/High
Unavailable parts or resources.	Parts are lost in transit or are ordered too late.	Parts are not available for rocket assembly, which removes the ability to conduct tests	Medium/ High	Team members will select their parts in advance and document them. When designs are approved, they can order the parts more easily.	Team members will keep online tables which detail each part required for their system as well as links for quickly finding	Low/High

		and launches on time.			sites to purchase materials.	
Unavailable launch dates.	Weather in the Northeast and limited launch window.	Delays in the project timeline, inability to qualify for competition, and risk of project failure.	Medium/ High	Team members will communicate with one another to finish their systems of the rocket in a timely manner and attempt to coordinate travel to locations at which launches may be performed.	Dates and locations of launches will be recorded and tasks lists will be overviewed during team meetings.	Medium/ Medium

6 Project Plan

6.1 Requirements Verification

Item ID	Verification Method	Verification Plan
General Requirements		
1.1	Inspection	Stony Brook University Rocket team consist exclusively of students who are working on this project as part of their senior design. All work will be completed by students with the exception of motor assembly and handling of black powder ejection charges.
1.2	Demonstration	The project plan is constantly being updated and discussed during team bi-weekly meetings to ensure that all project milestones, personal assignments, events and checklists are followed.
1.3	Inspection	Every team member will be asked about their citizenship status and a list of foreign nationals is to be submitted to NASA by PDR.
1.4	Inspection	A list of all team members and adult educators attending launch week activities is going to be submitted to NASA by CDR.
1.5	Demonstration	Every educational outreach event will be documented following STEM Engagement Activity Report template provided by NASA.
1.6	Demonstration	Social media accounts will be established and links will be delivered to NASA by October 25th.
1.7	Inspection	Team lead will send all the deliverables to the NASA team by the deadline and verify it with confirmation email from NASA project management team.
1.8	Inspection	All deliverables will be converted to PDF format before submission to NASA.

1.9	Inspection	Every report will have table of contents including major sections and their respective sub-sections.
1.10	Inspection	Every report will have page numbers at the bottom of each page.
1.11	Demonstration	All equipment to have successful video teleconference will be demonstrated during Kickoff video session.
1.12	Demonstration	The launch vehicle will utilize launch pads provided by Student Launch's launch services provider.
1.13	Inspection	The team has identified a mentor who meets all the requirements in the Proposal.
Vehicle Requirements		
2.1	Demonstration Testing Analysis	The launch vehicle will reach the target altitude by careful selection of motor, control of vehicle's mass, and overall shape of the rocket. The vehicle will be analyzed using OpenRocket simulations and tested during Vehicle Demonstration Flight.
2.2	Analysis	The target altitude will be identified based on the collected data from simulations and launch vehicle design.
2.3	Demonstration	One commercially available altimeter will be set aside for recording official altitude purposes
2.4	Demonstration Test	The launch vehicle will be designed to ensure it can be reused and launched on the same day.
2.5	Demonstration	The launch vehicle will have 3 independent sections.
2.5.1	Demonstration	Coupler/airframe shoulders will be 6 inches in length.
2.5.2	Demonstration	The nosecone shoulder will be 6 inches in length.
2.6	Demonstration Testing	The launch vehicle will be designed to ensure that it can be assembled in under 2 hours. The assembly time will be timed during Vehicle Demonstration Flight.
2.7	Demonstration Testing	Appropriate battery and the overall launch vehicle design is going to be chosen to remain in launch-ready configuration for at least 2 hours.
2.8	Demonstration	Standard 12-volt DC firing system is going to be utilized.
2.9	Demonstration	All electronics will be housed internally and only launch services provider equipment will be used to initiate launch.

2.10	Inspection	The motor certified by NAR and TRA will be used.
2.10.1	Inspection	The final motor selection is going to be declared by CDR.
2.10.2	Inspection	Any motor changes after CDR will be approved by NASA Range Safety Officer.
2.11	Demonstration	Launch vehicle motor will be a single stage motor.
2.12	Inspection	The motor will be L-class or lower.
2.13	Inspection	The launch vehicle will have no pressure vessels.
2.14	Analysis	The launch vehicle will be analyzed with OpenRocket software to ensure that the static stability margin is at least 2.0.
2.15	Inspection	Any protuberance will be located aft of the burnout CG.
2.16	Analysis	OpenRocket software will be used to determine exit velocity.
2.17	Demonstration	Subscale model launches have been scheduled to take place before December 1st.
2.17.1	Demonstration	Subscale model will be an exact scaled down shape of the launch vehicle with the same corresponding CG and CP.
2.17.2	Demonstration	Subscale model will be equipped with altimeter.
2.17.3	Demonstration	Subscale model will be a newly built vehicle.
2.17.4	Demonstration	Subscale model launch will be documented and flysheet information will be included in CDR report.
2.18.1	Demonstration	Vehicle Demonstration Flight will be performed to ensure that all the full-scale vehicle criteria are met.
2.18.2	Demonstration	Payload will be launched and recovered in the full-scale launch vehicle to ensure that all payload criteria are met.
2.19	Demonstration	FRR Addendum will be submitted if NASA-required Vehicle Demonstration Re-flight will take place after the FRR deadline.

2.20	Demonstration	Team contact information will be written on the rocket airframe.
2.21	Demonstration	All Lithium Polymer batteries will be enclosed in protective cases and brightly colored.
2.22	Demonstration	The launch vehicles will not utilize prohibited techniques outlined by NASA in section 2.22.
		Recovery System Requirements
3.1	Demonstration Testing	The launch vehicle will deploy its drogue parachute at apogee and the main parachute will be deployed later at the set altitude.
3.1.1	Demonstration Testing	The main parachute deployment altitude will be above 500 feet.
3.1.2	Demonstration Testing	The drogue parachute will be deployed within 2 seconds of reaching apogee.
3.1.3	Inspection	Motor will not be ejected.
3.2	Testing	Ground ejection tests will take place before subscale and full-scale launches.
3.3	Demonstration	Parachutes will be chosen to ensure that each independent section of the launch vehicle will have kinetic energy at landing under 75 ft-lbf.
3.4	Inspection	The launch vehicle will have a redundant altimeter.
3.5	Inspection	Each altimeter will have an independent power supply.
3.6	Inspection	Each altimeter will be armed with a dedicated mechanical switch accessible from the exterior of the rocket airframe.
3.7	Inspection	Each arming switch have a locking mechanism.
3.8	Inspection	Recovery and payload bay will be independent sections and have a separate electrical circuits.
3.9	Inspection	Removable shear pins will be used for all parachutes.
3.10	Testing Analysis	Delayed main parachute deployment will limit the drift of the launch vehicle to 2,500 ft radius.

3.11	Testing Analysis	Descent time will be timed during full-scale test flights and estimated in MATLAB.
3.12	Inspection	Tracking device will be attached to the vehicle.
3.12.1	Inspection	Payload will be attached with a tracking device.
3.12.2	Inspection	All tracking devices will be inspected before the official flight.
3.13	Inspection Testing	All recovery system electronics will be properly shielded. Recovery system altimeter will be located in a separate compartment.
Payload Experiment Requirements		
4.1	N/A	N/A
4.2	Demonstration	Payload will be designed that is capable being launched in a high power rocket, landing safely, and recovering simulated lunar ice from one of several locations on the surface of the launch field.
4.3.1	Inspection	All hardware will be housed inside the launch vehicle airframe.
4.3.2	Demonstration	The rover will recover sample material from one of the five recovery areas.
4.3.3	Demonstration	The recovered ice sample will be at least 10 milliliters.
4.3.4	Demonstration	The rover will safely store and transport recovered material 10 feet away from the recovery area.
4.3.5	Inspection	Team will abide by all FAA and NAR rules and regulations.
4.3.6	Inspection	Payload will utilize no black power or other energetics.
4.3.7	Inspection Testing	Payload will be securely attached to the launch vehicle until deployment. No excessive shear pins will be used in payload deployment mechanism.
4.4	N/A	N/A
Safety Requirements		

5.1	Inspection	Safety checklist will be generated by our team's safety officer and will be included in the FRR report. This checklist will be used during the LRR and any other launch day operations.
5.2	Inspection	Our team safety officer is Jonathan Sossover. Donald Stickevers is deputy safety officer.
5.3.1	Inspection	The safety officer will monitor all team activities with an emphasis on safety.
5.3.2	Demonstration	Safety officer will implement procedures and checklists to be used during construction, assembly, launch and recovery.
5.3.3	Demonstration	Safety office will keep detailed records of team's hazard analyses, failure modes analyses, procedures, and MSDS/chemical inventory data.
5.3.4	Demonstration	Safety office will assist in the writing and development of the team's hazard analyses, failure modes analyses, and procedures.
5.4	Demonstration	Team will abide by all the rules and regulations of the local rocketry club RSO.
5.5	Inspection	Team will abide by all rules set forth by the FAA.

6.2 Team Derived Requirements

6.2.1 Vehicle Derived Requirements

Description	Verification Method	Verification Plan
The launch vehicle will not surpass a weight of 50 lbs.	Inspection	The weight of the rocket affects our motor selection and maximum height above ground level (AGL). Lightweight materials will be chosen, and a strict mass budget will be enforced for all subsystems.
The vehicle will reach the target apogee of 4,500 ft with the payload and active VDS.	Testing Demonstration	Simulations will be produced in OpenRocket and hand calculations will be conducted to verify the flight profile. A full-scale launch with the payload and VDS prior to the competition will be completed.
The launch vehicle will reach the target apogee within 250 ft.	Testing	A subscale launch that is closely modeled after the full-scale launch will be used to verify the apogee during flight. A tolerance of ±250 ft is specified.

The vehicle will withstand the launch, flight and landing forces.	Testing Analysis	FEA and CFD simulations along with testing will ensure that the airframe and fins do not rupture during flight.

6.2.2 Recovery Derived Requirements

Description	Verification Method	Verification Plan
The telemetry bay will not interfere with payload deployment.	Inspection	The Recovery team will work closely with the Payload team in order to ensure their designs work in conjunction with one another.
The electronic tracking equipment will not have its signals blocked by sections of the rocket.	Inspection Testing	The telemetry bay will not be surrounded in metal or be housed in a section of airframe or nosecone that is made of carbon fiber or is painted with metallic paint, which would block RF signals of the GPS transmitter. Ground tests and test flights will also verify the transmission of RF signals to the ground receiver.
The electronic tracking equipment will send data to a ground receiver, which will not receive interference from other electronics tracking equipment on other rockets.	Inspection Testing	The tracking system will be connected or coded in such a way that the receiver in use by the SBU team only receives data from the proper GPS tracking device.
The parachutes will not only be deployed by the expansion of hot gases alone but will be assisted by a mechanical ejection mechanism as well.	Inspection Testing	Parachute deployment will be assisted by pistons that will push the parachutes out of their respective bays. Ground testing and flight tests will ensure the system works.
The parachutes will not be adversely affected by hot ejection gases.	Inspection	The parachutes will be protected by an object or device as nylon parachutes are susceptible to burning or melting.

6.2.3 Payload Derived Requirements

Requirement	Verification Method	Verification Plan
The rover must be reoriented to drive orientation before full deployment.	Demonstration	The reorientation system will be activated prior to full deployment of the rover.
The exiting and reorientation system, and the rover will be remotely controlled.	Demonstration	RF transmitters and receivers with appropriate range requirements will be used to control TEARS and the rover.
The rover must have the ability to traverse difficult terrain.	Testing	The tank tread design will be driven on various terrains under wet and dry conditions.
The sample collection unit must have the ability to perform collection multiple times	Demonstration	The sample collection scoop will have a generated path that allows transfer of collected sample to a storage container so that collection can happen again if necessary.
The payload batteries must be able to provide power to all electronics for a minimum of 45 mins.	Testing	Different batteries will be put through timed test under launch ready configuration set up to ensure the battery will last tat load
The payload must fit within a 6 inch diameter.	Demonstration	Electronics and batteries will be sized to optimize space within the rover.

6.3 Budget

6.3.1 Overall Budget

The budget is divided among the three subsystems: Structures, Aerodynamics & Propulsion (SAP), Navigation & Recovery (NNR), and Payload (PAY). The total cost of transportation and housing at competition is also considered in the overall budget.

Table 50: Overall Budget Distribution

Section	Amount
SAP	$2000
NNR	$1200
PAY	$475
Outreach	$100
Travel	$2000
Total:	**$5775**

A more detailed budget breakdown is given in the following sections.

6.3.2 SAP Budget

Table 51: Detailed SAP Budget

Item	Quantity	Unit Cost	Subtotal
Variable Drag System	1	$ 100.00	$ 100.00

L1420R-P	3	$ 279.99	$ 839.97
75mm LOC MMT	1	$ 16.00	$ 16.00
Aero Pack 75mm Retainer - L	1	$ 56.67	$ 56.67
L10 Fiberglass Fins	1	$ 20.00	$ 20.00
G12 Fiberglass Filament Wound Tube	2	$ 217.14	$ 434.28
G5000 ROCKETPOXY (2 Pint)	1	$ 43.75	$ 43.75
Metal Tip Fiberglass Nose Cone	1	$ 149.95	$ 149.95
Cameras	3	$ 40.00	$ 120.00
Raw Materials	1	$ 100.00	$ 100.00
General Hardware	1	$ 70.00	$ 70.00
Shipping Overhead	1	$ 40.00	$ 40.00
Total:			**$1,990.62**

6.3.3 NNR Budget

Table 52: Detailed NNR Budget

Item	Quantity	Unit Cost	Subtotal
Altimeter	2	$ 54.95	$ 109.90
Recovery Harness	1	$ 47.00	$ 54.00
U-Bolt	2	$ 6.66	$ 13.32
E-Match Starter Kit	1	$ 80.25	$ 80.25
GPS Chip	1	$ 9.80	$ 9.80
GPS Transmitter	1	$ 324.00	$ 324.00
Main Parachute	1	$ 348.15	$ 348.15
Drogue Parachute	1	$ 64.00	$ 64.00
Nomex Blanket	1	$ 54.00	$ 54.00
Nuts (100 pk)	1	$ 16.58	$ 16.58
Threaded Rods	2	$ 5.68	$ 11.36
ACDelco 9 Volt Batteries (12 pk)	1	$ 18.12	$ 18.12
General Hardware	1	$ 50.00	$ 50.00
Shipping Overhead	1	$ 50.00	$ 50.00
Total:			**$1,203.48**

6.3.4 PAY Budget

Table 53: Detailed PAY Budget

Item	Quantity	Unit Cost	Subtotal
Lithium Polymer Battery	1	$ 21.99	$ 21.99
Alkaline Batteries (5 pk)	1	$ 0.49	$ 0.49
Breadboard (4 pc)	1	$ 9.86	$ 9.86

Prototyping Boards (36 pc)	1	$ 11.99	$ 11.99
Resistors (37 pc pack)	1	$ 8.99	$ 8.99
Jumper Wires (120 pc)	1	$ 5.79	$ 5.79
Motors	2	$ 14.49	$ 28.98
Servo Motor	2	$ 16.99	$ 33.98
MicroSD	2	$ 4.00	$ 8.00
Raspberry Pi Zero Starter Kit	1	$ 27.00	$ 27.00
Xbee	1	$ 54.00	$ 54.00
FeatherWing Motor Controller	1	$ 23.00	$ 23.00
Rover camera	1	$ 17.00	$ 17.00
Bluetooth adapter dongle	2	$ 13.98	$ 27.96
Stepper Motor	1	$ 18.00	$ 18.00
Tank Motor Controller	1	$ 5.39	$ 5.39
Tank Tread	1	$ 99.95	$ 99.95
TEARS Motor Controller	1	$ 6.89	$ 6.89
7’’ Touchscreen	1	$ 50.00	$ 50.00
3.5’’ AV LCD Monitor	1	$ 16.00	$ 16.00
Total:			**$ 475.26**

6.4 Funding

The main source of funding that will go into this project will come from the money provided by Department of Mechanical Engineering to senior design teams. Each student is provided $280 to cover their senior design project expenses. Our team consist of 13 seniors, which gives us a total of $3640. Another source of funding is from the College of Engineering and Applied Sciences (CEAS). CEAS has played a crucial role in the past to help obtain third party sponsorships. We expect to receive around $2000 from local companies and CEAS sponsoring this project.

Department of Mechanical Engineering historically has been very supportive of competitive projects and thus we expect to receive $500 both during Fall and Spring semester, totaling $1000 for the entire project. And the last avenue our team plans on exploring is grants. We are in the process of applying to numerous grants such as NASA NY Space Grant. We expect to receive around $2000 total from grants throughout both Fall and Spring semesters. Table 54 summarizes the funding Stony Brook Rocket Team expects to receive for this project.

Table 54: Expected Funding Sources

Source	Amount
Senior Design Funding	$3640
CEAS	$2000
Department of Mechanical Engineering	$1000

Grants	$2000
Total:	**$8640**

6.5 Timeline

Our team has divided the project into five main phases. In the first proposal phase our team will focus on idea generation and determining team structure. PDR phase mainly consist of creating a design that meets all the general, vehicle, and payload requirements of the competition. CDR phase ensures that the previously created design is ready to fabricate. If it is not ready, necessary changes to the design are made to meet fabrication criterion. FRR phase tests vehicle and payload readiness for the competition. And finally, the Launch Phase mainly consist of Student Launch competition week and post launch assessment review. A detailed project timeline is shown in the following figure.

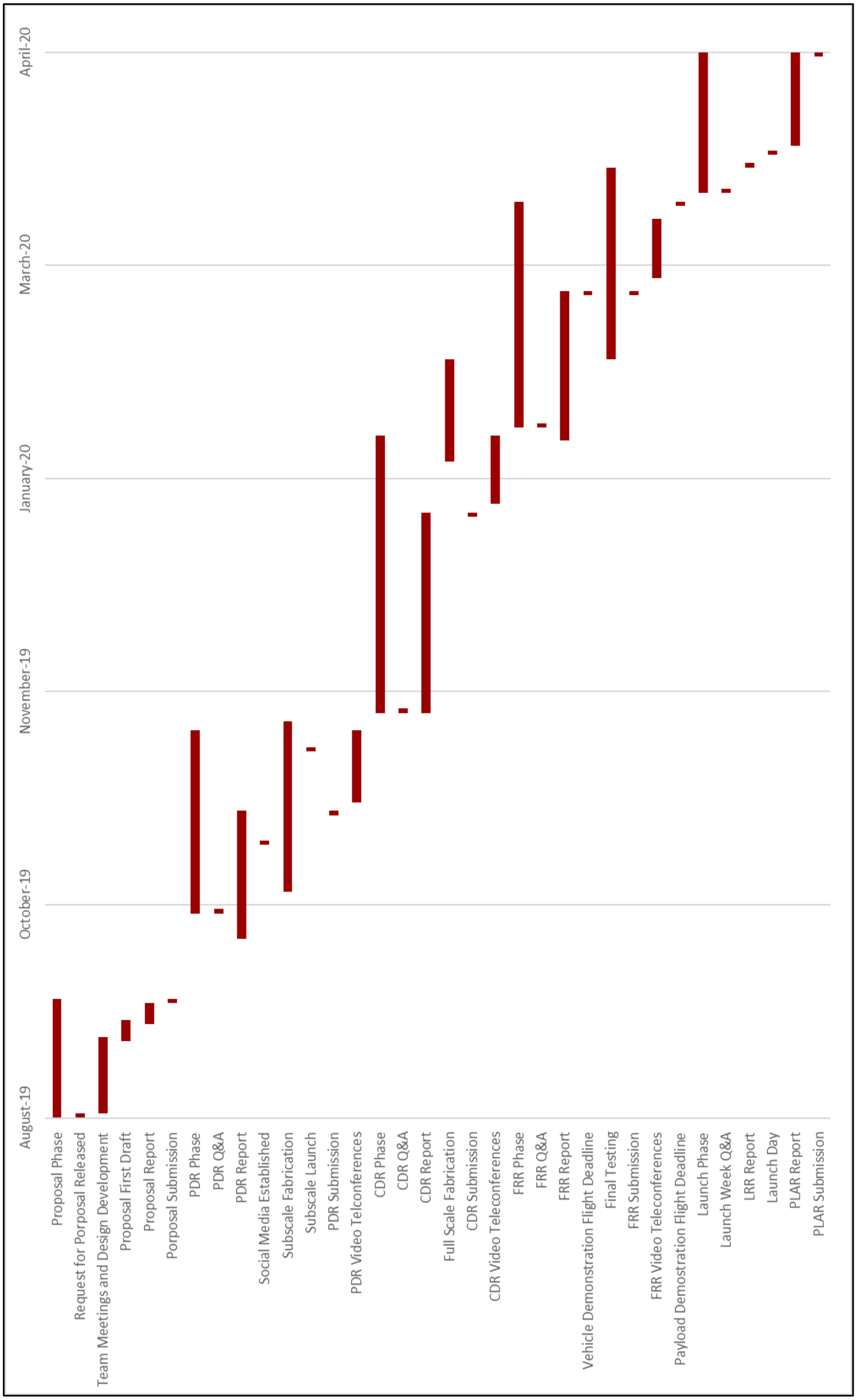

Figure 89: Project Gantt Chart

7 Appendix

7.1 List of Figures

7.2 List of Tables