Carnegie Mellon
Rocket Command

Carnegie Mellon Rocket Command
Carnegie Mellon University

Project SCOTTIE: Simultaneous Control Of Target Trajectory and Integrated Electronics

NASA University Student Launch 2018-2019
Preliminary Design Review
November 2, 2018

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5000 Forbes Ave
Pittsburgh, PA 15289

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1 Summary of Preliminary Design Review

1.1 Team Summary

Table 1: Team Summary

School Name	Carnegie Mellon University
Mailing Address	5032 Forbes Ave, SMC 5993, Pittsburgh, PA, 15289
Team Name	Carnegie Mellon Rocket Command
Project Title	SCOTTIE: Simultaneous Control Of Target Trajectory and Integrated Electronics
Project Lead	Michael Messersmith
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NAR, TRA Sections	NAR Section #473, TRA Section #1
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1.2 Launch Vehicle

The launch vehicle, SCOTTIE, is expected to be 115 in long with a diameter of 6.17 in. The preliminary dry mass is 33.81 lbm. Our primary motor choice is the CTI L1350, which brings our wet mass to 41.69 lbm. Our secondary motor choice is the Aerotech L1420, which brings our wet mass to 44.94 lbm. The official target apogee of our launch vehicle will be 5100 ft. The recovery system will include a SkyAngle Classic II 32” drogue parachute deployed 2 seconds after apogee, and a SkyAngle CERT-3 XXL main parachute deployed at 500 ft.

1.3 Payload Summary

CMRC will be participating in the Deployable UAV/Beacon Delivery Challenge. The UAV will be small form factor quadcopter or fixed wing that will fit tightly into the rocket coupler. Then, after being autonomously ejected from the rocket, the UAV will be manually flown from the launch site. Using a computer assisted overlay (indicating key points in the streamed image), the pilot will search for the tarp and fly the UAV above it. Then the pilot will actuate the servo and drop the beacon over the tarp. The UAV will feature a simple flight controller and manual piloting with autonomous assistance.

2 Changes made since Proposal

2.1 Changes made to Vehicle Criteria

The launch vehicle has grown from 108” to 115” in length between the proposal and PDR. This increased length was given to accommodate the packing volume of the SkyAngle CERT-3 XXL, which requires 16” of length in a 6” diameter airframe tube. In addition, the motor mount tube was grown from 30” to 31” long in order to accommodate potential future motor changes, which may be up to 31” long. The nose cone was changed from a 4:1 elliptical design to a 4:1 Ogive design due to the results of a study which showed that the 4:1 Ogive maximized the apogee of the launch vehicle. The number of fins was increased to 4 in order to shrink the planform and simplify manufacturing.

The Apogee Targeting System (ATS) has also been modified. Notable changes include a new method of measuring axial speed of the rocket as well as consideration of different aerodynamic designs of the drag-inducing flaps. Specifically, we plan to most likely measure axial speed of the rocket using the same IMU used to measure the attitude of the rocket. Additionally, we have decided to consider three different flap topologies: solid, gridded, and pin. The advantages and disadvantages of these topologies have been addressed in the ATS section.

The recovery system has also been modified, with main parachute growing from the SkyAngle CERT-3 XL to the XXL, and the drogue parachute growing from the SkyAngle Classic II 24” to the 32”. The parachute sizes were increased in order to accommodate the added mass of the larger launch vehicle while still meeting the landing kinetic energy requirement. In addition, the recovery bay altimeter sled has undergone a redesign in order to make the system more efficient and compact.

2.2 Changes made to Payload Criteria

The payload bay has been moved from the lower airframe to the upper airframe, just below the nose cone, due to deployment concerns. The lower airframe is angled downwards at landing due to the fins propping up the aft end, which would cause the UAV to be deployed at a downward angle into the dirt. Moving the payload toward the nose cone can avoid this problem.

The deployment system has also been changed from using ejection charges to remove the payload bulkhead to using stepper motors that drive lead screws which slowly push the contents out of the payload bay. This change will ensure a more controlled deployment process and reduce risk of damage to the UAV.

The UAV options have expanded to include 3 types of systems including two quadcopters and a fixed wing. Of the two quadcopters, one will feature a rolling cage and another featuring expanding arms. The other UAV is a simple efficient, fixed-wing design.

The originally proposed onboard system architecture written in QNX was database driven, which will prove too slow for our purposes. Functions of our UAV system will include: CV and GPS overlay, gyro-based localization, and, (if we choose piloted flight) a standard composite video feed via a fast C++ program as well as target detection to process and highlight the FEA for the pilot.

2.3 Changes made to Project Plan

A new STEM Engagement was added at the Pittsburgh Moon District Elementary School, planned for November 16th, which would involve giving a rocketry presentation to around 200 1st - 4th grade students. This event was added due to a connection that was made when planning the STEM event at the CMU Children's School.

The budget was modified to account for additional hardware costs expected by the Payload and Avionics team respectively. Likewise, we added new funding sources; the Avionics team is expected to receive a $1000 research grant to assist with the development of the ATS, and the crowdfunding goal was increased to $5000 to cover increased travel expenses of our expanding team.

3 Vehicle Criteria

3.1 Launch Vehicle

3.1.1 Overview

The launch vehicle, named SCOTTIE, will be 115 in long with a diameter of 6.17 in, constructed primarily out of G12 fiberglass. The nose cone is a G12 fiberglass 4:1 Ogive design which has removable ballast near the tip. The main parachute (SkyAngle CERT-3 XXL) is stored in the upper airframe, and the drogue parachute (SkyAngle Classic II 28") is stored in the lower airframe. The GPS (Eggfinder) is attached to the inside edge of the middle airframe. The motor (CTI L1350) is stored in a 75mm motor mount tube with appropriate motor casing and thrust plate. Four trapezoidal fins connect to the motor mount tube at the aft end of the lower airframe.

Separation points occur at the payload bay and ATS bay during main and drogue ejection charges respectively. Both of these shoulders are 6 in long.

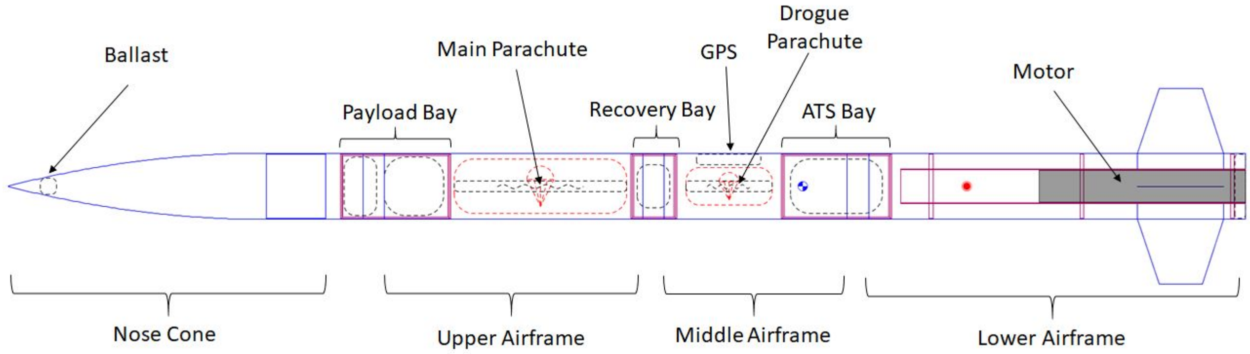


Figure 1: SCOTTIE Launch Vehicle Design

Table 2: SCOTTIE Launch Vehicle Properties

Parameter	Value
Length	115 in
Diameter	6.17 in
Dry Mass	541 oz (33.81 lb)
Wet Mass (CTI L1355)	667 oz (41.69 lb)
Airframe material	G12 Fiberglass
Airframe thickness	0.17 in
Coefficient of Drag (ref. Diam = 6.17 in)	0.35

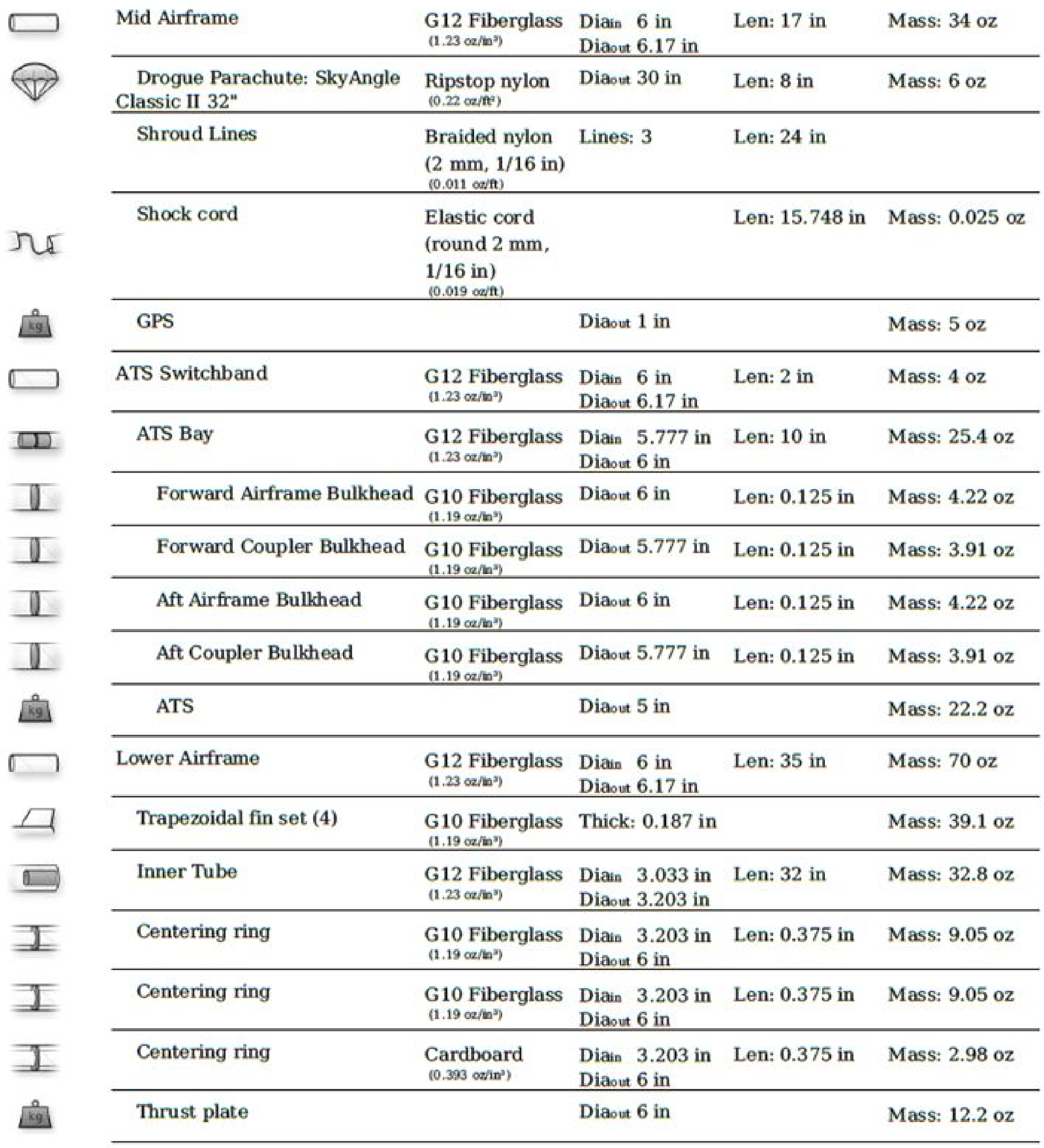
The launch vehicle will have three independent sections. The upper section consists of the nose cone and payload bay. The middle section consists of the upper airframe, recovery bay, and middle airframe. The lower section consists of the ATS bay and the lower airframe. Separation points occur at the payload bay shoulder and the ATS bay shoulder

Table 3: Independent Section Masses

Section	Mass (oz)
Upper Section	99.13
Middle Section	199.7
Lower Section (No motor)	242.8
Lower Section (With CTI L1350)	368.8
Lower Section (With CTI L1350, after burnout)	313.4

Below is the breakdown of the mass estimates for all of the components of the launch vehicle.

Nose cone	G12 Fiberglass (1.23 oz/in^3)	Ogive	Len: 24 in	Mass: 28 oz
Ballast		Dia$_{out}$ 1.5 in		Mass: 0 oz
Body tube	Cardboard (0.393 oz/in^3)	Dia$_{in}$ 6.013 in Dia$_{out}$ 6.17 in	Len: 9 in	Mass: 5.33 oz
Payload Switchband	G12 Fiberglass (1.23 oz/in^3)	Dia$_{in}$ 6 in Dia$_{out}$ 6.17 in	Len: 2 in	Mass: 4 oz
Payload coupler	G12 Fiberglass (1.23 oz/in^3)	Dia$_{in}$ 5.777 in Dia$_{out}$ 6 in	Len: 10 in	Mass: 25.4 oz
Aft Coupler Bulkhead	G10 Fiberglass (1.19 oz/in^3)	Dia$_{out}$ 5.777 in	Len: 0.125 in	Mass: 3.91 oz
Aft Airframe Bulkhead	G12 Fiberglass (1.23 oz/in^3)	Dia$_{out}$ 6 in	Len: 0.125 in	Mass: 4.35 oz
Forward Coupler Bulkhead	G10 Fiberglass (1.19 oz/in^3)	Dia$_{out}$ 5.777 in	Len: 0.125 in	Mass: 3.91 oz
Forward Airframe Bulkhead	G10 Fiberglass (1.19 oz/in^3)	Dia$_{out}$ 6 in	Len: 0.125 in	Mass: 4.22 oz
Payload Mass		Dia$_{out}$ 5.5 in		Mass: 16 oz
Drone Mass		Dia$_{out}$ 5.5 in		Mass: 4 oz
Upper Airframe	G12 Fiberglass (1.23 oz/in^3)	Dia$_{in}$ 6 in Dia$_{out}$ 6.17 in	Len: 24 in	Mass: 48 oz
Main Parachute: SkyAngle Cert 3 XXL	Ripstop nylon (0.22 oz/ft^2)	Dia$_{out}$ 105 in	Len: 16 in	Mass: 64 oz
Shroud Lines	Elastic cord (round 2 mm, 1/16 in) (0.019 oz/ft)	Lines: 12	Len: 100 in	
Shock cord	Tubular nylon (14 mm, 9/16 in) (0.172 oz/ft)		Len: 15 in	Mass: 0.215 oz
Recovery Bay Switchband	G12 Fiberglass (1.23 oz/in^3)	Dia$_{in}$ 6 in Dia$_{out}$ 6.17 in	Len: 2 in	Mass: 4 oz
Recovery Bay	G12 Fiberglass (1.23 oz/in^3)	Dia$_{in}$ 5.777 in Dia$_{out}$ 6 in	Len: 4 in	Mass: 10.2 oz
Forward Airframe Bulkhead	G10 Fiberglass (1.19 oz/in^3)	Dia$_{out}$ 6 in	Len: 0.125 in	Mass: 4.22 oz
Forward Coupler Bulkhead	G10 Fiberglass (1.19 oz/in^3)	Dia$_{out}$ 5.777 in	Len: 0.125 in	Mass: 3.91 oz
Aft Airframe Bulkhead	G10 Fiberglass (1.19 oz/in^3)	Dia$_{out}$ 6 in	Len: 0.125 in	Mass: 4.22 oz
Aft Coupler Bulkhead	G10 Fiberglass (1.19 oz/in^3)	Dia$_{out}$ 5.777 in	Len: 0.125 in	Mass: 3.91 oz
Electronics		Dia$_{out}$ 4 in		Mass: 17.3 oz



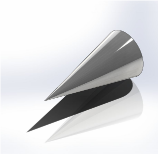
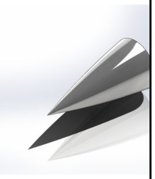
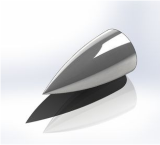
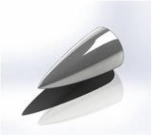
Mid Airframe	G12 Fiberglass (1.23 oz/in^3)	Dia$_{in}$ 6 in Dia$_{out}$ 6.17 in	Len: 17 in	Mass: 34 oz
Drogue Parachute: SkyAngle Classic II 32"	Ripstop nylon (0.22 oz/ft^2)	Dia$_{out}$ 30 in	Len: 8 in	Mass: 6 oz
Shroud Lines	Braided nylon (2 mm, 1/16 in) (0.011 oz/ft)	Lines: 3	Len: 24 in	
Shock cord	Elastic cord (round 2 mm, 1/16 in) (0.019 oz/ft)		Len: 15.748 in	Mass: 0.025 oz
GPS		Dia$_{out}$ 1 in		Mass: 5 oz
ATS Switchband	G12 Fiberglass (1.23 oz/in^3)	Dia$_{in}$ 6 in Dia$_{out}$ 6.17 in	Len: 2 in	Mass: 4 oz
ATS Bay	G12 Fiberglass (1.23 oz/in^3)	Dia$_{in}$ 5.777 in Dia$_{out}$ 6 in	Len: 10 in	Mass: 25.4 oz
Forward Airframe Bulkhead	G10 Fiberglass (1.19 oz/in^3)	Dia$_{out}$ 6 in	Len: 0.125 in	Mass: 4.22 oz
Forward Coupler Bulkhead	G10 Fiberglass (1.19 oz/in^3)	Dia$_{out}$ 5.777 in	Len: 0.125 in	Mass: 3.91 oz
Aft Airframe Bulkhead	G10 Fiberglass (1.19 oz/in^3)	Dia$_{out}$ 6 in	Len: 0.125 in	Mass: 4.22 oz
Aft Coupler Bulkhead	G10 Fiberglass (1.19 oz/in^3)	Dia$_{out}$ 5.777 in	Len: 0.125 in	Mass: 3.91 oz
ATS		Dia$_{out}$ 5 in		Mass: 22.2 oz
Lower Airframe	G12 Fiberglass (1.23 oz/in^3)	Dia$_{in}$ 6 in Dia$_{out}$ 6.17 in	Len: 35 in	Mass: 70 oz
Trapezoidal fin set (4)	G10 Fiberglass (1.19 oz/in^3)	Thick: 0.187 in		Mass: 39.1 oz
Inner Tube	G12 Fiberglass (1.23 oz/in^3)	Dia$_{in}$ 3.033 in Dia$_{out}$ 3.203 in	Len: 32 in	Mass: 32.8 oz
Centering ring	G10 Fiberglass (1.19 oz/in^3)	Dia$_{in}$ 3.203 in Dia$_{out}$ 6 in	Len: 0.375 in	Mass: 9.05 oz
Centering ring	G10 Fiberglass (1.19 oz/in^3)	Dia$_{in}$ 3.203 in Dia$_{out}$ 6 in	Len: 0.375 in	Mass: 9.05 oz
Centering ring	Cardboard (0.393 oz/in^3)	Dia$_{in}$ 3.203 in Dia$_{out}$ 6 in	Len: 0.375 in	Mass: 2.98 oz
Thrust plate		Dia$_{out}$ 6 in		Mass: 12.2 oz

Figure 2: Mass List

3.1.2 Nose Cone

Based off of the preliminary research done in the proposal, CMRC has an overall idea of how each nosecone will perform relative to one another. The results can be summarized in the nose cone design matrix below. From this information, many of the sold nose cone designs can be filtered down to those most suited to the scale of our launch from this design matrix. Although Elliptical and Parabolic score the highest, many rocketry supply vendors only have Haack (Von Karman), Ogive, or Conic Nose cones available.

Table 4: Nose Cone Design Matrix

	Weight	Conic	Ogive	Parabolic	Haack	Elliptical
Mfg / Access	40%	10	8	7	2	7
Subsonic Performance	50%	3	5	9.5	9	10
Transonic Performance	10%	6	7	7	8	8
Image						
Total Rank		6.1	6.4	8.25	6.1	8.6

Using mandatory parameters such as an outer diameter of 6” and fiberglass material, our choices reduced. We chose fiberglass as our material for a nose cone because of its high strength/durability of ~12.3 ksi, as well as its moderately low price and lightweight.

In addition to the mentioned prerequisites, CMRC has considered many nosecones with differing characteristics. This includes having a metallic tip, varying fineness ratios, and shapes. In order to determine the most ideal nose cone, we ran several simulations on OpenRocket to compare the different Coefficient of Drags each nosecone would produce. Another feature we analyzed was the overall apogee. It might seem somewhat redundant to compare both the maximum altitude as well as the coefficient of drag; however, the added weight for some of the shapes caused a reduced altitude, even if the coefficient of drag was lower than another shape.

Below is a design matrix with all of the examined weighted components. Overall, the Public Missiles Ogive without the Aluminum tip, the Madcow Ogive 3:1 with the Aluminum tip, and the Madcow Ogive 5:1 without the Aluminum tip had the performed the best. The specific results from the Open Rocket simulations are very strenuous to interpret in a report, so instead this design matrix provides a general guide to how each nose cone behaved.

Acronyms

MC= MadCow
PM= Public Missiles
AR= Apogee Rockets
PH= Performance Hobbies
WM= Wildman Rocketry
VK= Von Karman

Table 5: Overall Nose Cone Design Matrix

	Ratio	**Shape**	**Weight**	**Size**	**Apogee**	**Cd**	**Cost**	**Total**
Weight	10.00%	10.00%	10.00%	5.00%	28.00%	27.00%	10.00%	100.00%
MC Ogive 3:1 w/ tip	1	4	3.6	5	3.9	4.9	1	3.625
MC Ogive 4:1 w/tip	4.7	4	2.7	3.2	2.2	5	1	3.366
PM Ogive 4:1 w/o tip	4.7	4	5	3.2	5	1.5	4.3	3.765
MC Ogive 5:1 w/o tip	4.8	4	4.2	1.8	4.9	1.3	5	3.613
MC Ogive 5:1 w/tip	4.8	4	1.4	1.8	1.2	1.3	1	1.897
AR Ogive 5:1 w/o tip	4.8	4	4.1	1.8	4.9	1.3	3.8	3.483
PH Ogive 4:1 w/ tip	4.7	4	1.8	3.2	2.2	1.2	1	2.25
PH Ogive 5:1 w/tip	4.8	4	1.4	1.8	2.1	1.3	1	2.149
WM VK 5:1 w/ tip	4.8	3	1.4	1.8	2.15	1.2	2.4	2.176
MC VK 5.5:1 w/ tip	4.9	3	1	1	1.1	1	1	1.618
PH VK 5.5:1 w/tip	4.9	3	1	1	1.1	1	1	1.618
MC Conical 5:1 w/ tip	4.8	2	1.4	1.8	1	1.4	1	1.668
AR Conical 5:1 w/o tip	4.8	2	4.1	1.8	2.2	1.2	4.5	2.57
PH Conical 5:1 w/ tip	4.8	2	1.4	1.8	1	1.2	1	1.614

Below describes how the thresholds for each design matrix were chosen. The highest and lowest score represent the minimum and maximum for each category, except for the shape who's score is derived from the proposals' design matrix.

Table 6: Threshold Summary: Nose Cone Design Matrix

	5	**4**	**3**	**2**	**1**
Drag Coefficient	0.52867	0.7252275	0.921785	1.1183425	1.3149
Altitudes	6080.7	5948.3	5815.9	5683.5	5551.1
Weight	28	37.17316667	46.34633333	55.5195	64.69266667
Cost	$ 94.95	$ 108.70	$ 122.45	$ 136.20	$ 149.95
Space (length)	3	3.625	4.25	4.875	5.5

From this data, the optimum nose cones for SCOTTIE were determined . Their general specifications and plotted performance (Velocity, Altitude, Drag Coefficient vs Time) is provided below.

1) Public Missiles 4:1 Ogive
    a) *Apogee = 6080.7’*
    b) *Drag Coefficient = 1.271*
    c) *Weight = 28 oz*

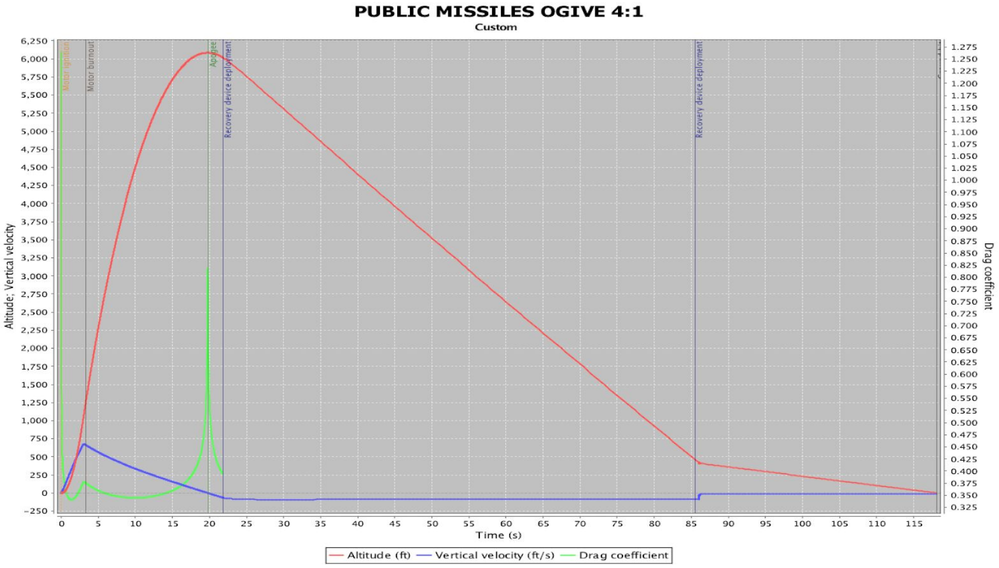


Figure 3: PM 4:1 Ogive Sample Flight Data

2) Madcow 3:1 Ogive w/ AL tip
    a) *Apogee = 5881.7’*
    b) *Drag Coefficient = 0.535*
    c) *Weight = 46.7 oz*

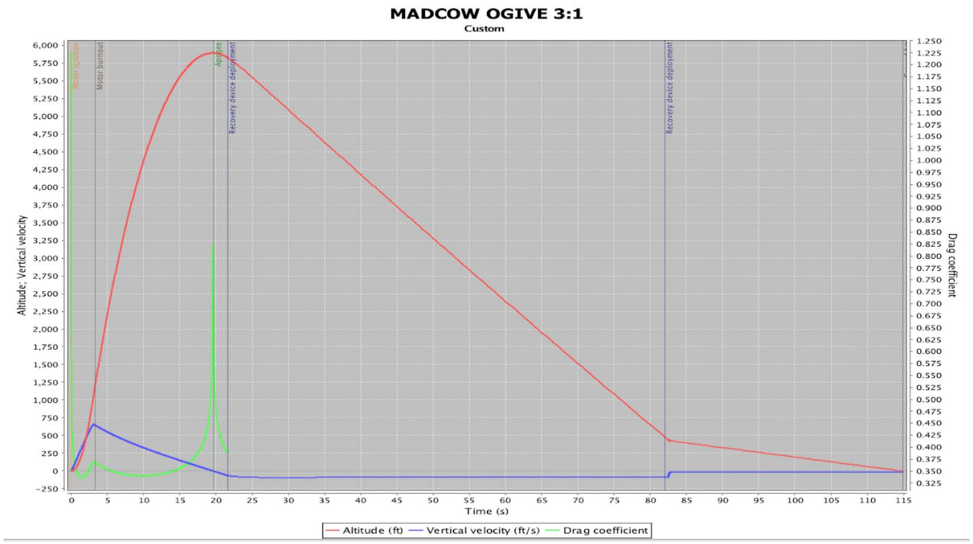


Figure 4: MC 3:1 ogive data for sample flight

3) Madcow 5:1 Ogive
    a) *Apogee = 5978.5'*
    b) *Drag Coefficient = 1.3019*
    c) *Weight = 36 oz*

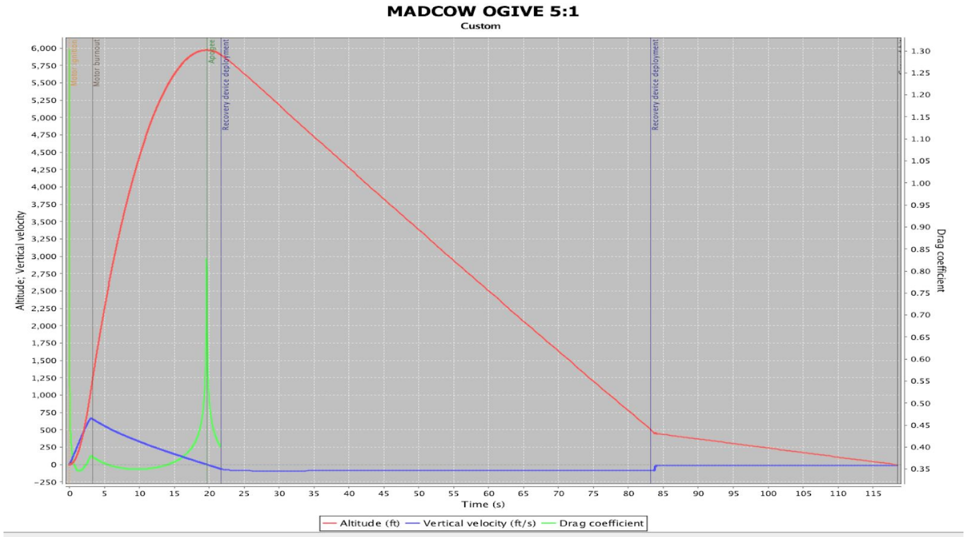


Figure 5: MC 5:1 ogive data for sample flight

In conclusion, our search for nose cones has narrowed from 14 different options to 3 Ogive nose cones with varying fineness ratios as well as weights. Further computational analysis through Ansys will be done to determine and validate our final decision.

3.1.3 Airframe

CMRC is considering two different materials for the frame of our rocket: fiberglass and carbon fiber. We focused on these two materials because of their composite behavior, increasing the strength to weight ratio.

For fiberglass, G10 and G12 are the primary candidates. Since both materials are fiberglass, the main differentiation between the two is the fiber orientation which affects the manner in which the materials approach strength handling. G10 uses glass cloth soaked in epoxy resin, in which half of the fibers are wound parallel to the tube's centerline and the other half perpendicular. G12 uses wound filament for its tubing and polyester resin. Its compressive strength is lower than that of G10, and G12 has fibers wrapped at 45 deg to the centerline instead of both perpendicular and parallel like G10. This is the reason why G12 is less equipped in the compressional strength direction. However, G12 is much less expensive than G12, and more produced by rocketry vendors.

In addition to fiberglass, we considered carbon fiber due to its popular characteristics of weight reduction as well as strength capabilities. The tubing is filament wound using carbon fiber tow and epoxy. Although performance wise, carbon fiber is the obvious solution, ease of manufacturing as well as cost is taken into account. Our team is familiar with fiberglass, and has a limited budget that we would like to prioritize.

Overall, the three options analyzed all provided benefits. However, CMRC would like to direct our financial resources to other innovative features on our rocket. G12 can effectively handle the forces our rocket will undergo (proven by our previous rockets), is relatively light, and is a material we have easy access to. Further tests will be performed to ensure that G12 can withstand the amount of compressive forces as well as any other external loads the frame might encounter.

Table 7: Material Comparison

Type	Density (oz/in^3)	Cost	Image	Thread Directions
G-10 Fiberglass	1.193	$$		0-90 deg wrt. centerline
G-12 Fiberglass	1.231	$		30-45 deg wrt. centerline
Carbon Fiber	0.903	$$$		20-45 deg wrt. centerline

Therefore, the upper, middle, and lower airframe of the launch vehicle will be made out of G12 fiberglass tubing.

3.1.4 Fins

In this section, CMRC will outline the various analyses that contributed to the preliminary fin design. This will include analyses of fin planform, number of fins, fin cross section, and fin flutter. Based on the results of each of these analyses, the features of the preliminary fin design were determined.

3.1.4.1 Fin Planform Analysis

In our initial analysis, we compared the performance of three types of fin planforms: trapezoidal, elliptical, and clipped-delta. Our criteria for choosing fins included manufacturability, stability, and coefficient of drag (C_D).

In order to test stability and the coefficient of drag for each planform, we analyzed dozens of trapezoidal, elliptical, and clipped-delta fin configuration in OpenRocket. For simplicity, we will include the results of one configuration for each of the planforms, shown and illustrated below.

Table 8: Fin Planform Design Parameters

	Trapezoidal	Elliptical	Clipped Delta
Number of Fins	3	3	3
Root Chord (in)	8	8	8
Tip Chord (in)	4	N/A	4
Height (in)	8	8	8
Cross Section	Airfoil	Airfoil	Airfoil

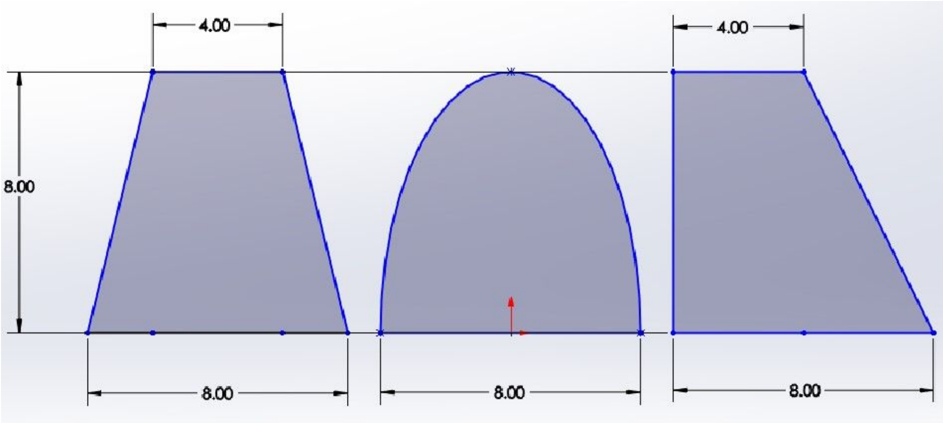


Figure 6: Fin Planform Designs

Here, we deliberately made as many parameters of the configuration the same as possible. Namely, the number of fins, root chord length, height, and cross section shape were made the same for each of these fins. Additionally, the tip chord length of the trapezoidal and clipped delta fins were made the same, as this parameter does not apply to the elliptical fin.

Table 9: Fin Planform Stability

Mach Number	**Stability (cal)**		
	Trapezoidal	Elliptical	Clipped Delta
0.1	2.49	2.86	2.57
0.2	2.5	2.87	2.59
0.3	2.52	2.89	2.61
0.4	2.55	2.92	2.65
0.5	2.59	2.96	2.69

When analyzing the stability of the rocket under these fin configurations, we wanted to see a stability in the range of about 2.5 to 3 calipers. From this data, we can affirm that each of these fin platforms, from a stability point of view, is equally viable.

Table 10: Fin Planform C_D

Mach Number	**Total C_D**		
	Trapezoidal	Elliptical	Clipped Delta
0.1	0.38	0.38	0.38
0.2	0.36	0.37	0.36
0.3	0.36	0.37	0.36
0.4	0.37	0.38	0.37
0.5	0.39	0.4	0.37

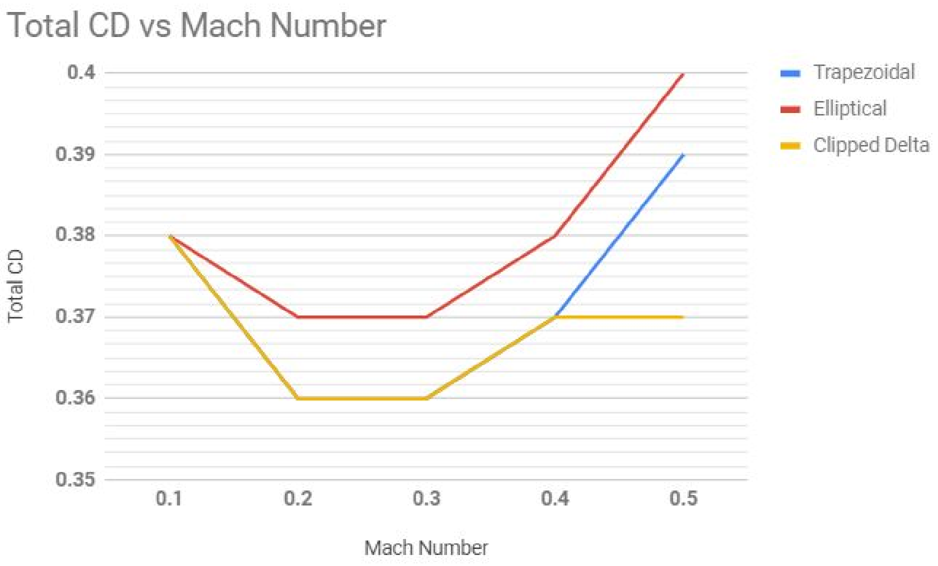


Figure 7: Total C_D vs Mach Number

When looking at the coefficient of drag (C_D) analysis, we desired fin configurations that lowered the total C_D as much as possible. The data suggested that each planform has similar coefficient of drags at the speeds we tested, with the trapezoidal and clipped delta fins performing slightly better than the elliptical fins.

From the C_D analysis, we decided to rule out the elliptical fins. Although theoretically they are the ideal planform, they actually performed the worst out of the three, and are very difficult to manufacture. The benefit of elliptical fins would not be realized unless we flew at a larger mach number. Since clipped delta and trapezoidal fins had similar performance, we chose the trapezoidal fins as our baseline due to their structural stability compared to clipped delta.

Table 11: Fin Planform Rating

Trapezoidal	Elliptical	Clipped Delta
1	3	2

3.1.4.2 Number of Fins Analysis

We ran OpenRocket simulations on configurations with 3, 4 and 5 fins. While the coefficient of drag rose as the number of fins rose, the four fin configuration was particularly attractive for a variety of reasons. The differences in coefficient of drag were relatively small (around .02 out of a total coefficient of drag of .4). The four fin configuration will be easier to balance since the fins are placed at right angles to one another and will hence be less likely to fail due to manufacturing error while the three fin configuration would require precise placement at angles of 120 degrees. In addition, the fourth fin would allow us to reduce the size of all of the fins making them less likely to break under strain. While three fins remains a plausible strategy, the team currently leans strongly toward a four fin design.

3.1.4.3 Fin Cross Section Analysis

The cross section of the fins have been greatly discussed in literature regarding all forms of rocketry. Many mid to high powered rockets simply have a rectangular cross section due to the simplicity of manufacturing. Fins may sometimes be purchased with a bevel along the outer edges at a specified angle, but any other cross sectional geometries are difficult to purchase from suppliers and thus must be manufactured in house or outsourced. CMRC is attempting to quantify the impact that various cross sections of the fins will have on the aerodynamic performance of the launch vehicle. Four designs were investigated: rectangular, beveled, rounded, and airfoiled.

Our objective was to generate drag and lift polars for all designs and compare their performance. To do this, we used a 2D compressible flow simulation in ANSYS Fluent. All geometries were meshed using a global element size of 0.375”, an element size of 0.150” around the fin and the wake, and an element size of 0.015” along the fin surface. Inflation was added to the surface of the fin, with 10 layers and a growth rate of 1.2. These meshing parameters were kept constant across all designs in order to ensure similarity of mesh quality. A sample picture of the mesh is shown below.

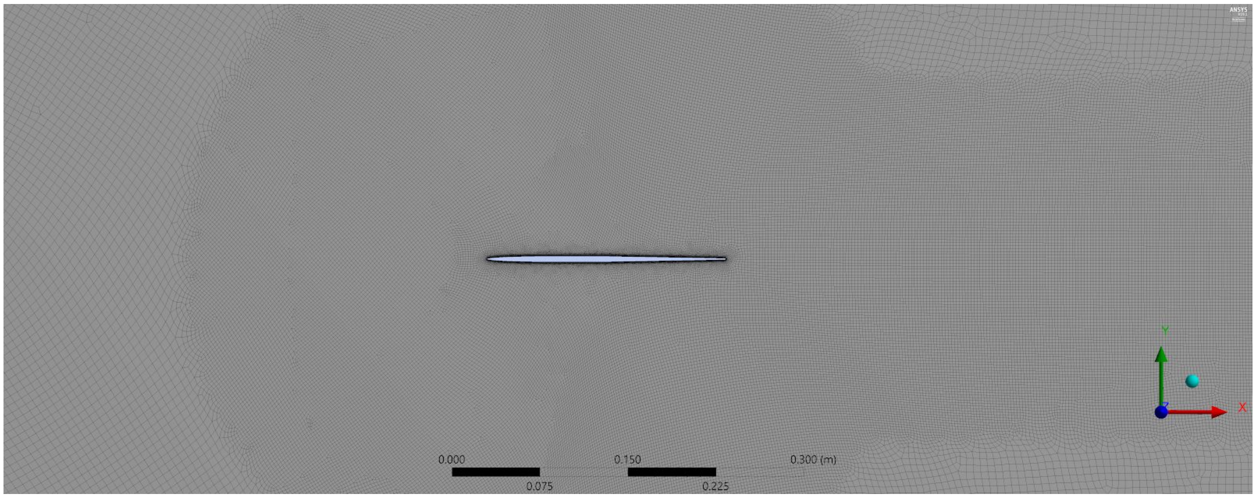


Figure 8: CFD Mesh

Air was modeled as an ideal gas to allow for compressibility effects which will occur at speeds above approximately mach 0.2 to mach 0.3. Since our launch vehicle will near mach 0.6, we performed simulations at mach 0.1, 0.3 and 0.5. For each air velocity, simulations were run at varying angles of attack, from 0 to 10 degrees. To capture turbulence, the Spalart-Allmaras viscosity model was used. Simulations were run for approximately 3000 iterations to ensure convergence of all residuals and the values of coefficient of lift and drag.

Rectangular

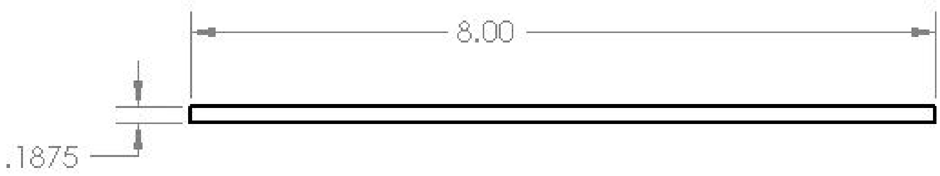


Figure 9: Rectangular Cross Section

Rectangular cross sections have 90° corners. The rectangular cross section is the easiest to make, as it requires no modification once the fin outline is cut out. We predicted that it would be the least efficient of the fin shapes, so we analyzed it to determine how much of an improvement we can gain from each of the following cross sectional shapes.

The rectangular fins had the highest coefficient of drag, significantly greater than the other fin shapes. The fins also had the highest coefficient of lift, which we had not predicted. Due to the high drag, it is likely that we will alter the fins from the rectangular shape in order to make the rocket more aerodynamic.

Bevel

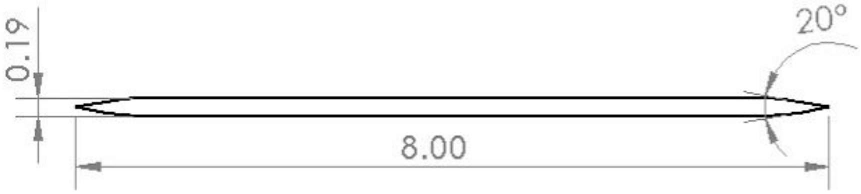


Figure 10: Beveled Cross Section

Beveled cross sections have symmetric tapered leading and trailing edges. The design that we studied had a 10 degree bevel for both upper and lower edges, for a total 20 degree point. These are difficult to manufacture uniformly if done by hand through sanding, however with a CNC they can be made with relative ease. For this reason, beveled fins are often available from suppliers who take custom fin requests. For example, Public Missile Works will add a bevel to any edge for an additional $2.95 per edge. By adding the bevel, we will have a sharp point that divides the air as it flows over the airfoil, thus leading to less drag compared to the rectangular fin.

Beveled fins performed very similarly to airfoils both in respect to lift and drag. They offer a commercially viable alternative to airfoils for nearly identical drag and lift characteristics in the velocity region we can expect our launch vehicle to operate in.

Rounded

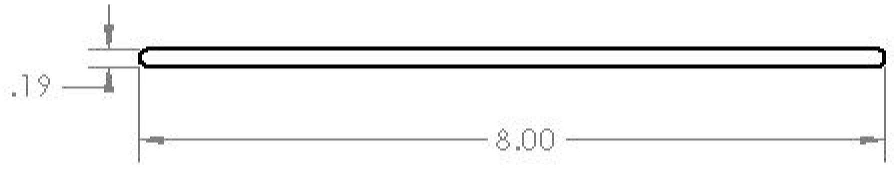


Figure 11: Rounded Cross Section

We predicted that the rounded cross section, due to its curvature at the ends, will be more aerodynamic than the rectangular cross section. Rounded fins are significantly easier to manufacture than a complete airfoil, requiring only rounding of the corners rather than more complicated machine operation. They can be manufactured simply by sanding a fin with a rectangular cross section. However, it is made difficult due to the need to ensure uniform curvature over the entire length of the edge. Asymmetries between fins can produce asymmetric aerodynamic forces that reduce the stability of the launch vehicle.

The rounded fins surprisingly had the lowest coefficient of drag however they will probably not be an attractive candidate due to to their low coefficient of lift. Since we need a relatively high coefficient of lift to maintain stability, rounded fins are likely to be summarily ruled out in further consideration of fin shape.

Airfoil

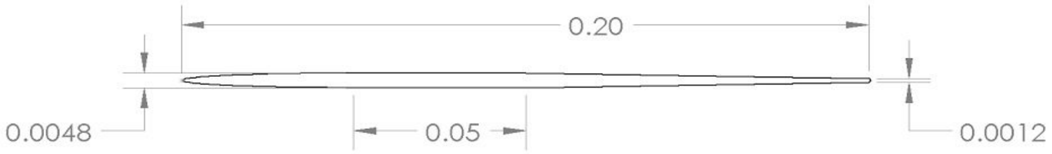


Figure 12: Airfoil Cross-section Dimensions

An airfoil is the ideal shape for minimizing drag. We ran simulations using two types of airfoil: an ideal airfoil and a "strong" airfoil where the shape was simplified to include straight lines and a greater minimum width, for easier manufacturing. The airfoil, including even the strong airfoil, is significantly more difficult to manufacture than other designs. If we were to manufacture the fins ourselves, it would require us to sand the airfoil by hand. Using this method, it would be very difficult to produce identical airfoils, which could potentially introduce differences in performance for each fin. The alternative is to order the fins from a manufacturer, however this would be very expensive.

Summary

Below is a comparison of the coefficient of drag and lift for all fin cross section geometries. As expected, the rectangular cross section had the highest amount of drag. However, it was notable that the rounded, and not the airfoil, had the lowest amount of drag. Airfoil and bevel performed similarly over the range of angle of attack studied.

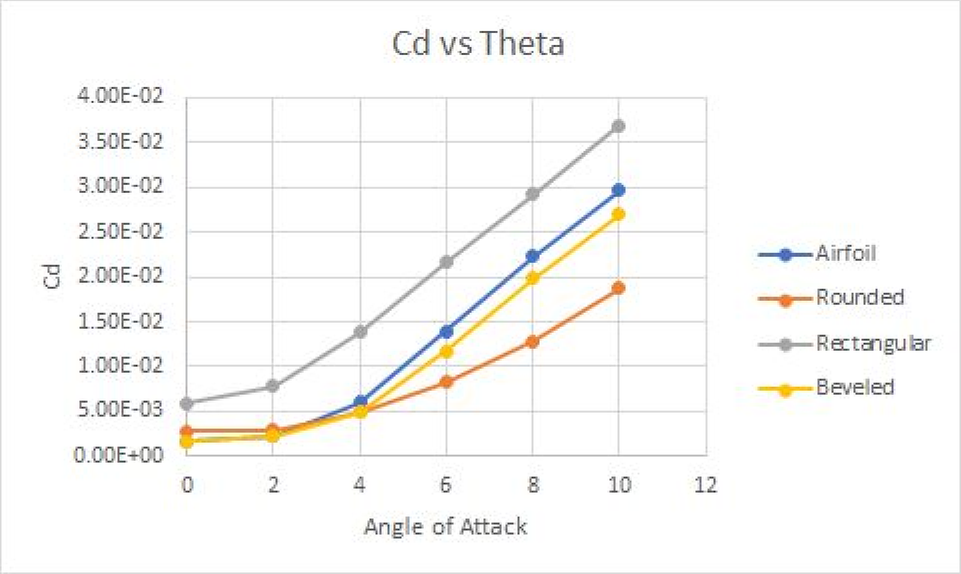


Figure 13: Coefficient of Drag for all Cross Section Geometries

With respect to lift, curiously the rectangular geometry reported the highest lift coefficient. Disregarding the rectangular cross section, we see that the airfoil had the next highest lift coefficient, followed by bevel and then rounded.

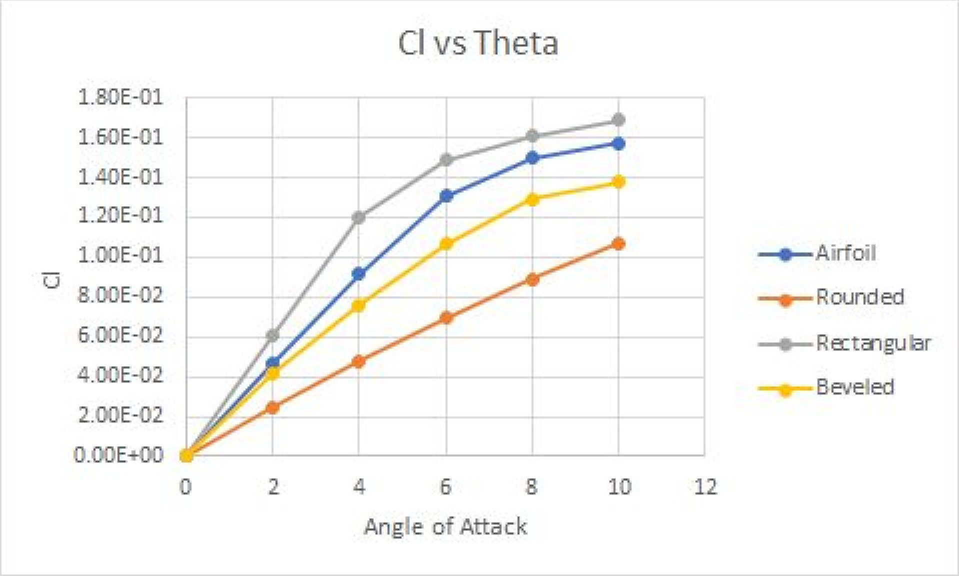


Figure 14: Coefficient of Lift for all Cross Section Geometries

Finally, we computed the ratio of the coefficients of lift and drag to characterize the efficiency of the airfoil. Now we can see that although the airfoil previously did not have the lowest drag or highest lift, it does have the most efficient geometry. The beveled fin was nearly as good as the airfoil, however the rounded and rectangular geometries had much lower efficiencies.

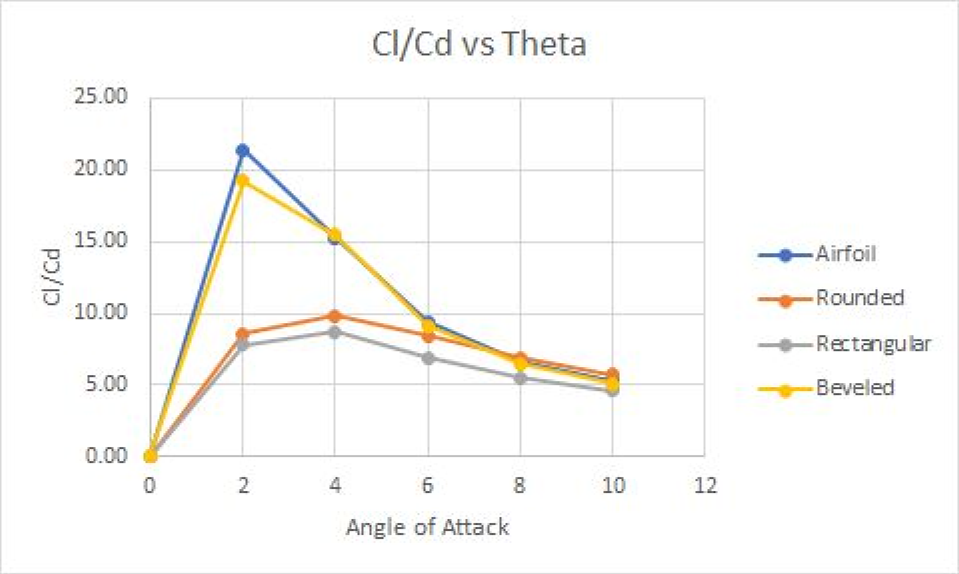


Figure 15: C_L/C_D for all Cross Section Geometries

Factoring in the manufacturing complexity and cost of each design (1 is best and 10 is worst), we have decided to propose that our fin cross section be a beveled. It offers a balance of improved lift and drag without the burdensome manufacturing process of an airfoil. Furthermore, bevels can be inexpensively added to custom fin orders by Public Missile Works.

Table 12: Fin Cross Section Summary Table

Cross Section	C_D (avg)	C_L (avg)	C_L/C_D (avg)	Manuf. Ease	Cost
Rectangular	0.019	0.110	5.583	1	1
Rounded	0.008	0.056	6.588	5	2
Bevel	0.011	0.082	9.252	3	3
Airfoil	0.013	0.096	9.676	10	10

3.1.4.4 Leading Fin Design

Based on the results of the above studies, CMRC has developed the leading design for the launch vehicle. It will be constructed out of 3/16” G10 fiberglass, with a 40 degree bevel. Note that a 40 degree bevel was chosen rather than the 20 degree bevel that was used for the analysis. This was done so that the bevel would not extend all the way through the fin tab and thus reduce the thickness of the fin tab at the connection to the motor mount tube. In addition, the height was decreased to 6 in from the original 8 in detailed in the planform analysis. This was done due to the switch to a four fin design, which required a smaller fin to achieve the same stability caliber. Bringing the span to 6 in will also allow our aspect ratio to be exactly 1, which is ideal. These fins will be custom ordered from Public Missile Works in order to have them cut to our specifications.

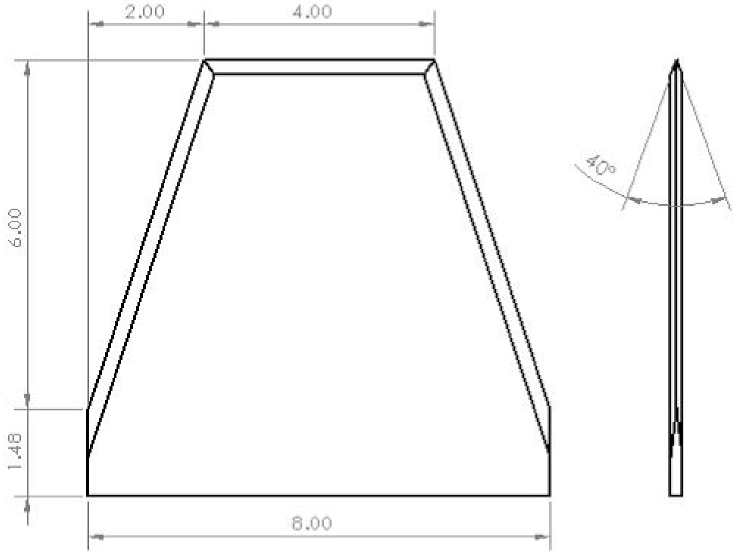


Figure 16: Overall Fin Design Schematic

Table 13: Fin Dimension Summary

Root chord	8 in
Tip chord	4 in
Height	6 in
Fin tab height	1.4835 in
Thickness	0.1875 in
Area ($S = \frac{b}{2}(c_r + c_t)$)	36 in^2
Aspect ratio ($B = \frac{b^2}{S}$)	1
Fin taper ratio ($\lambda = \frac{c_t}{c_r}$)	2
Normalized thickness ($T = \frac{t}{c_r}$)	0.02344 in
Bevel	40 deg
Material	G10 Fiberglass
Shear Modulus	2,400,000 psi

Fin Flutter Analysis

With this fin design, we must also ensure that fin flutter does not occur. Fin flutter occurs when the air flowing over the fins excite the natural bending and torsional modes of the fins. Thus, we must fly at a velocity that is below the critical excitation velocity for fin flutter. The physics of fluid structure interactions becomes very complex, however, simplified equations have been presented by Apogee Peak of Flight Newsletter, Issue 411, that solve this very problem. It postulates that:

$$V_f = 1.223\left[C_s(h)\sqrt{\frac{P_0}{P(h)}}\right]\left[\sqrt{\frac{G}{P_0}}\sqrt{\left(\frac{2+B}{1+\lambda}\right)}\left(\frac{T}{B}\right)^{3/2}\right]$$

Which can be simplified to:

$$V_f = 1.223C_{s,0}e^{0.4h/H}\sqrt{\frac{G}{P_0}}\sqrt{\left(\frac{2+B}{1+\lambda}\right)}\left(\frac{T}{B}\right)^{3/2}$$

Where:

c_r = Root chord

c_t = Tip chord

b = Fin height

t = Fin thickness

G = Shear modulus

H = Atmospheric scale height at sea level (26500 ft)

P_0 = Atmospheric pressure at sea level (14.7 psi)

$C_{s,0}$ = Speed of sound at sea level (1116 ft/s)

P(h) = $P_0 e^{-h/H}$ Pressure (function of altitude)

$C_s(h)$ = $C_{s,0} e^{-0.1h/H}$ Speed of sound (function of altitude)

S = $\frac{b}{2}(c_r + c_t)$ Fin area

λ = $\frac{c_t}{c_r}$ Fin taper ratio

B = $\frac{b^2}{S}$ Aspect ratio

T = $\frac{t}{c_r}$ Normalized thickness

According to Open Rocket flight simulations, our maximum velocity occurs at approximately 3000 ft. Using this value and the parameters of our fins, we can find the flutter velocity.

$$V_f = 1.223 C_{s,0} e^{0.4h/H} \sqrt{\frac{G}{P_0}} \sqrt{\left(\frac{2+B}{1+\lambda}\right)} \left(\frac{T}{B}\right)^{3/2}$$

$$V_f = 1.223(1116) e^{0.4(3000/26500)} \sqrt{\frac{2400000}{14.7}} \sqrt{\left(\frac{2+1}{1+0.5}\right)} \left(\frac{0.02334}{1}\right)^{3/2}$$

$$V_f = 2909\, ft/s$$

The maximum expected velocity of the launch vehicle is 646 ft/s, which has a factor of safety of 4.5 with respect to the flutter velocity. What this suggests is that our fins could be made thinner and still have a high factor of safety for flutter. However, future analyses will be required in order to determine the structural requirements of the fin to handle ground impact. The thickness will be left at 0.1875 *in* until it can be proven that a thinner design will not break during landing.

3.1.5 Motor Retention

The leading design for this year's motor retention system at the current moment is using a manufactured 75mm motor retainer system from ApogeeComponents, and a custom thrust plate. The assembly from ApogeeComponents comes in two major parts not including hardware: the retainer base, and the retainer cap. The retainer base is flanged such that it can be screwed into a bulkhead or a thrust plate. The cap screws onto the retainer base, and covers the end of the motor casing. We chose to manufacture our own thrust plate in order to make it more customized for the needs of our rocket. With the preliminary dimensions of the rocket in mind, an in house motor retainer would be more expensive than store-bought, whereas the opposite is true for the thrust plate.

Table 14: Motor Retention Options Summary

	Motor Retainer Cap and Base		Thrust Plate	
Component	Bought	In House	Bought	In House
Price	$55.56	$100 - 8"x8"x1.5" 6061-T651 Al	$65.05	$24.93 - 8"x8"x0.5" 6061-T651 Al
Mechanical Feasibility	Easy	Feasible (3 axis CNC mill)	Easy	Easy (3 axis CNC mill)

Motor Retainer Base

The preliminary CAD model and drawing are shown below. Dimensions were measured using electronic calipers. Threads and all tapped holes are excluded for sake of simplicity.

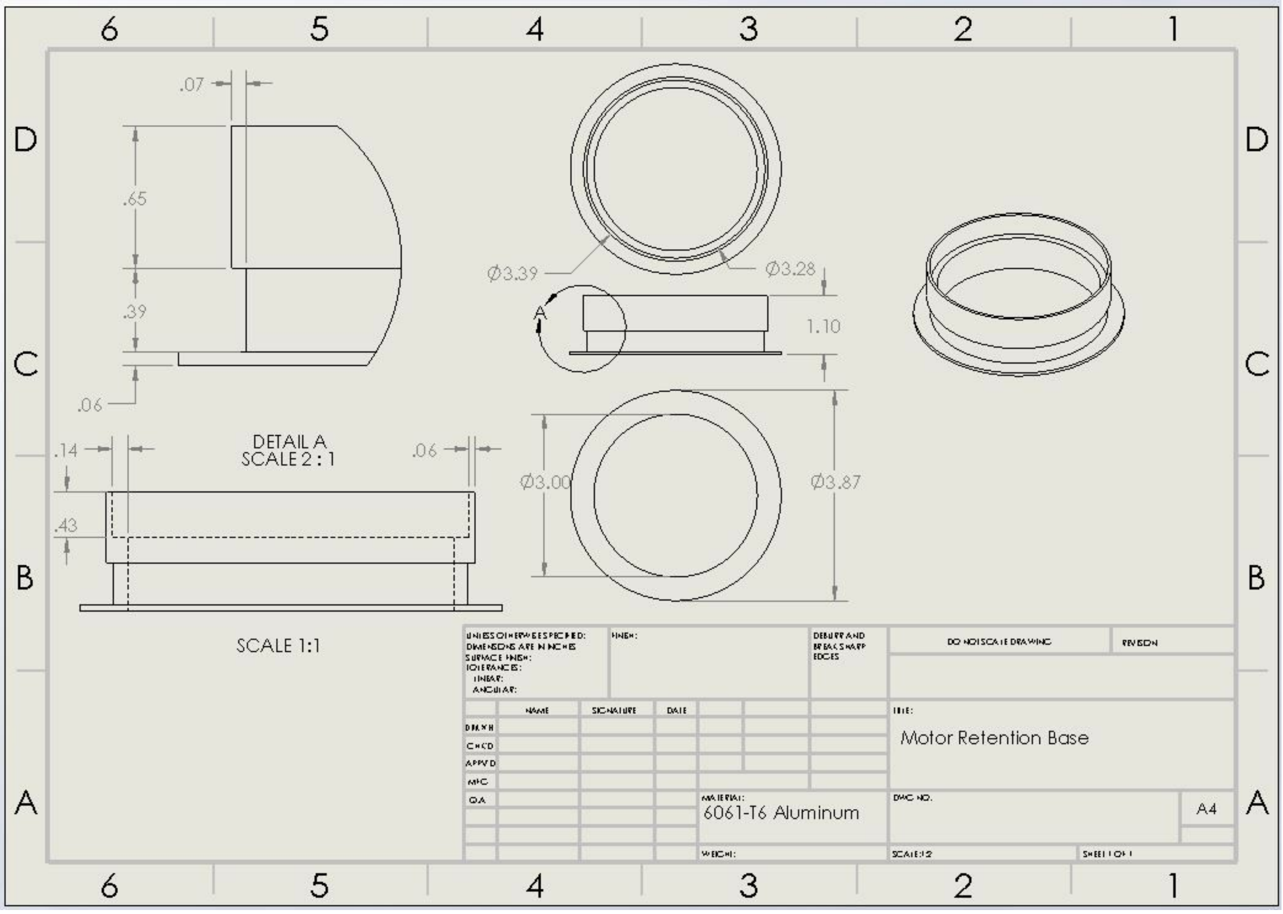


Figure 17: Motor Retention Base Drawing

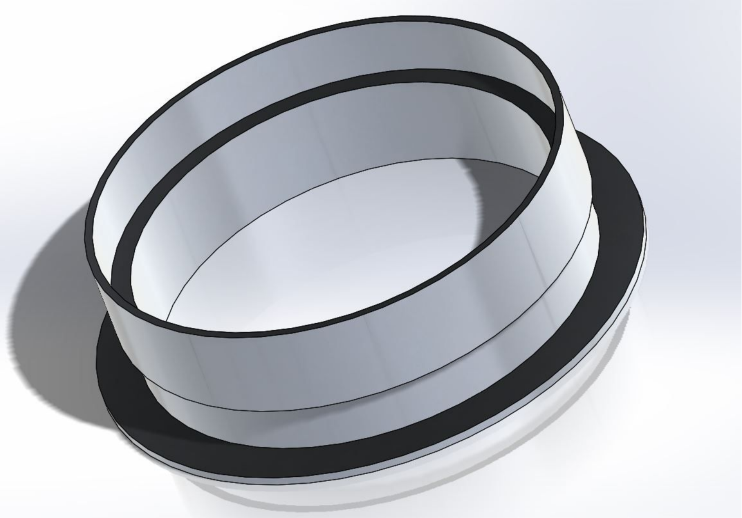


Figure 18: Motor Retention Base CAD model

Motor Retainer Cap

Like the base, the CAD model for the cap was derived from measurements made by calipers. Finish on outside of cap and threads were not modeled for sake of simplicity.

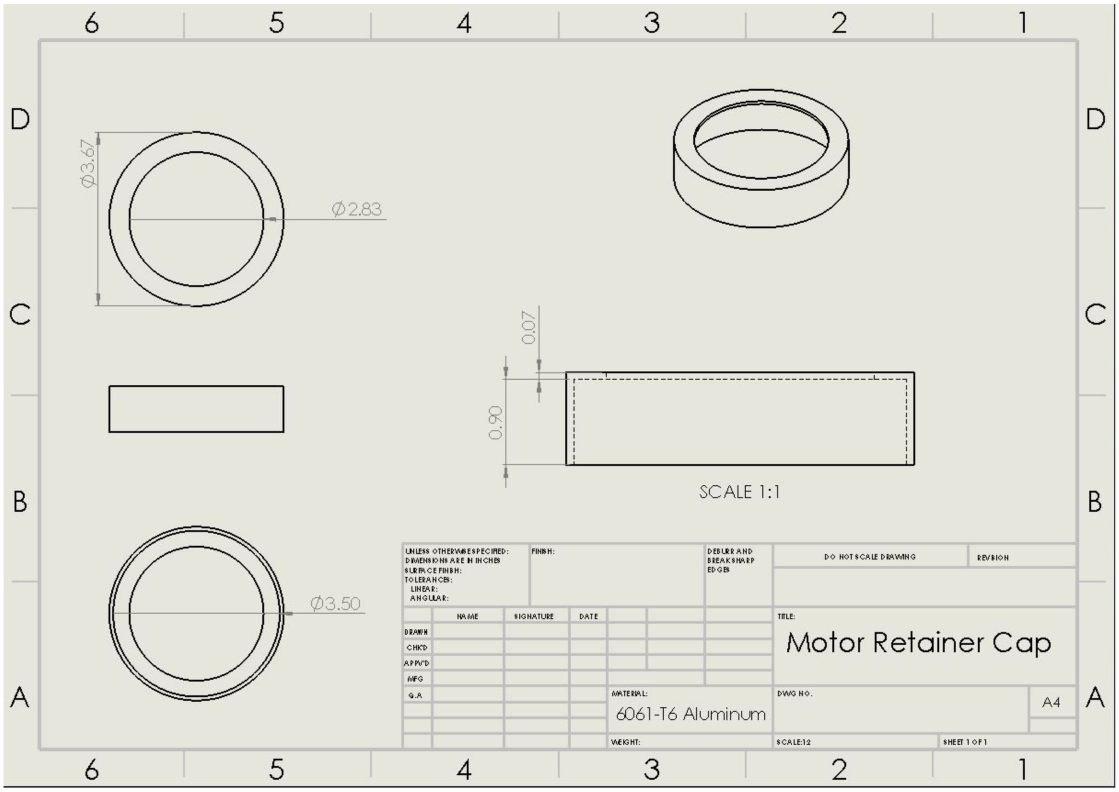


Figure 19: Motor Retainer Cap Drawing

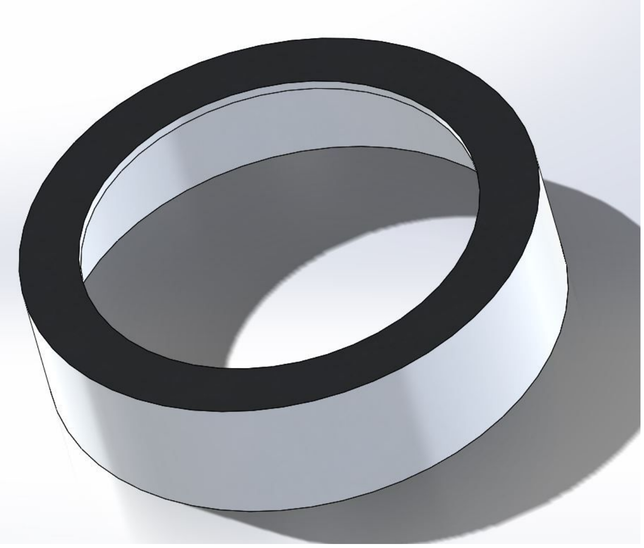


Figure 20: Motor Retainer Cap CAD model

Thrust Plate

Since the thrust plate is being designed and manufactured in house, some calculations in regard to general restrictions were done in order to generally constrain the thrust plate and motor dimensions.

The first of the calculations done was with regard to the axial stresses that a portion of the thrust plate will handle, under the forces exerted by the motor retainer system. In order to simplify the model, the following assumptions were made:

1. the inner diameter of the thrust plate is 3 inches,
2. the thrust plate only feels axial stress on the places were it comes in contact with the motor retainer base,
3. the retainer simply rests on the thrust plate (i.e. it does not screw into the thrust plate),
4. the motor retainer exerts forces equal in magnitude to the force of the motor (i.e. internal deformation of the motor retainer from Apogee Components does not occur).

With these assumptions, the calculation was relatively simple.

$$\sigma_{motor} = \frac{F_{motor}}{A}$$

$$A = \pi(R^2_{retainer,\ outer} - R^2_{inner}) = \pi(\frac{3.87^2}{4} - \frac{3^2}{4}) = 4.694\ sq.\ in.$$

Using the current proposed motor, the CTI L1350, $F_{motor,\ max} = 1540.73\ N\ =\ 346.37\ lbf$, according to RocketReviews.com.

$$\sigma_{motor} = \frac{346.37}{4.694} = 73.9\ psi$$

Since we are planning on using 6061-T651, the yield tensile strength is $42100\ psi$ at 212ºF, according to MatWeb.com. Assuming a factor of safety = 3, the new yield tensile strength is 14033.33 *psi*, which is 3 orders of magnitude higher than the experienced axial stress.

The maximum thrust of the motor under a FoS of 3 can be calculated using the reverse process. Using the same area as before, the maximum thrust of a motor that we can use will be 66 kip, which is far beyond the NASA restriction, and far beyond anything we would ever logically use.

Another failure mode of the thrust plate to consider is failure through bending stress. In order to simplify the model, these assumptions were made:

1. the thrust plate is a circular plate of constant width,
2. the applied force form the motor acts evenly on the inner ring of the thrust plate
3. the edges of the thrust plate are firmly fixed (as if they were epoxied to the body tube.

With these assumptions in place, equations were located in *Roark's Formulas for Stress and Strain*. In the seventh edition, case 1e. on page 461, the equation $M_{bending}=K_m \omega r_{outer}$. From the special case table within that same page, $K_M=0.2379$. ω is force per unit length, and thus $\omega = \frac{346.37}{3\pi} = 36.75\ lb\ in^{-1}$. Using $r_{outer} = 6in$, $M_{bending}=52.46$. On page 457, it is stated that stress due to bending can be related with the moment in the relation $\sigma = \frac{6M}{t^2}$. Assuming the maximum stress with a FoS of 3, the minimum thickness with our current motor selection would be 0.150 *in*.

The maximum thrust of the motor can be calculated using the same relation, but solving for ω. In this calculation, the assumption was made that t=0.375, which is approximately the thickness of the commercial thrust plate from ApogeeComponents.

$$\omega = \frac{\sigma t^2}{6K_M r_{outer}} = 230.423\ lb\ in^{-1}$$

Thus, the maximum possible force of the motor is 2171.7 lb with these assumptions.

Preliminary CAD models of the thrust plate were made to conform to these limitations, and the figures below show dimensions and the CAD model itself.

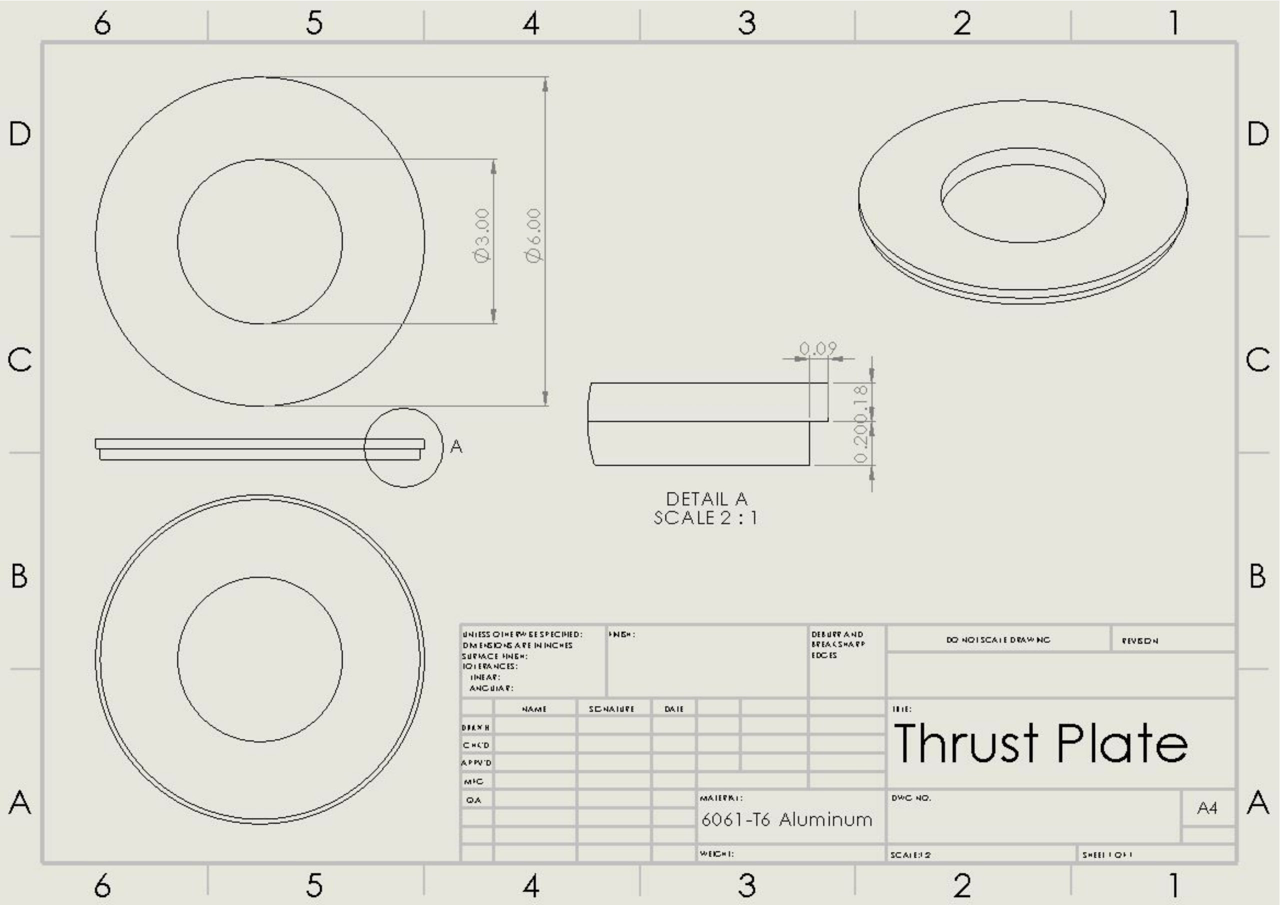


Figure 21: Thrust Plate Drawing

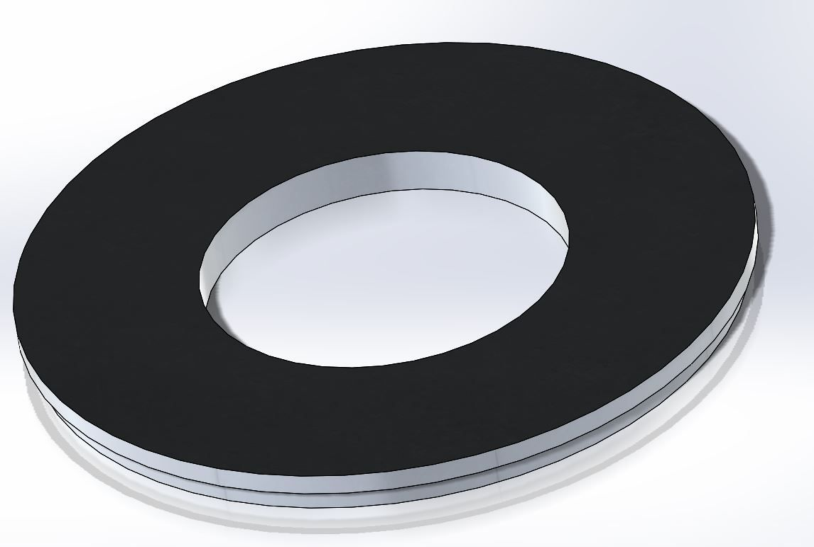


Figure 22: Thrust Plate CAD

3.2 Recovery Subsystem

3.2.1 Overview

The recovery bay will be made out of a G12 fiberglass coupler, switch band, and bulkheads. Inside of the coupler, there will be a customly designed electronics bay. The bay includes a redundant system of two Stratologger CF altimeters, a 3D printed 9V battery casing, and 3D printed switch standoffs.

Also part of the recovery subsystem is the GPS system. We will be using an Eggfinder GPS tracking system. The Eggfinder will have data logging capabilities through an OpenLog data logger. Both components will be hooked up to a Breadboard Power Supply Stick, which is connected to a LiPo battery pack.

Our selected parachutes include a SkyAngle CERT-3 XXL for the main and a SkyAngle Classic II 32” for the drogue. The drogue will deploy two seconds after apogee, and the main will deploy at 500 ft. Black powder will be used as our ejection charges, with separate charges connected to each independent altimeter.

3.2.2 Recovery Bay

Leading Design

The leading electronics bay design is built around a bulkhead perpendicular to the long axis of the rocket. The design features redundant altimeter and power systems, with 2 batteries and 2 altimeters. Multiple views of the electronics bay (without hardware) can be seen in the figures below.

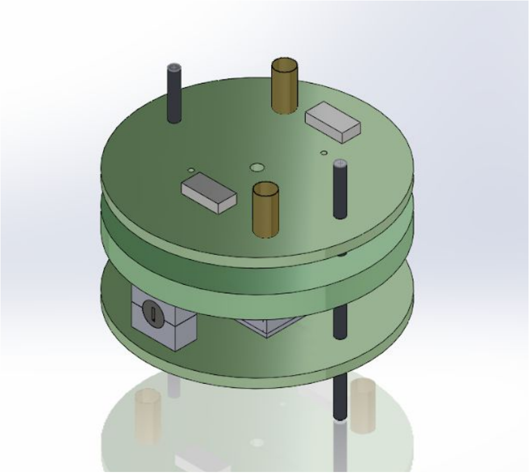


Figure 23: Isometric View of Electronics Bay

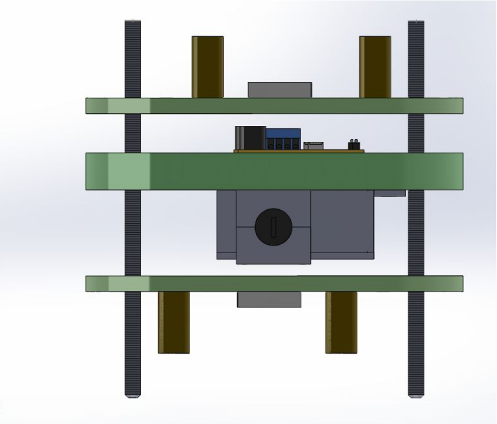


Figure 24: Front view of Electronics Bay

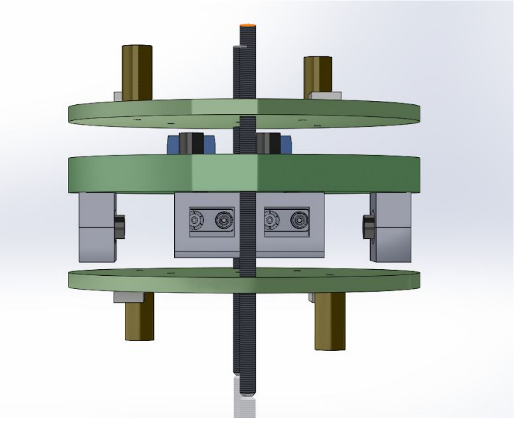
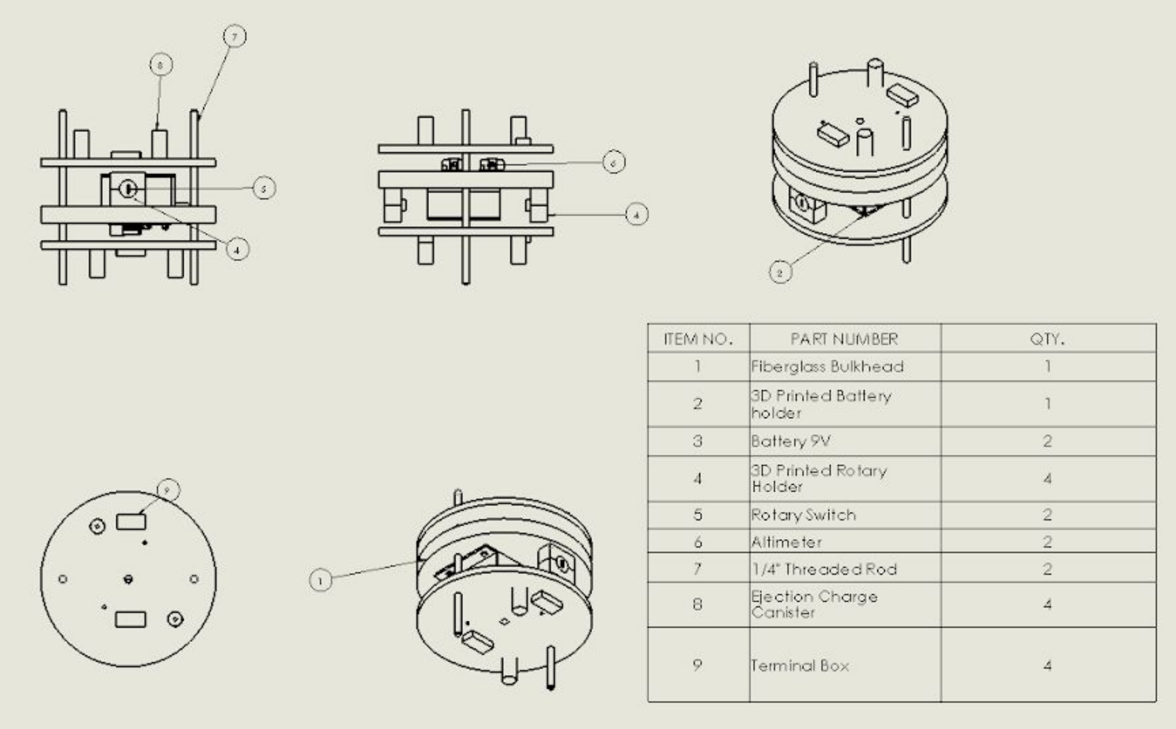


Figure 25: Right view of electronics bay

A bill of materials for the recovery bay and the locations of each component can be seen in the drawing below.



ITEM NO.	PART NUMBER	QTY.
1	Fiberglass Bulkhead	1
2	3D Printed Battery holder	1
3	Battery 9V	2
4	3D Printed Rotary Holder	4
5	Rotary Switch	2
6	Altimeter	2
7	1/4" Threaded Rod	2
8	Ejection Charge Canister	4
9	Terminal Box	4

Figure 26: Itemized Drawing of Leading Recovery Bay Design

In order to analyze how the recovery bay design will affect SCOTTIE as a whole, we have compiled an estimate of the mass of each component of the recovery bay and estimated the total mass of the recovery bay. These estimated mass values are given in the table below.

Table 15: Estimated Mass of Recovery Bay Assembly

Component	Estimated Mass of Component (g)	Number of Components in Recovery Bay	Total Estimated Component Mass (g)
Fiberglass Bulkhead	135.0	3	270.0
Stratologger CF Altimeter	10.77	2	21.54
9V Batteries	30.00	2	60.00
Battery Connector	15.88	2	31.76
Rotary Switch	3.690	2	7.38
Terminal Block	12.19	4	48.76
Eyebolt	0.7300	2	1.460
3D Printed Battery	35.00	1	35.00

Casing			
3D Printed Rotary Switch Standoffs	10.00	2	20.00
Ejection Charge Canisters	8.000	4	32.00
Threaded Rods (¼”-20)	13.83	2	27.66
Other Hardware	45.00	N/A	45.00
		Total Estimated Mass (g) **600.6**	

Leading Design Advantages

The leading design of the electronics bay has many positive aspects, which ultimately led us to choose the design over other competing designs. The orientation of the electronics sled inside of the electronics bay allows the entire coupler to be more compact. The whole coupler will be between four and five inches in length, which will save over seven inches of body tube space, as compared to last year’s design, which was twelve inches long. This saved space can be used for other components of the rocket and will also help cut back on weight.

The new design was created keeping simplicity and ease of construction in mind, so unlike other alternative designs, it will need very little 3D printing. The construction of the electronics bay is also simple in nature, requiring only screwing components into the fiberglass sled piece.

Battery Case

We decided for ease and simplicity of design and construction, to create and print our own battery case and cover. The batteries are housed in a 3D printed case on the underside of the bulkhead, and are secured by a cover with screws. The wires to power the altimeters and ignite the ejection charges will protrude through holes on each side of the case. The battery clips will attach to the batteries through a hole in the front of the case. The battery case can be seen in the figures below.

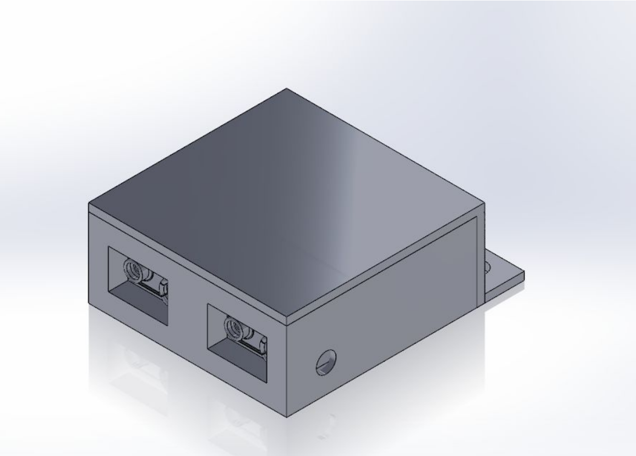


Figure 27: Isometric view of battery case with batteries inside

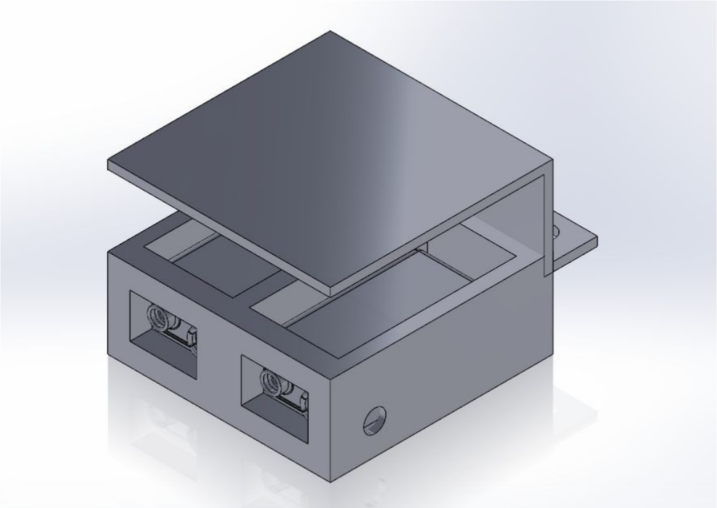


Figure 28: Exploded view of battery holder

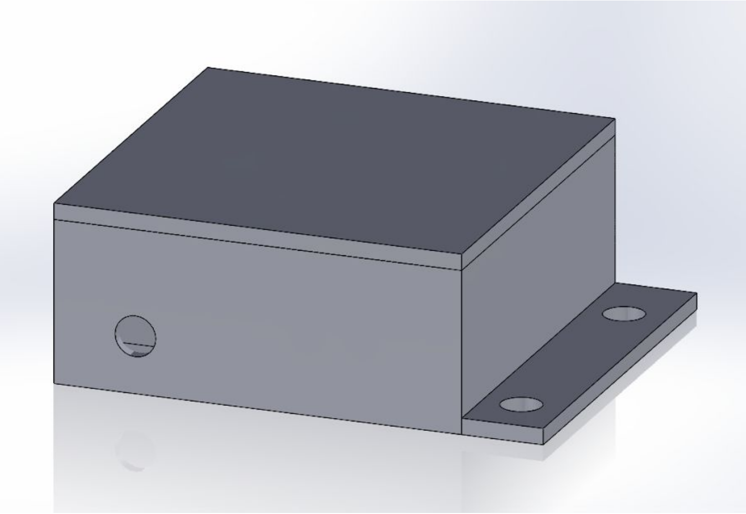


Figure 29: Side view of battery holder

Design Advantages

We could have used the battery cover system from the Additive Aerospace sled, that is pictured below, which we used in our recovery bay last year, but we found numerous advantages to creating our own.

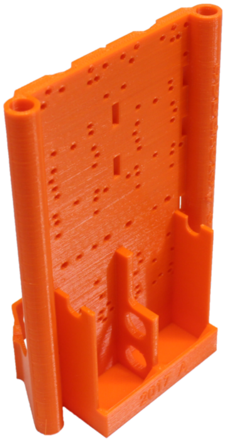


Figure 30: Additive Aerospace battery casing

Figure 31: Additive Aerospace battery cover

As you can see in the images above, the case that holds the batteries is connected to the sled. Because of this, we would have either had to use the Additive Aerospace sled or have used the Additive Aerospace (AA) battery cover and still 3D print our own casing. We did not want to use the AA sled because it is not nearly as compact as our sled design. Using the AA sled would have caused our rocket to have a bay length of twelve inches.

We also chose not to use the AA battery cover because the end is specially made to slide into a certain shaped slot. If you look closely at the end of the battery cover, you will notice that it has a triangular shape to it. This is the part of the cover that slides into the casing. In order to use this cover properly, we would have to 3D print a battery case that had an area to slide the exact shape and size of the end of the battery cover into. Designing a version that is easier to manufacture that still securely holds the batteries was the best choice.

This battery cover that we 3D print can be easily reused for future projects. It is designed to screw into and out of sleds without damage. Since it is not customly made for any particular sled design, it can be used in numerous different sizes and types of sleds. This will be an asset for Carnegie Mellon Rocket Command in future competitions.

Altimeters and Switches

The altimeters are located on the opposite side of the plate from the batteries, and are also secured with screws. To make sure the screws do not poke through and interfere, the batteries and altimeters are offset from each other. The switches for the altimeters are mounted on 3D printed plastic standoffs that will be secured to the main bulkhead with screws. By securing the switches to the sled, we are avoiding the possibility of having difficulties sliding the electronics bay into the body tube. Because the switches are secured to the sled, they will not get caught on other components of the rocket during assembly. This custom designed switch holder will ensure a strong grip on the switches throughout flight and will allow the switches to be reused. Holes will be needed in the recovery bay switchband to allow access to the arming switches. The altimeter switch holder can be seen in the figure below.

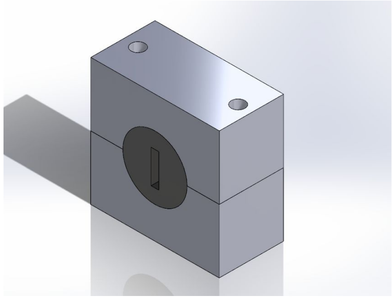


Figure 32: Isometric view of altimeter switch holder

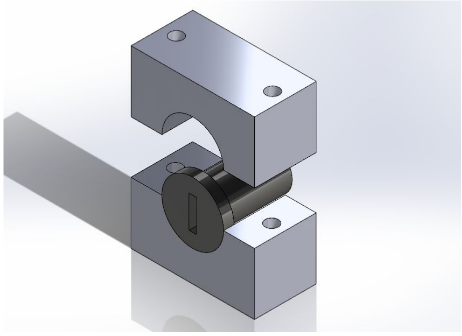


Figure 33: Exploded view of altimeter switch holder

3.2.3 Altimeters

The Recovery System includes two altimeters, which are used in order to analyze launch flight data. Features that the altimeters determine are the accuracy of different heights, the notification of when to release the black powder charges/parachutes, and the collection of data (including apogee). After the rocket reaches apogee, the altimeters will send redundant signals to fire the black powder held to confirm the altimeter reading and drogue chute deployment. As the rocket starts to descend, the altimeters will release another black powder signal at 500 feet to release the main parachute.

Data will be collected and transferred to a computer after the launch either wirelessly, or with other data transfer hardware and a software analytic program to be processed for future adjustments.

There are many options for high power rocket altimeters. These options have a wide range of capabilities and prices. A few altimeter choices have been summarized below.

Table 16: Altimeter Specifications

	PerfectFlite Stratologger CF	Missile Works RRC2+	Missile Works RRC3
Price	$58.80	$44.95	$79.95
Dimensions	2"L 0.85"W 0.5"H	2.28"L 0.925"W ~0.5"H	3.92"L 0.925"W 0.563"H
Weight	0.38 oz	0.35 oz	0. 59 oz
Altitude Accuracy	± 0.1%	Not given	Not given
Operating Voltage	9V nominal (4V to 16V)	9V(3.5VDC-10VDC)	9V(3.5VDC-10VDC)

The table above describes the different components of the altimeters we are currently evaluating. The altitude accuracy is the most important feature of the altimeter, therefore it is crucial that we compare and choose altimeters that have optimal precision. The dimensions, weight, voltage, and launch trigger are other factors that affect the recovery system electronics design and layout. In addition to the functions and characteristics of the altimeters, price is also an important consideration in relation to our budget.

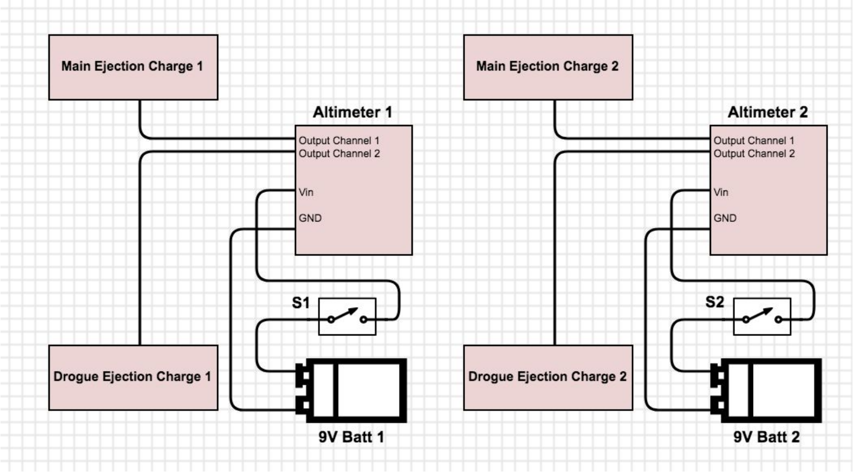


Figure 34: Altimeter Electronics Layout

Table 17: Overall Comparison Chart between altimeters

Altimeter	Pros	Cons
PerfectFlite Stratologger CF	● Audibly reports peak altitude & max flight velocity via beeps ● Up to 100,000’ msl altitude ● Output: drogue/main ● Collects 20 samples/sec ● Stores 16 flights ● (18 min/each) of data	● 2 output channels ● Does not include dt4u data transfer kit
Missile Works RRC2+	● Programmed using a DIP switch configuration ● Up to 100,000 msl altitude ● Programmable High/low audible beep tone ● Output: drogue/main ● Easily mountable ● 16 bit series mCU / altitude sensor has 24 bit ADC	● 2 output channels
Missile Works RRC3	● Reports peak altitude & max flight velocity ● Up to 100,000’ msl altitude ● Programmable High/low audible beep tone ● Altimeter sensor has 24 bit adc ● Stores 15 flights ● (28 min/each) of data ● 3 output channels: drogue/main/auxiliary	● Heavier ● Longer

Our primary choices for the two altimeters are the PerfectFlite Stratologger CF, and the Missile Works RRC2+. Both of these altimeters are very accurate as well as consistent. The PerfectFlite Stratologger CF and Missile Works RRC 2+ altimeters perform very well, and are affordable. Although the Missile Works RRC3 has more channels, the RRC 2+ has the advantage of its dimensions. The ability to fit the altimeters with the other electronics in the recovery system has higher precedence over an extra output channel. The altimeters can still be used as redundant systems to ensure the accuracy with or without the extra output channel.

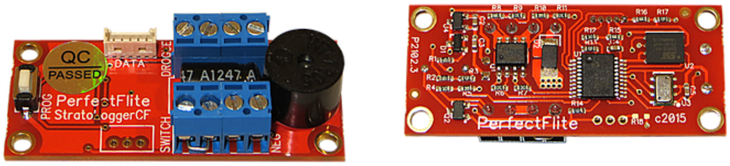


Figure 35: PerfectFlite Stratologger CF

Figure 36: Missile Works RRC 2+

Figure 37: Missile Works RRC 3

The first three images are the altimeters described and compared in the previous Altimeter Specs and Pros and Cons table. We ultimately chose to use the PerfectFlite Stratologger CF because of its small size and affordability.

Black Powder Charges

In order for our parachutes to eject properly and safely, we need to ensure that the altimeters will notify when the black powder charges should trigger, and that the correct proportion of black powder is prepared. The charge has to be enough to separate the airframes as well as cause the shear pins to disengage with the fiberglass frame. The calculations below come from the Ideal Gas Law; given the Pressure, Volume, and Combustion Temperature, we can find the black powder masses. The Volume is determined from the airframe, and its respective dimensions, and the Combustion Temperature is provided from the black powder specifications.

Apogee Rockets, the manufacturer for the shear pins we are purchasing, advise using a force of about 40 lbs/shear pin for our particular Nylon Screw. Since we are using four shear pins, we multiply to get a total peak, shear load of 160 lbs. To ensure SCOTTIE separates, we will use a force of 250 lb, this amounts to a pressure of ~8 psi. The typical recommended pressure from several rocketry sources is 8-15 psi. Although this force exceeds the force required by the distributor of the shear pins, we would rather have a little too much black powder, than run the risk of not deploying.

Using electronic matches to ignite the black powder in metal canisters, two charges will fire at either end of the electronic bay's bulk plates, when SCOTTIE reaches apogee as well as a second predetermined height. Calculations are provided below, describing how we reached the conclusion of using 1.16 g for our drogue chute at apogee, and 2.19 g for our main chute at 500'.

Givens:

$$Diameter\ (D) = 6.17"$$

$$length_{\ Main\ Chute\ Compartment}\ (l) = 17"$$

$$length_{\ Drogue\ Chute\ Compartment}\ (l) = 9"$$

$$Force = 250\ lbf$$

$$Black\ Powder\ Gas\ Constant\ (R) = 266\ \frac{in*lbf}{lbm}$$

$$Combustion\ Temperature\ (T) = 3307\ °R$$

$$1\ lbf = 453.59\ grams$$

Equations:

$$Area\ (cross\ sectional) = \frac{\pi D^2}{4} = \frac{\pi(6.17)^2}{4} = 29.90\ in^2$$

$$Pressure\ (p) = \frac{F}{A} = \frac{250}{\frac{\pi D^2}{4}} = \frac{250}{\frac{\pi(6.17)^2}{4}} = 8.361\ psi$$

$$Volume\ (V) = Area\ (A) * length\ (l) = \frac{\pi D^2}{4} * l = \frac{\pi(6.17)^2}{4} * l$$

$$pV = mRT$$

$$\therefore\ m = \frac{pV}{RT}$$

Table 18: Black Powder Masses

	Length (in)	Volume (in^3)	Mass (lbs)	Mass (g) per canister
Main Charge	17	508.29	0.00483	2.19
Drogue Charge	9	268.10	0.00255	1.16

3.2.4 GPS

Eggfinder GPS Tracking System

Carnegie Mellon Rocket Command will use the Eggfinder GPS Tracking system from Eggtimer. It transmits on the 900 MHz license-free ISM band at 100mW, and has a range of over 8000 feet without loss of signal using the included antenna, which will be more than sufficient for SCOTTIE’s predicted altitude. The Eggfinder system includes a TX transmitter module and an RX receiver module to form a complete GPS telemetry system.

The Eggfinder TX Module includes a Maestro Wireless GPS module that is accurate up to 2.5 m, and sends out a position update every second. The transmitter is powered from a single 2S 7.4V LiPo battery source connected to a Power Stick, and will draw current at 70-100 mA during operation and 10-20 mA during standby. This battery will allow the Eggfinder GPS to maintain full functionality during the time the launch vehicle is on standby on the launch pad and during the flight.

The Eggfinder RX Module can be connected by USB cable into a computer. It uses a simple serial-NMEA data connection to stream the data transmitted from the Eggfinder TX module.

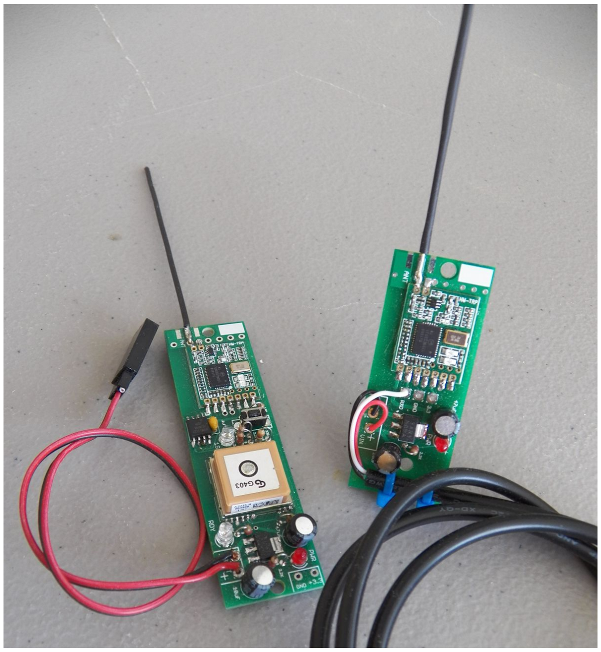


Figure 38: Eggfinder TX Module (left) and RX Module (right)

Data Logging Capabilities

In order for our payload to be successful, the GPS system must have a data logging capability. The Eggfinder TX can be interfaced with a data logging system like OpenLog, which would write data to an on board microSD memory card. The SparkFun OpenLog uses an ATmega328 running at 16MHz. The OpenLog draws approximately 2-3mA in idle mode. During a full record

OpenLog can draw 10 to 20mA depending on the microSD card being used.The OpenLog is an open source data logger that works over a serial connection. It can store up to 32GB of data, depending on the size of the microSD card that you decide to use. A picture of the OpenLog data logger can be seen below.

Figure 39: OpenLog Data Logger

To connect the Eggfinder to the OpenLog, the TX pin from the Eggfinder must be connected to the RX pin on the OpenLog. Then the GPS and the OpenLog will both be connected to a Breadboard Power Supply Stick. This allows for the GPS and the OpenLog to each have their own regulated power souce. The Power Stick takes the LiPo battery voltage and will output a either 5V or 3.3V. The Power Stick is shown in the following image.

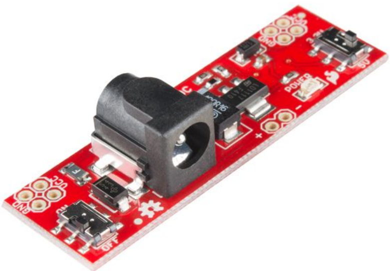


Figure 40: Breadboard Power Supply Stick

The Power Stick will be connected to a 7.4V LiPo battery pack. This battery pack is small in size and does not weight very much, but gives out enough power to supply the Power Stick. It is much more compact than a 9V battery and allows us to supply the correct amount of power to the Power Stick. Therefore a LiPo Battery is the best choice for the GPS and OpenLog circuit shown below.

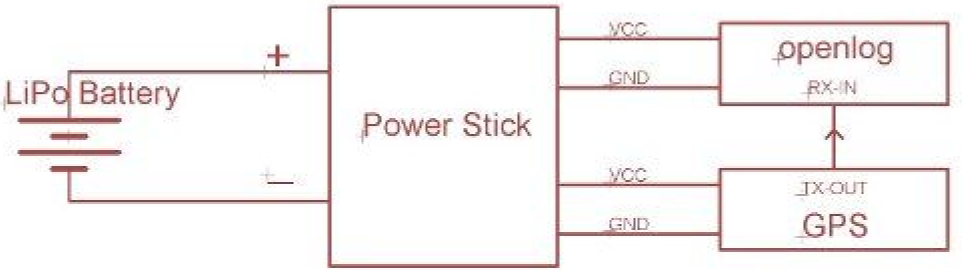


Figure 41: GPS and OpenLog Circuit

Other GPS Options

Our main alternative is the Beeline 100 mw GPS system. The Beeline 100mw GPS system is one of the most popular hobby grade GPS systems. It includes a GPS receiver and antenna, a microcontroller-based APRS data encoder and 70 cm radio transmitter. It also features a serial connector that can be used for wired data transmission.

The unit can run for up to 10 hours on its integrated one cell LiPo battery, with the ability to record data at a rate of 1hz for about two hours. The recorded data includes latitude, longitude and altitude. The unit is programmable, and the programming software may be downloaded in the device’s user manual. Charging, programming and setup of the transmission characteristics are all controlled via USB interface.

Beeline offers a similar product which transmits with at a power level of 16 mw. The advantages of this unit is that it is slightly cheaper, and the lower power level means that it may be less likely to interfere with deployment altimeters. However, the 100 mw unit is newer, slightly lighter, and features a configurable transmission power level.

One important note is that the unit may require up to 20 minutes to acquire a satellite lock once turned on. Also, the unit’s integrated microcontroller includes no safety mechanisms to protect against overcharging and over-discharging of the integrated battery. Furthermore, this GPS will require an amateur radio licence to use, which is the main reason for choosing the Eggfinder over the Beeline.

Location of GPS System

The GPS System will be located in a 3D printed casing that will be attached to the interior wall of the body tube. The proposed location for the casing is below the recovery bay.

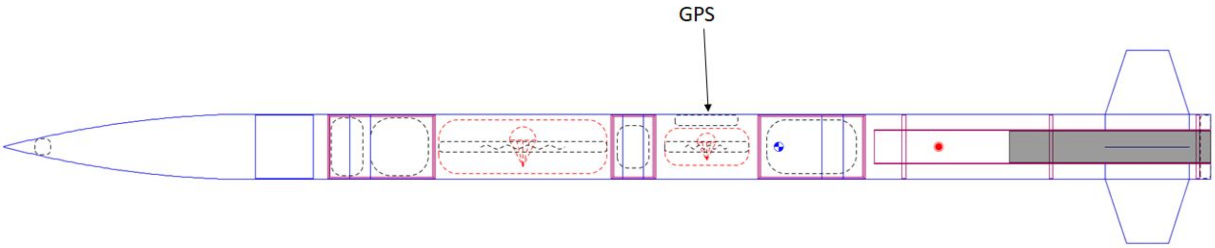


Figure 42: Proposed GPS System Location

The 3D printed housing module will be around eight inches in length, so that it is able to house the GPS system, the OpenLog, the LiPo battery pack, and the Power Stick. The housing module will be secured to the inner wall of the rocket by screws. These screws will be heavy duty enough that they are not torn out when the ejection charge is lit. They will most likely be secured with epoxy as well. A rough sketch of the general shape of the GPS housing module is shown below.

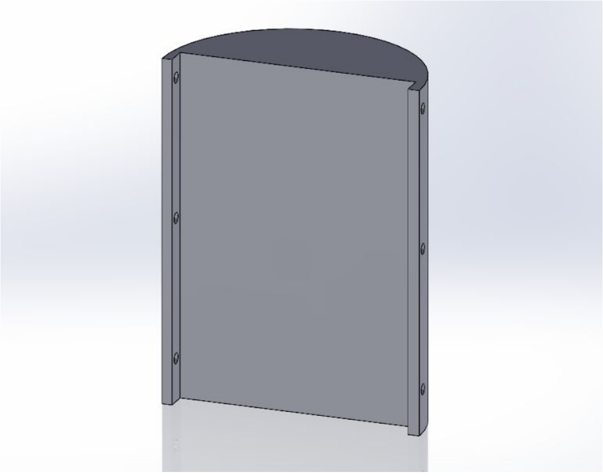


Figure 43: Rough CAD of GPS Housing for Interior Wall

Of course, there will be housing sections for each part of the GPS system that will be integrated into the CAD later on. However, this model shows the general shape of the 3D printed casing. As you can see, the casing will follow the curvature of the rocket's body tube in order to ensure that it is secured. There will be epoxy, in addition to screws in the side tabs of the casing, applied to the curved portion of the module to redundantly make sure that it does not detach when the ejection charge is lit. This design will allow the team to easily access the GPS system at any point during assembly. Therefore, it will be easy to turn the GPS on and off when needed. Also, this design is very rigid and secure. With a hard plastic casing around it, all components of the GPS system will be safe throughout flight.

Another option as to where the GPS system could be housed is in a 3D printed sled that will be affixed to the shock cord connecting the nose cone to the upper air frame. The sled would be more compact than the sled on interior wall of the vehicle, and it would also have a metal eye bolt attached to one end in order to secure it to the shock cord. The shock cord GPS holder design could look something like this, but with an additional housing section for the data logger.

Figure 44: GPS Shock Cord

Housing Design

We ultimately decided to not use this location for the GPS because it would be difficult to turn the GPS system on. We would have to make sure that the system was on before assembling the rocket. Because the GPS system is located on the inner wall of the body tube, it can easily be turned on while on the launch rod.

3.2.5 Parachutes

Parachutes are integral to the successful recovery of our launch vehicle. The drogue, which deploys at apogee, must be small enough to prevent SCOTTIE from falling too slowly and drifting far away, but also must be large enough to minimize the shock that occurs when the main parachute deploys. The main parachute must be sufficiently sized in order to prevent any independent section of the launch vehicle from exceeding the kinetic energy limit upon landing, as well as ensuring that the launch vehicle will not drift outside the allotted 2500 ft radius. Furthermore, all parachutes must be able to fit inside the airframe sections when properly and safely packed, and the design of the parachute must be conducive to preventing the shroud lines from getting tangled. With these parameters, CMRC performed the parachute analysis.

First, the main parachute was considered. Using the total mass of the launch vehicle after motor burnout, we determined the velocity at which the rocket would land as a function of the $A*C_D$ of the parachute. When we take the rocket and the main parachute as the system at a terminal velocity with a parachute, $\Delta p = 0$. Thus, according to Newton's Second Law:

$$\Delta p = F_{net,\, ext}\Delta t$$
$$0 = F_{gravity} - F_{drag}$$
$$F_{gravity} = F_{drag}$$
$$Mg = \frac{Cd\rho V^{2}A}{2}$$
$$V = \sqrt{\frac{2Mg}{\rho A C_D}}$$

Note that M is the total mass of the rocket during the recovery phase. Now the kinetic energy can be calculated using the equation,

$$KE = \tfrac{1}{2}mV^{2}$$

Note that for this equation, m is the maximum mass of any independent section. Since we assume that all sections land at an identical velocity, the section with the highest mass will have the highest kinetic energy. Using this relationship, we can determine the minimum A*C_D of a parachute that will allow the rocket to satisfy the kinetic energy condition.

Table 19: Independent Section Masses for KE Calculations

Section	Mass (oz)
Upper Section	99.13
Middle Section	199.70
Lower Section	313.40
Total Landing	612.23

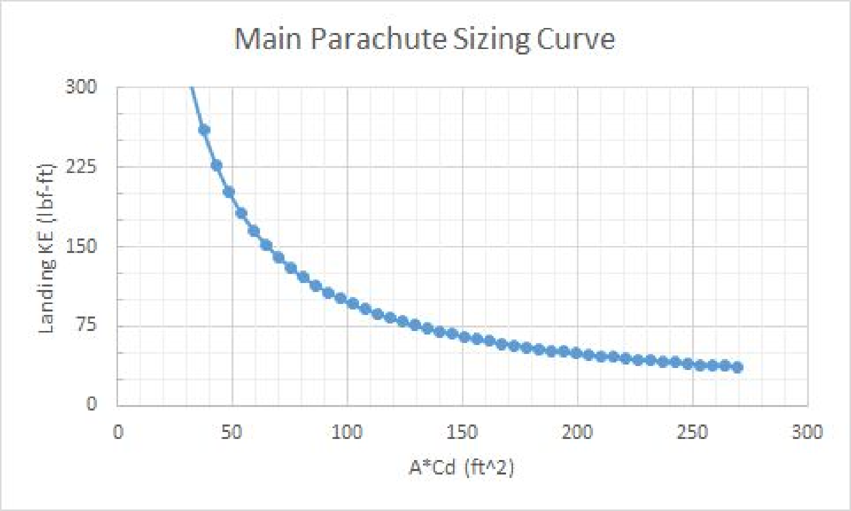


Figure 45: Main Parachute Sizing Curve

From the main parachute sizing curve, we found that the parachute required an A*C_D of at least 135 ft^2. Our competing parachutes were the Skyangle CERT-3 series, Iris Ultra Standard series, and the Rocketman Standard series. Based on information collected from the suppliers, effective A*C_D terms were evaluated for all parachutes. Note that for some suppliers, a C_D was not provided, but rather an expected terminal velocity for a given mass. By manipulating the equations above, we can solve for A*C_D even if not provided by the supplier directly.

Table 20: Parachute Summary

Parachute Name	Area (ft^2)	C_D	A*C_D (ft^2)	Cost
CERT-3 XXLarge	59.87	2.92	174.81	$239
Iris Ultra 120”	76.11	2.200	167.44	$402
Rocketman 14 ft	201.06	0.770	156.85	$155

SkyAngle CERT-3

This parachute design is a canopy with panels, made of rip-stock nylon with thick mil-spec tubular nylon suspension lines. It is also asymmetrical, which allows the parachute to spin naturally more than a symmetrical parachute would. This natural spin helps to minimize oscillation and shaking of the vehicle on the way down as well as preventing shroud lines from getting tangled. One disadvantage of this parachute, however, is the bulky size. These parachutes typically are the largest of their class, with the XXL requiring 16” of length in a 6” airframe for packing.

Figure 46: SkyAngle CERT-3

Fruity Chute Iris Ultra

This parachute design is toroidal, which is known for high drag for low packing volume. Shroud lines connected to the inner rim pull down during descent to create a torus shape which increases the drag of the parachute. This high efficiency means that a smaller diameter can be used to generate the same amount of drag, thus decreasing the overall volume of material required. The Iris Ultra 96” would only require a little over 7” of length in a 6” diameter airframe tube. However, these benefits come at a price; the Iris Ultra parachutes are by far the most expensive at $402 for the 96”.

Figure 47: Fruity Chute Iris Ultra

Rocketman

This parachute design is a canopy with panels, similar to the CERT-3. It is made of low porosity rip-stock nylon and tubular shroud lines. The primary benefit of the Rocketman is the economical price of $155, which is the lowest out of all parachutes considered. In terms of design, the Rocketman is unique in that no shock cord is required for recovery; the four shock cords are made of tubular nylon which can withstand the shock of deploying the parachute.

Figure 48: Rocketman Parachute

CMRC has chosen the SkyAngle CERT-3 XXL as the main parachute for the leading design, with the Iris Ultra 96” as an alternative if the size constraints of the CERT-3 become too burdensome and there is sufficient funding for the additional cost.

The drogue parachute was considered next. For a successful drogue, the descent time must be less than 90 seconds, and the shock at opening the main must be less than the maximum force that the shock chords are designed for with a reasonable factor of safety. Flight simulations in Section 3.3 provide us with information on the duration of decent and acceleration of the launch vehicle during main parachute deployment. Through various simulations we have found that in order to achieve a 90 second decent time, an approximately 32” drogue parachute is required. Based on these parameters, we have chosen the SkyAngle Classic II 32” as the leading drogue parachute choice.

3.2.6 Shock Cords

Shock cords will be used to tether all independent sections of the rocket. One shock cord will connect the upper section to the middle section, which will absorb the shock of the main deploying. The other shock cord will connect the middle section to the lower section, which will absorb the impact of the drogue deploying.

CMRC considered kevlar and tubular nylon shock cords. Kevlar is notably stronger, however it is also stiffer than tubular nylon. Therefore although it can take higher loads without breaking, it will not extend as much while loaded. This will create a large impulse on the launch vehicle as the main parachute deploys, which could cause damage to other components. Tubular nylon, however, is more elastic. It will elongate and thus spread the shock of the main deploying out over a longer period of time. This will reduce the impulse that the rocket experiences and help to protect the electronics. However, the max load is lower so a larger size shock cord would be required to have the same factory of safety.

Table 21: Shock Cord Comparison

	Maximum Load	**Cost per yard**
Tubular Shock Cord	4000 lb	$1.87
Kevlar Tubular Shock Cord	7200 lb	$3.89

Given the mass of the launch vehicle, we believe that the investment of additional mass is warranted in order to reduce the shock of parachutes deploying, and so CMRC has chosen to use tubular nylon shock cords for the preliminary design. There will be 20 feet connecting each independent section, and each will be tied to the eye-bolts that are epoxied to the bulkheads of each coupler.

Figure 49: Tubular Nylon Shock Cord

3.3 Mission Performance Predictions

3.3.1 Overview

The key mission performance prediction parameters of the launch vehicle are summarized below. All of these values will be discussed further in later sections. With respect to apogee, the official target is 5100 ft. In order to achieve this, CMRC will use a variable amount of ballast to bring SCOTTIE to approximately 5300 ft. Then, the ATS system will be utilized to increase drag and reduce the apogee further to 5100 ft. This will allow for SCOTTIE to correct for any variation in weather condition that might cause the flight path to deviate from our calculations, and thus we can achieve a specific apogee with each launch.

Table 22: Mission Performance Prediction Parameters

Parameter	Value
Official Apogee Target	5100 ft
Static stability margin at rail exit	2.72 cal
Velocity at rail exit	72.2 ft/s
Maximum velocity	614 ft/s
Maximum ballast	41.6 oz
Drogue parachute deployment timing	Apogee + 2 sec
Main parachute deployment altitude	500 ft
Maximum landing kinetic energy	56.03 lbf-ft
Maximum recovery radius	2300 ft
Descent time	89.4 sec

3.3.2 Motor Selection and Flight Profiles

The propulsion system selection criteria is as follows:

1. The motor must be reloadable
2. It must be manufactured by CTI or Aerotech
3. The output apogee range must be within a range of 5300 - 6000 ft
4. The required ballast to lower the apogee to 5100 ft must be less than 10% of the total design weight, including the motor
5. Must provide a rail-exit velocity of above 52 ft/s
6. Must be commercially available with multiple suppliers
7. Must be an L-class motor

Reloadable motors require a higher initial investment compared to single and hybrid classes. However, since the cost per propellant is much less than the cost of a whole new motor, the investment pays back significantly in the long run. Given the wide variety of reloadable motor options, we have opted to limit our search to these motor types. Furthermore, based on past experience, we believe that limiting our search to motors manufactured by CTI and AeroTech will help ensure that our motor will have high commercial availability and up-to-date technical documentation. By limiting to motors that will produce an apogee between 5300 - 6300 ft, we can ensure that through a combination of adding ballast and using the ATS system to induce extra drag, we will be able to achieve our target apogee of 5100 ft. After filtering through motors and running simulations in Open Rocket, the following motors have satisfied all criteria.

Table 23: Primary and Secondary Motor Choices

Motor	**Diameter**	**Type**	**Peak Thrust**	**Average Thrust**	**Duration**	**Total Impulse**	**Class**
CTI L1350	75mm	Reloadable	1672.5 N	1349.6 N	3.2 s	4263.1 Ns	67% L
AeroTech L1420	75mm	Reloadable	1814.0 N	1420.0 N	3.2 s	4603.0 Ns	80% L

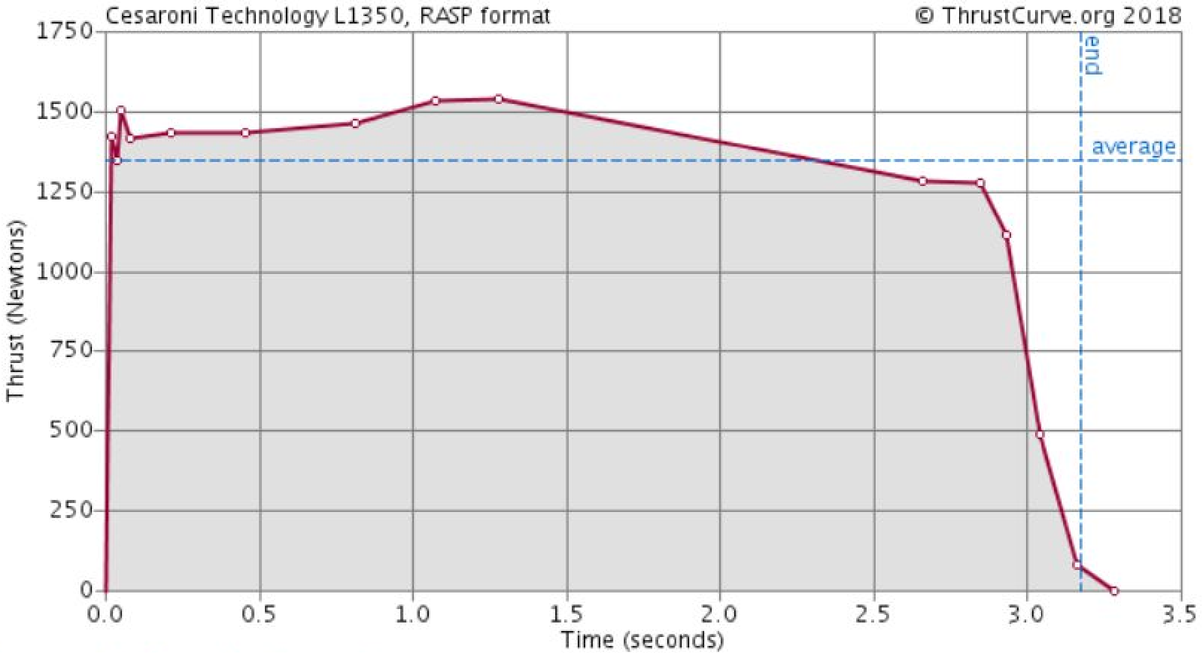


Figure 50: CTI L1350 Thrust Curve

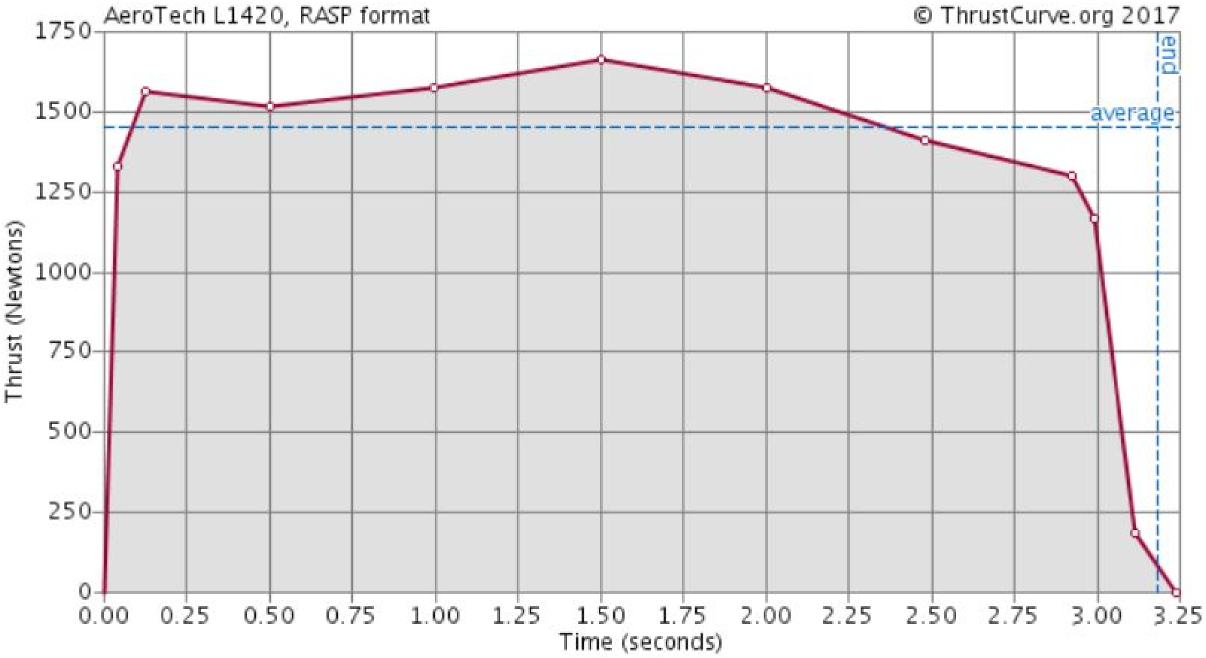


Figure 51: AeroTech L1420 Thrust Curve

We found that without ballast, the CTI L1350 resulted in apogees between 5400 to 5600 ft as shown in the figure below. This matches well with our ideal apogee ranges, and the required ballast to bring the apogee down to a constant value is within the 10% maximum of the launch vehicle mass, making this motor the ideal candidate for the launch vehicle. In comparison, the AeroTech L1420 resulted in apogees between 5950 and 5750, which is on the higher end of the apogee ranges we were looking for. With ballast, the AeroTech L1420 can achieve a constant 5300 ft apogee, as shown in the figure below. However, to achieve a constant apogee of 5200 ft or 5100 ft, the launch vehicle would require more than 10% of the total mass as ballast. For this reason, the AeroTech L1420 is kept as a backup motor if the final launch vehicle is heavier than the current design. For heavier designs, this motor would produce a more viable option. If the launch vehicle became lighter, we would simply remove ballast from the CTI L1350 configuration.

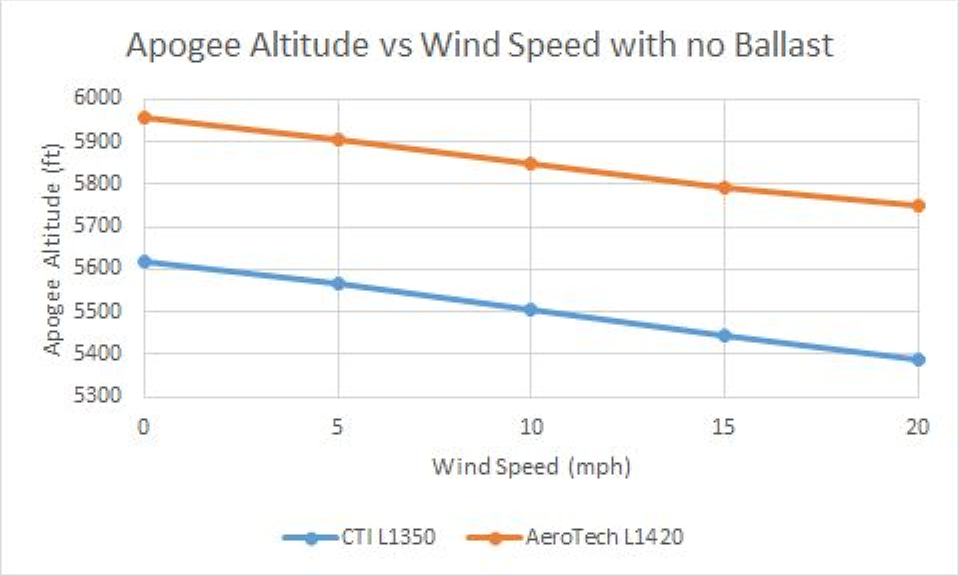


Figure 52: Apogee vs Winds Speed with no Ballast

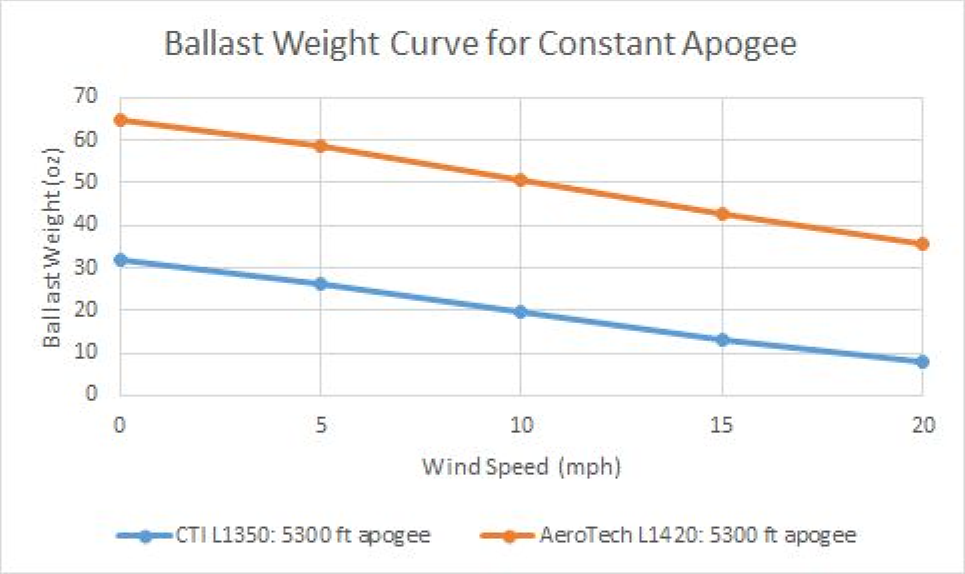


Figure 53: Ballast Weight Curve for Constant Apogee

Table 24: Ballast Curve for CTI L1350

Wind Speed (mph)	**Ballast weight (oz) required for constant apogee**		
	5100 ft	5200 ft	5300 ft
0	51.75	41.64	31.75
5	45.67	35.83	26.13
10	38.18	28.81	19.58
15	30.53	21.72	13.15
20	23.52	15.52	7.69

Table 25: Ballast Curve for AeroTech L1420

Wind Speed (mph)	**Ballast weight (oz) required for constant apogee**		
	5100 ft	5200 ft	5300 ft
0	85.95	75.45	64.45
5	79.19	68.79	58.55
10	70.53	60.45	50.81
15	61.14	51.95	42.75
20	52.62	43.99	35.51

3.3.3 Flight Profile Simulations

With the CTI L1350 considered as the primary motor, we performed more rigorous flight profile simulations. All flight profile simulations were conducted assuming a 12 ft launch rod at a 5 degree angle. Various wind speeds and wind angles were applied over different simulations. Note that for each wind speed, the appropriate amount of ballast was added to ensure that the apogee was kept constant at around 5100 ft in order to simulate the apogee of the launch with the ATS system deployed.

The default launch assumed no wind speed. Based on the flight profile, we can see that the apogee is within 21 ft of the goal, real exit velocity is greater than 52 ft/s, max velocity is less than mach 1, landing velocity agrees with values calculated for kinetic energy, and decent time is below 90 seconds.

Table 26: Default Launch Performance

Test Name	Apogee (ft)	Rail Exit Velocity (ft/s)	Max Velocity (ft/s)	Landing Velocity (ft/s)	Descent Time (s)
Default Launch	5079	78.7	594	13.0	89.6

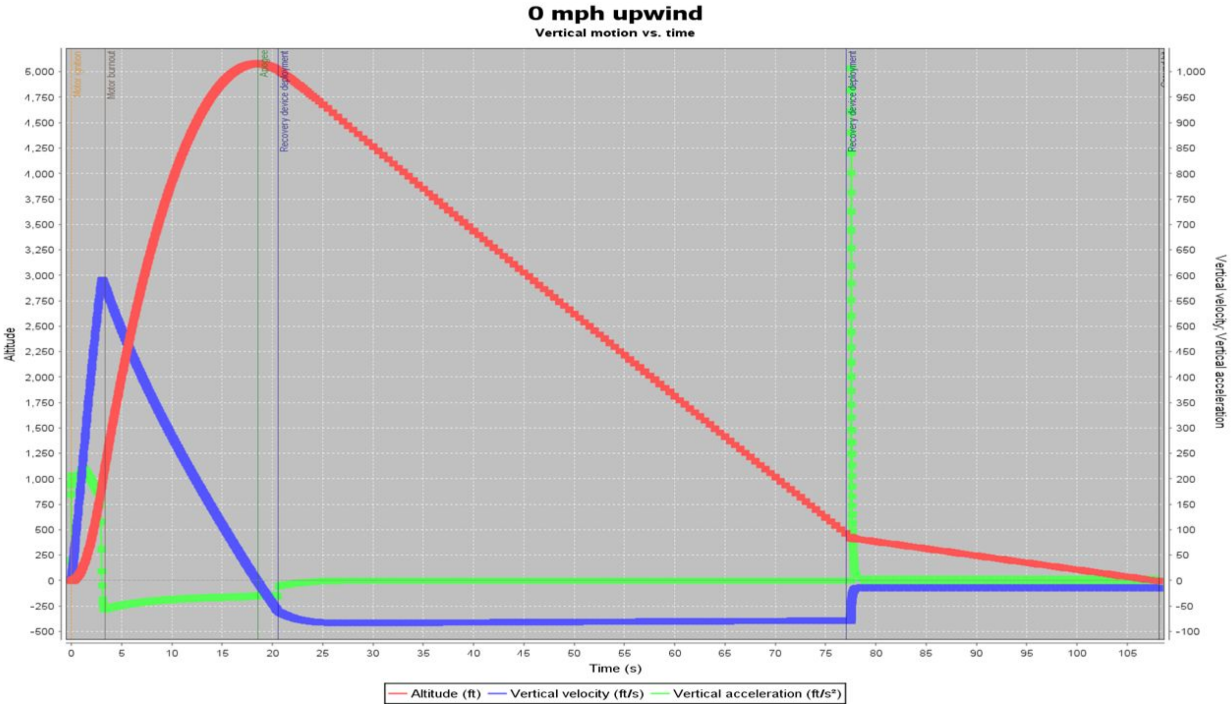


Figure 54: CTI L1350 with 0 mph wind

We also studied the effect of turbulence on the apogee of the launch vehicle. Using a 15% turbulence, which sets the standard deviation of wind speeds to 15% of the set value for wind speed, we recorded the corresponding variation in apogee altitude. Shown below, we see that the maximum amount of variation is around 25 ft, which is not very significant. Other factors such are paint job, sanding, and miscellaneous screwheads on the launch vehicle will likely account for a far greater impact on apogee than turbulence.

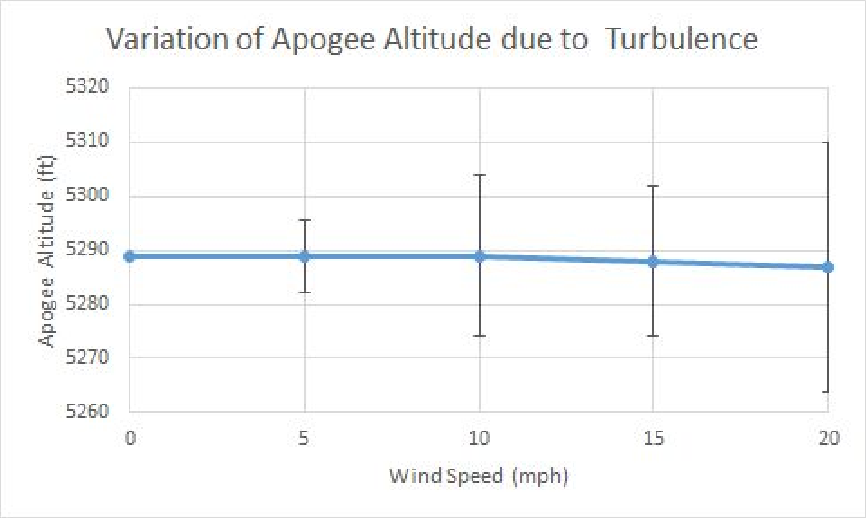


Figure 55: Variation of Apogee Altitude due to Turbulence

3.3.4 Stability Margin

The following table summarizes the static stability of the launch vehicle with each potential motor. Note that the AeroTech L1420 motor requires a minimum of 16.5 oz of ballast to meet the CMRC derived requirement of 2.20 cal static stability, while the CTI L1350 can satisfy the requirement without any ballast.

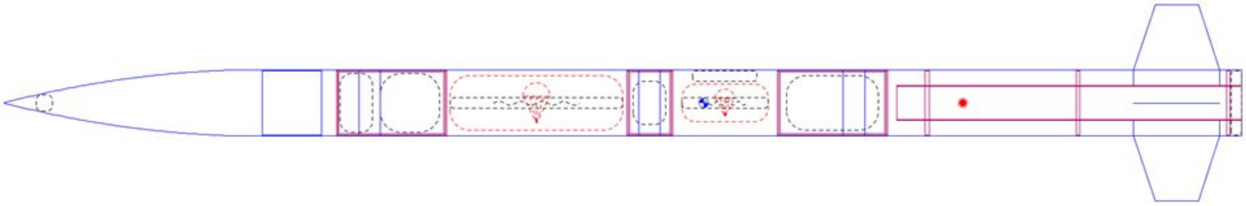


Figure 56: Stability with No Motor

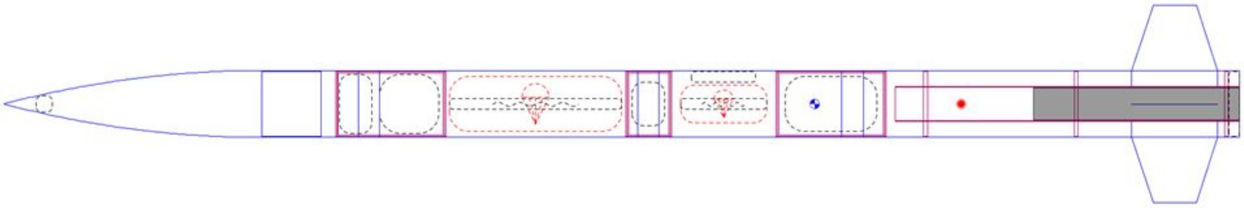


Figure 57: Stability with CTI L1350, min ballast

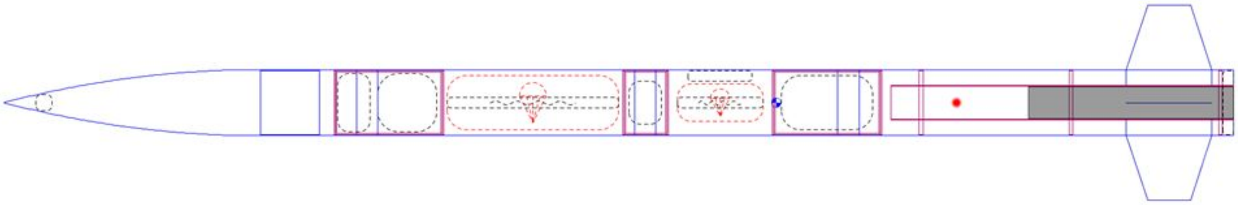


Figure 58: Stability with CTI L1350, max ballast

Table 27: Static Stability of Launch Vehicle

Case	Stability Margin (cal)	CG Location (in from tip)	CP Location (in from tip)
No Motor	3.33	68.596	89.114
CTI L1350, min ballast (0 oz)	2.20	75.541	89.114
CTI L1350, max ballast (31.75 oz)	2.73	72.284	89.114
AeroTech L1420, min ballast (16.5 oz)	2.20	75.541	89.114
AeroTech L1420, max ballast (65 oz)	2.94	71.004	89.114

The stability margin will also change dynamically during flight. This occurs as the mass of the fuel is ejected and the angle of the launch vehicle changes during flight. Below is a plot of the CP and CG locations and the overall stability margin. We can see that the CG moves forward over time as the fuel is depleted, thus increasing the stability margin. The center of pressure remains relatively constant during ascent, and then greatly fluctuates as the drogue parachute is deployed after apogee. However, stability is no longer a concern at that point so the fluctuation can be disregarded. Based on these simulations we find that the launch vehicle in any configuration can be made stable with ballast that weighs less than 10% of the total mass.

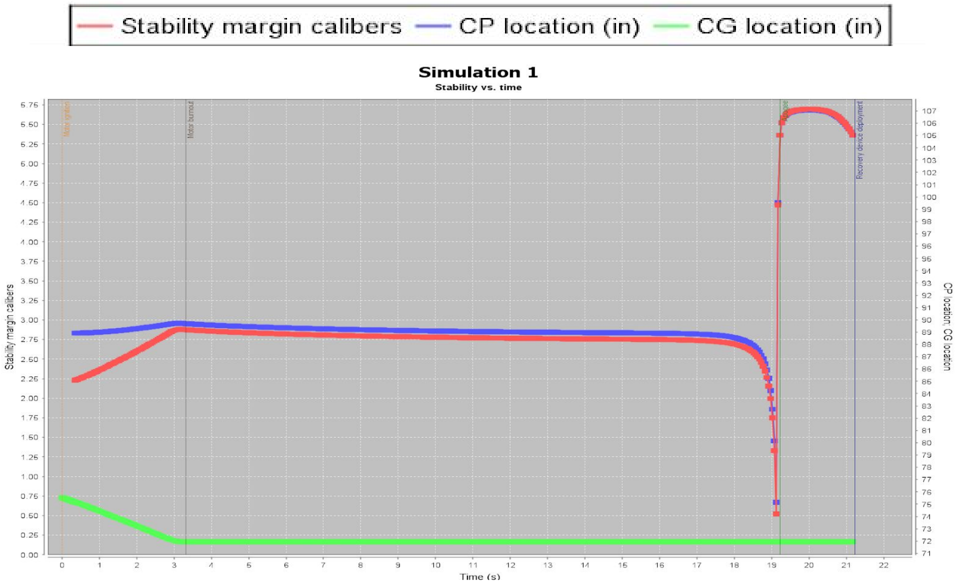


Figure 59: Dynamic Stability of Launch Vehicle

3.3.5 Kinetic Energy

Using the parameters of the selected main parachute, the SkyAngle CERT-3 XXL, and the equations for terminal velocity and kinetic energy derived in section 3.2.5, we can find the kinetic landing of each independent section of the launch vehicle.

$$V = \sqrt{\frac{2Mg}{\rho A C_D}} = \sqrt{\frac{2(38.25\ lbm)(32.2\ ft/s^2)}{(0.0765\ lbm/ft^3)(174.81\ ft^2)}} = 13.57\ ft/s$$

$$KE = \tfrac{1}{2}mV^2 = \tfrac{1}{2}(19.59\ lbm)(15.73\ ft/s)^2/(32.2\ lbm/slug) = 56.03\ lbf - ft$$

Table 28: Kinetic Energy Summary

Section	Mass (oz)	Kinetic Energy (lbf-ft)
Upper Section	99.13	17.72
Middle Section	199.70	35.70
Lower Section	313.40	56.03
Total Landing	612.23	N/A

3.3.6 Drift Calculations

In order to estimate the maximum bounds on drift, we performed three simulations at the maximum wind speed of 20 mph. The direction of the wind was varied in comparison to the launch angle. For upwind, the launch vehicle was angled into the wind. This resulted in very little drift as the wind carries the launch vehicle back towards to the launch site. For downwind, the rocket is angled in the the same direction of the wind. This resulted in very high drift since the rocket continually is pushed away from the launch site. However, it stays well within the 2500 ft radius. For crosswind, the launch vehicle was launched perpendicularly to the direction of wind. This resulted in a moderate amount of drift.

Table 29: Maximum Drift given windspeed

Test Setup	Apogee (ft)	Maximum Drift (ft)
20 mph upwind	5078	151
20 mph downwind	5091	2152
20 mph crosswind	5091	1175

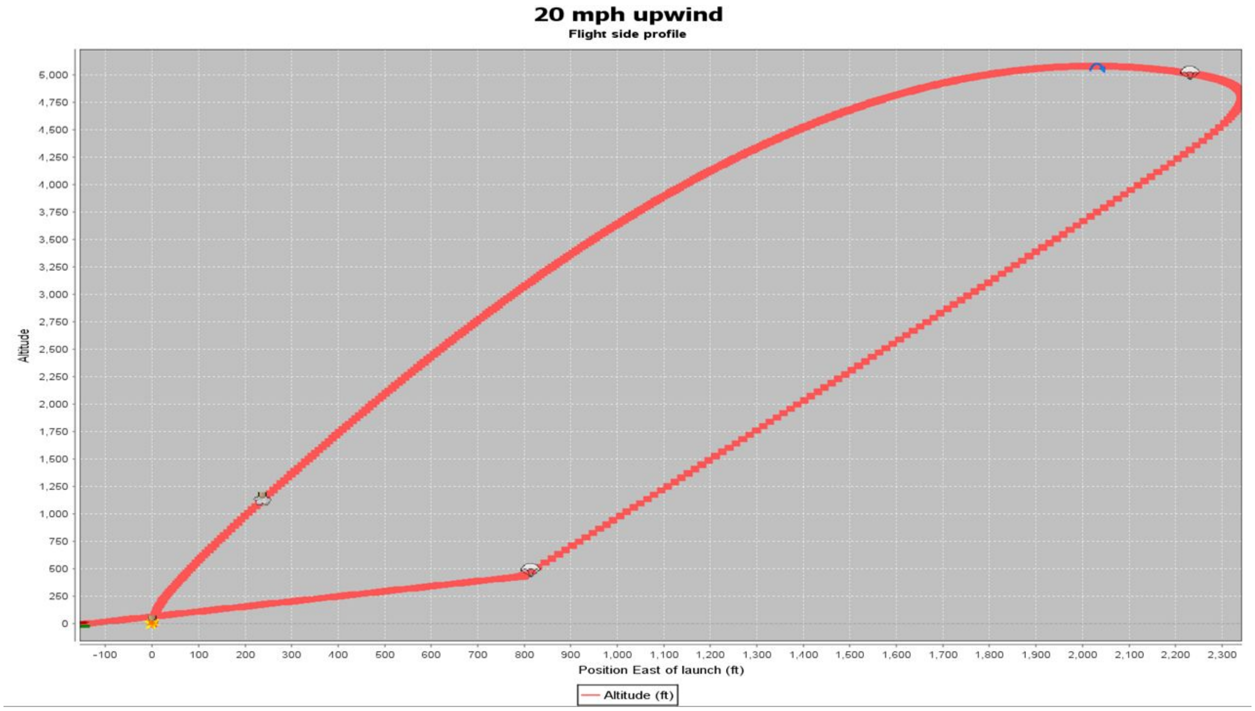


Figure 60: Flight with 20 mph winds launching upwind

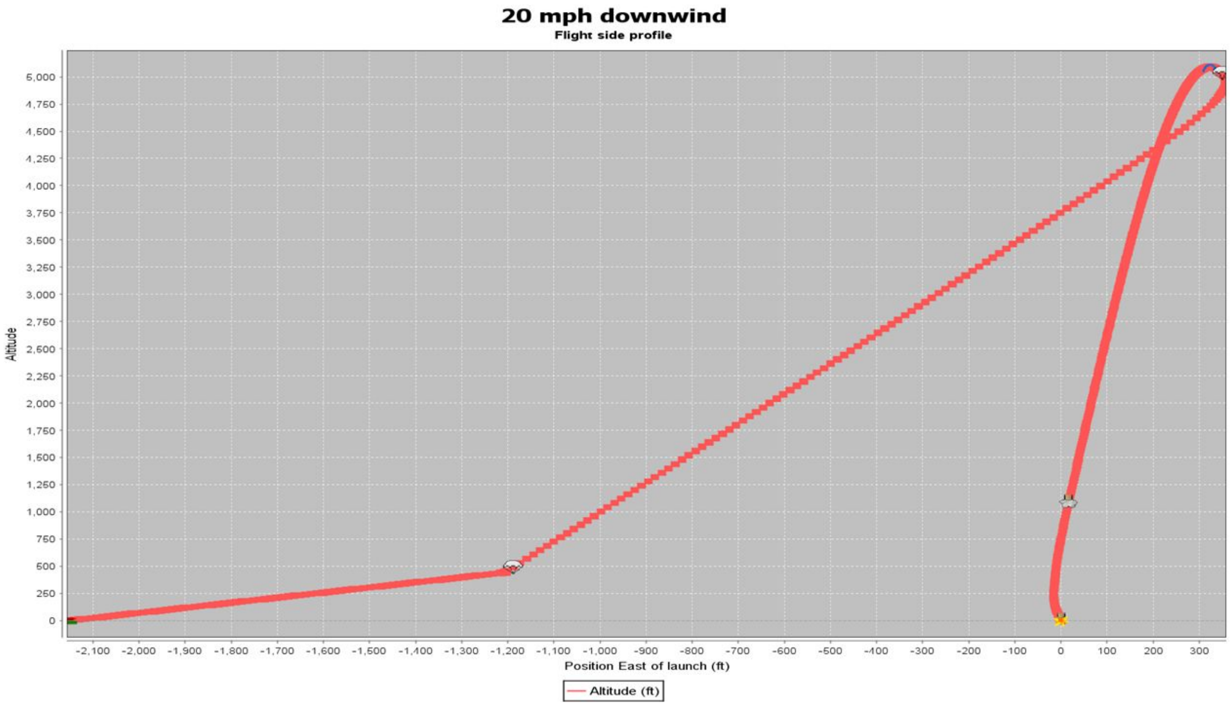


Figure 61: Flight with 20mph winds launching downwind

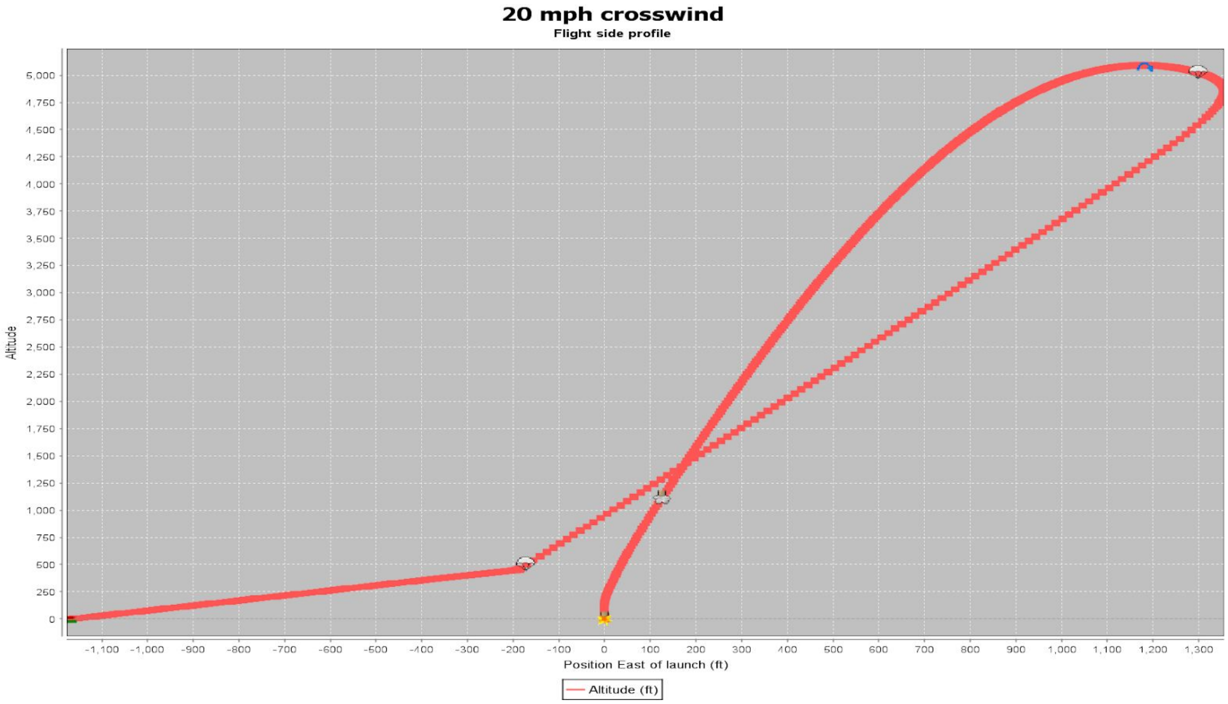


Figure 62: Flight with 20mph winds launching crosswind

Based on this, we concluded that launching downwind results in the most amount of drift for any launch configuration. Therefore all future drift calculations are assumed to be launched downwind. These tests were repeated for 0, 5, 10, 15 and 20 mph configurations.

As a second verification method, we can also assume that the rocket will drift at the same velocity as the wind. Assuming a perfectly vertical launch, we can then estimate the total drift of the launch vehicle using the determined descent time.

Table 30: Predicted Drift Approximation

Wind Speed	Open Rocket Predicted Drift	Predicted Drift
0	1198	0
5	1320	657
10	1568	1314
15	1823	1971
20	2152	2628

It could be noted that for 20 mph, the predicted total drift of the launch vehicle exceeds 2500 ft. However, this approximation method is known to overestimate the total drift, which can be shown by the nearly 500 ft difference between the simulated drift and the approximated drift. The reason for this is that the assumption of the launch vehicle drifting at the speed of the wind in not accurate and will always cause the launch vehicle to drift faster than it naturally would.

In order to fully satisfy this requirement, with the both simulated methods and approximation predicting under 2500 ft for drift at 20 mph winds, the descent time would have to be decreased to 85 seconds. In order to achieve this, there are several possibilities. First, the drogue could be decreased, however this would dangerously raise the impulse of deploying the main parachute. Second, we could have the launch vehicle descend in two sections, allowing both to fall at a faster rate. However, since this would require a significant redesign, and that the Open Rocket simulations show the launch vehicle landing well within the 2500 bounds, CMRC does not believe it to be advisable to change the design at this time. In future design reviews, the drift will be reconsidered as to whether additional measures need to be taken.

3.4 Apogee Targeting System

3.4.1 Overview

The apogee targeting system (ATS) is a feedback-driven airbrake system used to actively control the kinetic energy of the launch vehicle so that the desired apogee of 5100 feet is achieved. A set of motorized drag-inducing flaps will be able to extend and retract from the sides of the rocket at the command of a prediction and control algorithm acting on the launch vehicle's current state. Included below is a graphic displaying a rough timeline for ATS activation. The total mass of the ATS system is estimated to be 630 grams.

Figure 63: ATS Timeline Schematic

3.4.2 Air Brake Deployment

Overview

The air brake deployment system consists of a central turnpiece, 3 connecting arms, 3 brake supports, and 3 brake guides. The central turnpiece is directly connected to the shaft from the actuator, which turns the entire system, retracting and extending the brakes. The central piece is connected by pins to the three arms, which are in turn connected to the brakes by pin connections.

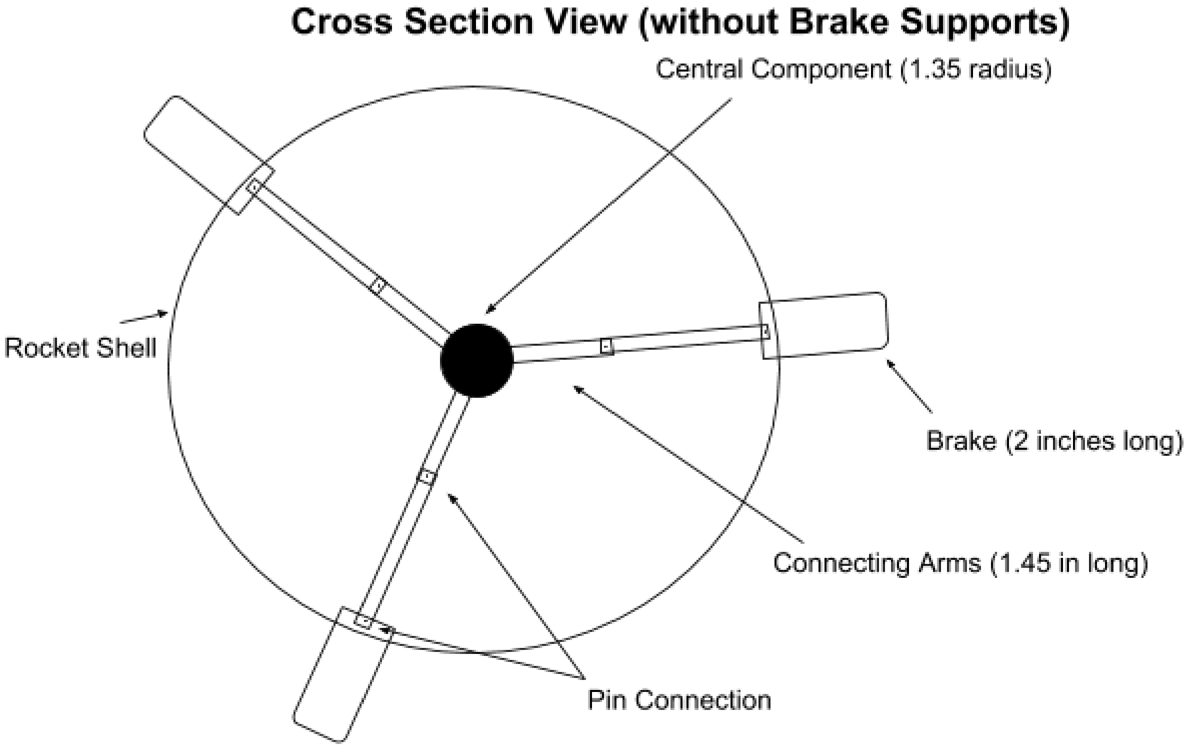


Figure 64: ATS Cross Section View

The brake support is rigidly connected (24 hour epoxy) to the brake and fits tightly within the brake guide. The connecting arm can slide through a slot in the brake guide, allowing it to connect directly to the brake, while not allowing the brake support to move in relation to the brake guide.

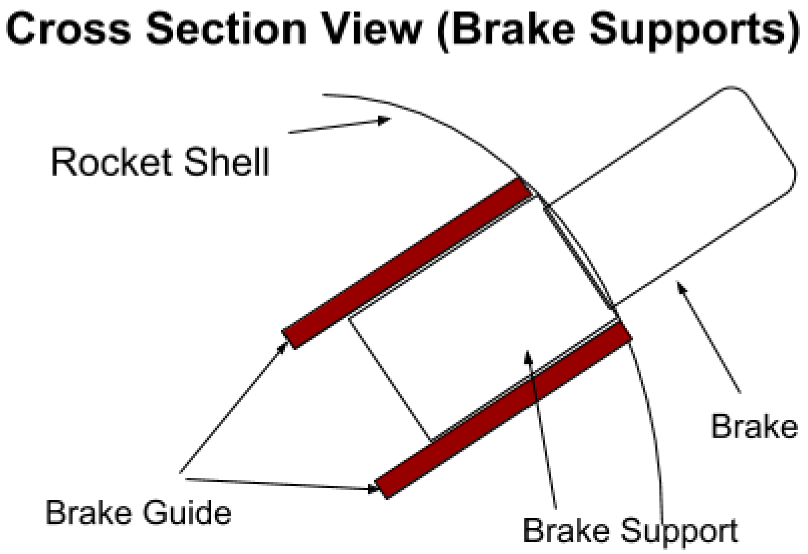


Figure 65: ATS Brake Supports

The bulkhead support is below all deployment components and is rigidly attached (with screws) to the rocket shell. The brake support and central turnpiece are supported by the bulkhead. The central component is attached to the bulkhead by a thrust bearing, allowing it to rotate while providing support, while the brake support is rigidly attached to the bulkhead.

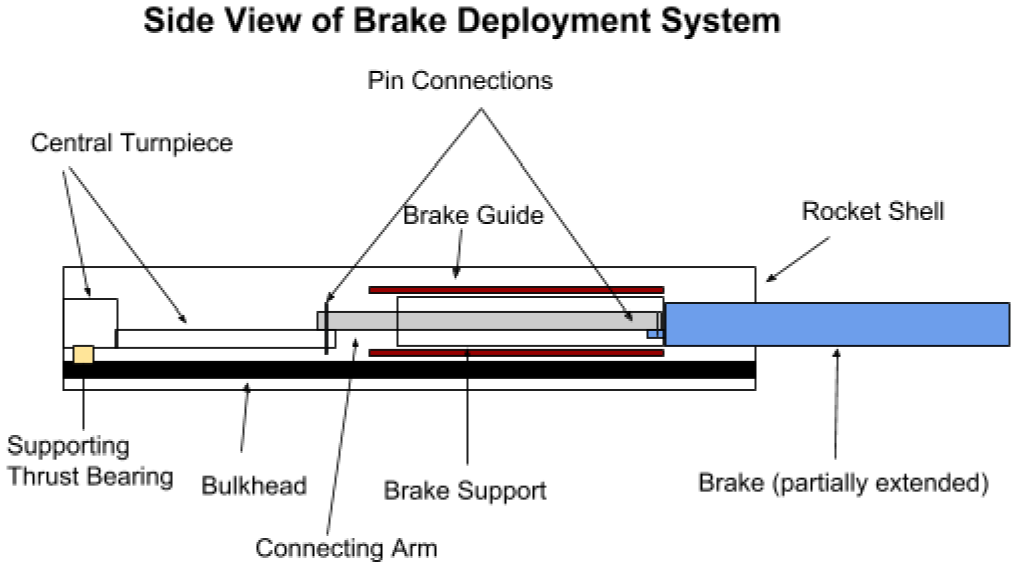


Figure 66: Side View of Brake Deployment System

Materials

The central component, connecting arm, brake support, and connecting arm will be made of aluminum. Aluminum provides the flexibility, strength, and lightness required for the design. The bulkhead will be made of aluminum as well, while the thrust bearing and pins will be made of stainless steel. The brake will be made of Fiberglass, while the tab used to pin the brake to the connecting arm will be made of aluminum. The outside of the brake support and the inside of the brake guide will be coated with teflon. This significantly reduces the friction between the components, reducing the required torque from the actuator.

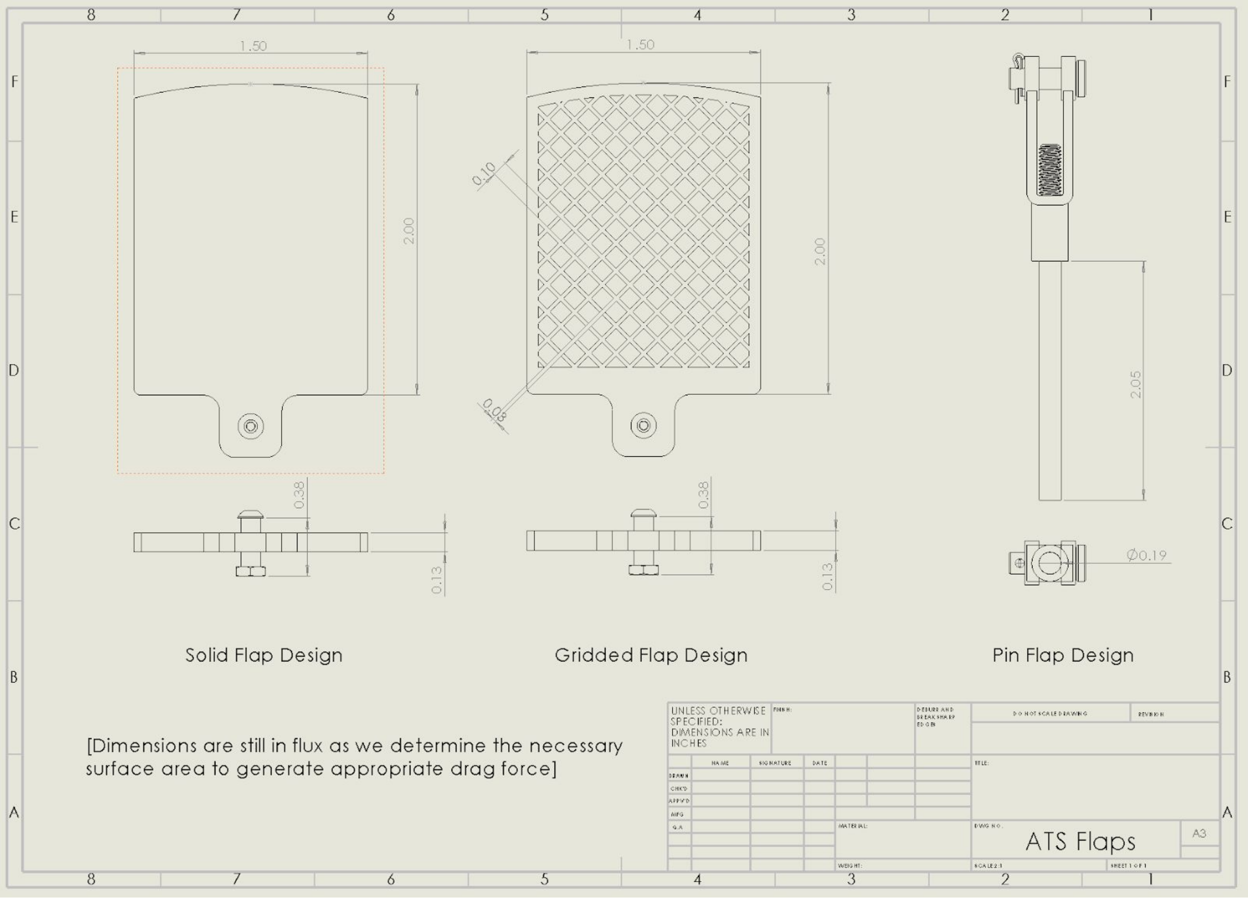
Calculations

The radius of the central component and the length of the connecting arm were optimized to gain the most extension possible. An equation relating the radius of the central component and the total possible extension possible was used to get the final size values of a 1.35 in radius central component and a 1.45 in long connecting arm.

It is necessary to calculate the maximum torque on the central turnpiece, so we can select an actuator with an adequate maximum torque. The force required to retract the brake was calculated assuming 30 lbs of drag force on the air brakes. It was assumed that the brake guide would support this entire force, so the force required to retract the brake is proportional to the current downward force on the brake and the estimated coefficient of friction between the teflon on the outer part of the brake support and the inner part of the brake guide. It was then possible to graph the relationship between the angle of rotation of the central turnpiece and the torque due to this friction on the central component from the connecting arm. We were then able to find the angle at which torque is at a maximum and found the torque value at that point to be 0.6 lb · ft.

3.4.3 Air Brake Flap Design

Three designs have been proposed for the airbrake flaps: a solid flap design with a curved edge that is flush with the airframe when the fin is fully retracted, a gridded flap with the same curvature at the top, and a pin flap. The solid and gridded flaps are connected to the deployment system via a circular standoff that acts as a pin connector. The screw and nut on either side of the standoff prevent the deployment arm from slipping off the standoff. For the pin flap design, a single thread-ended rod is screwed into the female connector on a clevis that attaches to the deployment arm. For a given extension length under subsonic flow, the solid flap design is expected to perform better than the other designs given the fact that it will have the greatest cross-sectional area of the three. However, simulations will be performed to verify this prediction for a given flap extension length (the length and width of solid and gridded flaps will be the same and the length of the pin will be the same as the length of the other flaps). Once the flap structure is selected, multiple CFD simulations will be conducted of different flap dimensions to decide the appropriate sizing under worst-case conditions (unballasted flight). Calculations show that unballasted flight will require each flap to provide ~6 lbs of drag at full extension. Stress analyses conducted on the different flap structures (assuming 7075 aluminum) of the dimensions shown in Figure 63, reveal that the solid and gridded flaps can withstand loads exceeding 30 lbs while the pin flap can withstand forces of up to around 20 lbs. Therefore, all three flaps designs not only fit within the launch vehicle, but have been shown to be structurally sound for forces well above the expected loads.



[Dimensions are still in flux as we determine the necessary surface area to generate appropriate drag force]

Figure 67: Dimensional Drawing of Different Flap Designs

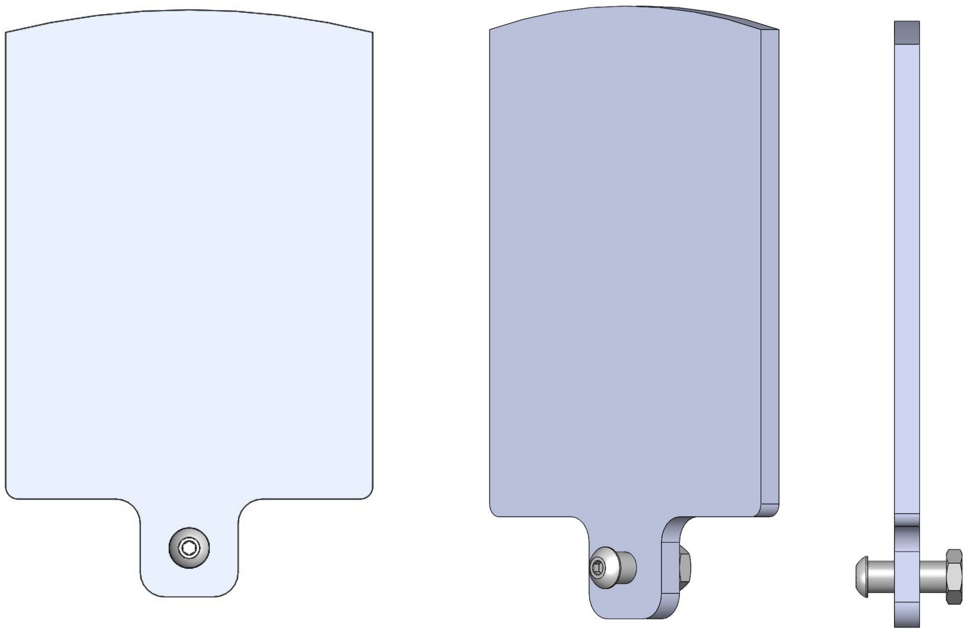


Figure 68: Model of Solid Flap Design

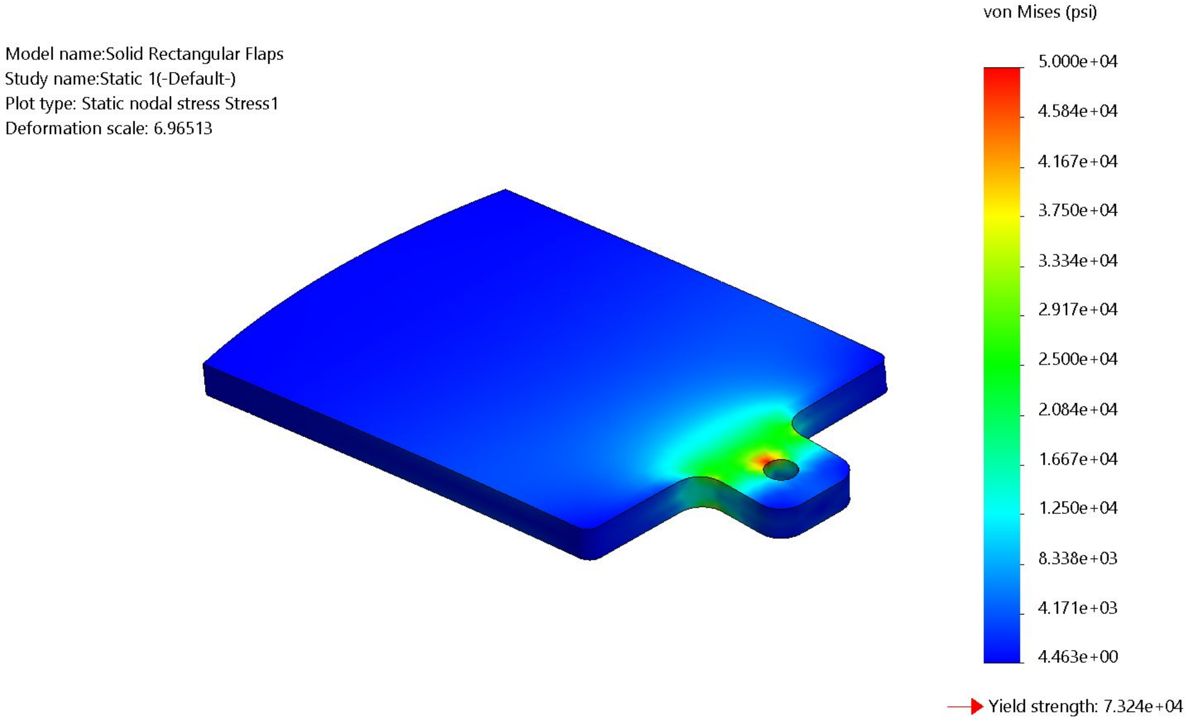


Figure 69: Stress Analysis on Solid Flap under 30 lbs load

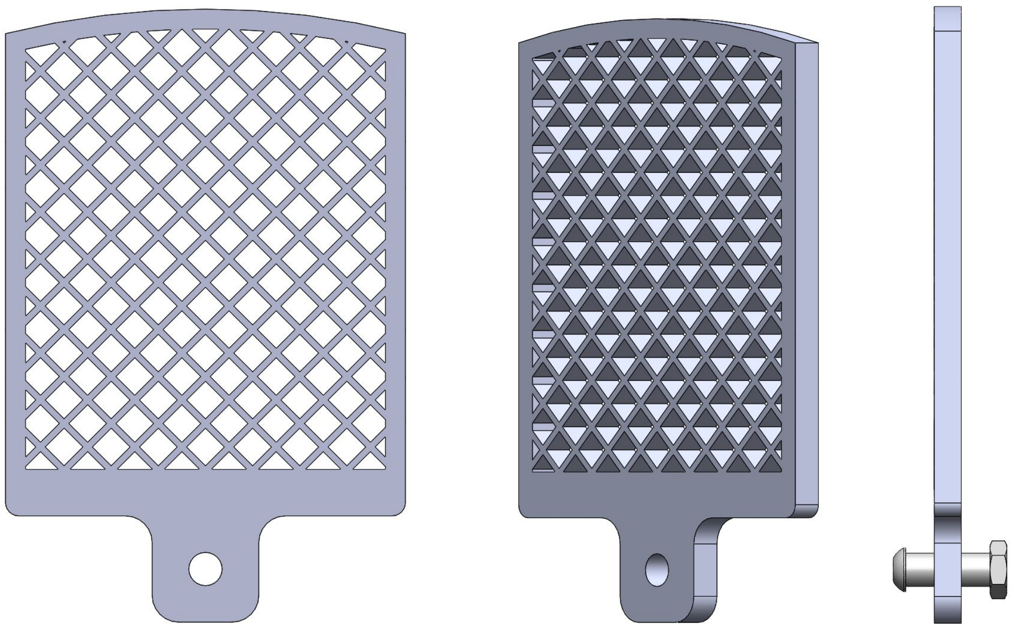


Figure 70: Model of Gridded Flap Design

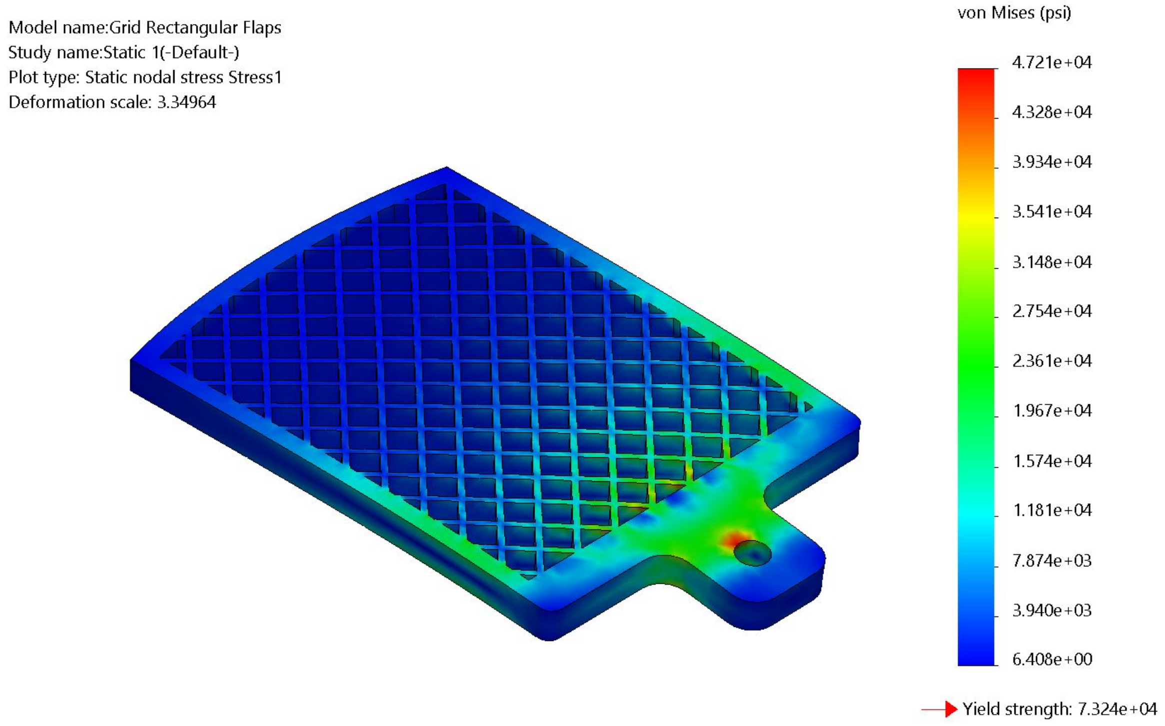


Figure 71: Stress Analysis on Gridded Flap under 30 lbs load

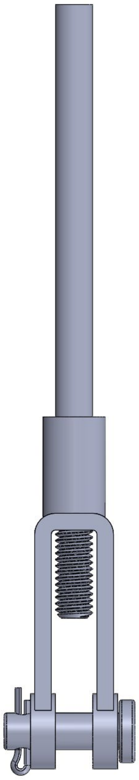


Figure 72: Model of Pin Flap Design

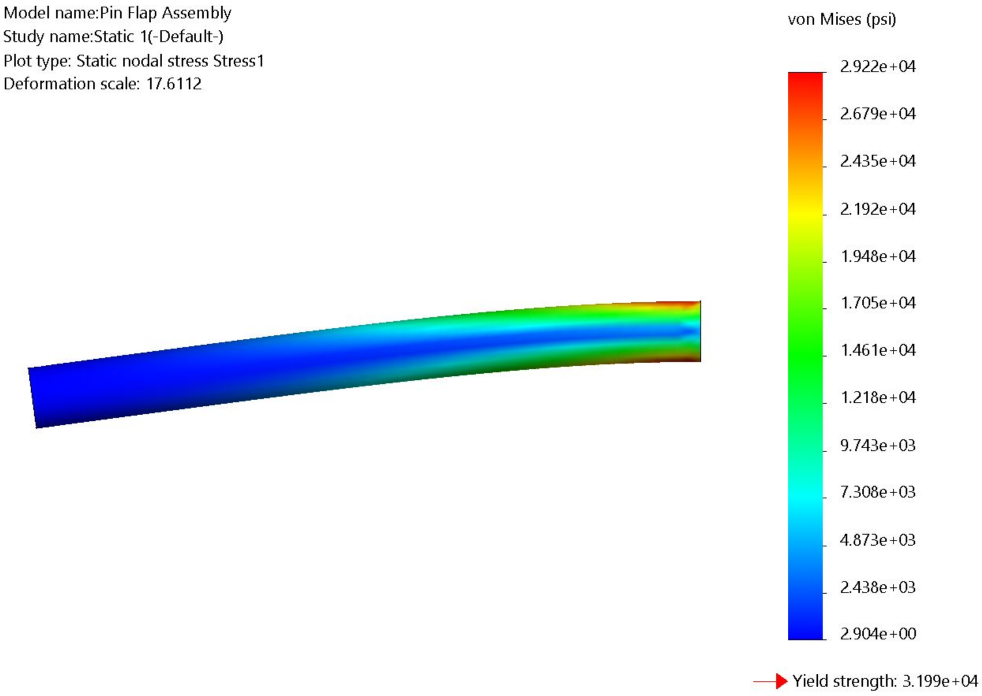


Figure 73: Stress Analysis on Pin Flap Design under 20 lbs load

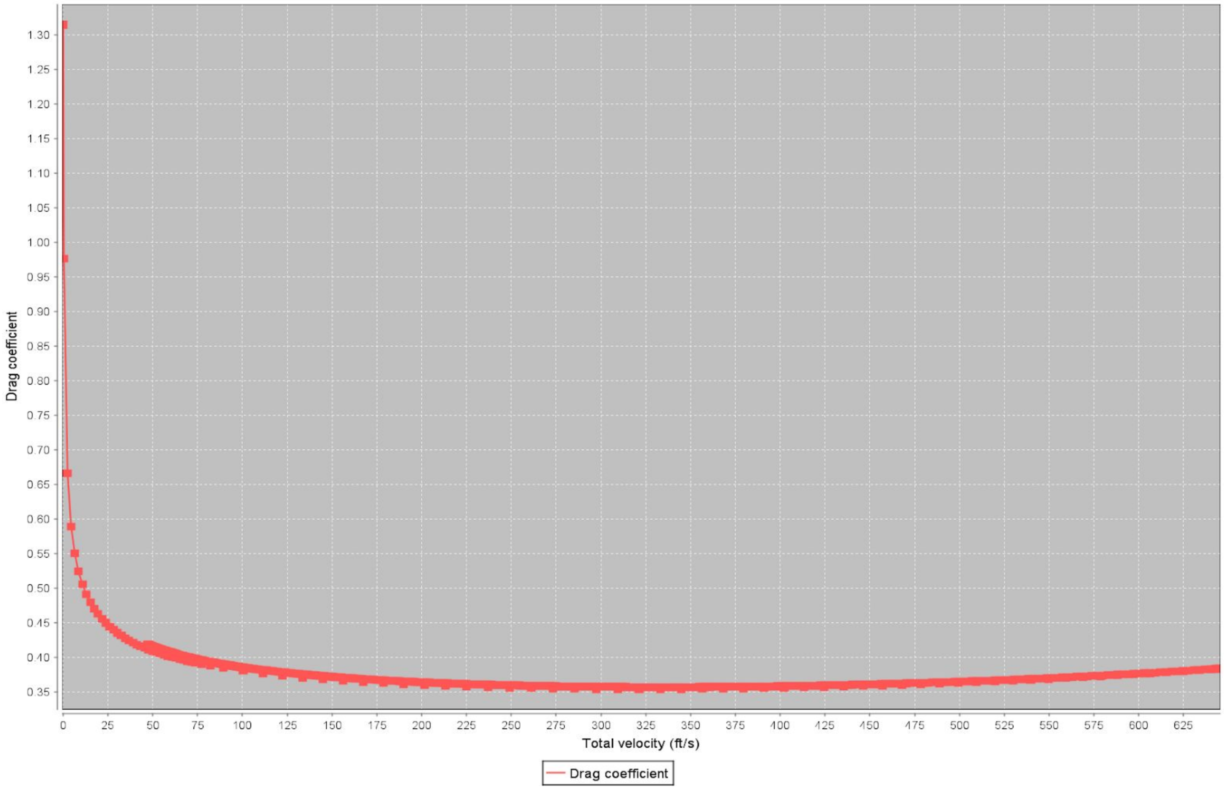


Figure 74: Plot of Drag Coefficient as a Function of Velocity

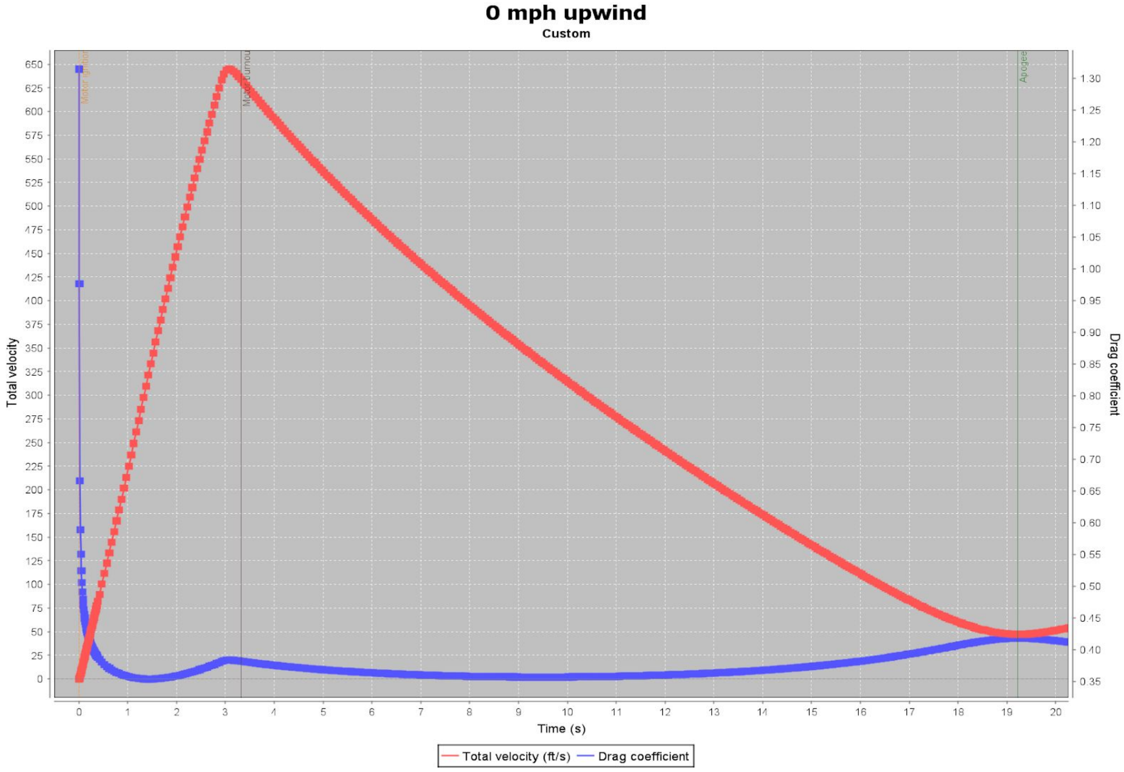


Figure 75: Drag Coefficient and Velocity vs. Time: 0 mph winds

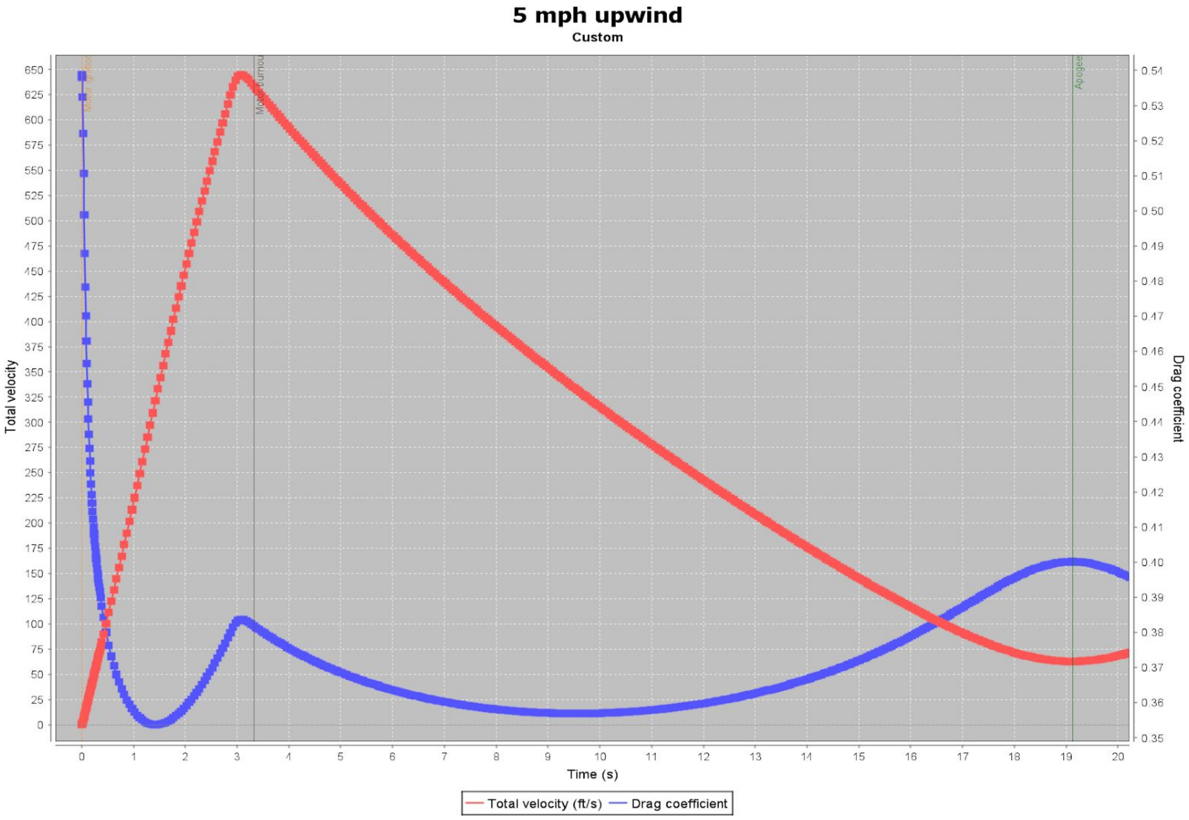


Figure 76: Drag Coefficient and Velocity vs. Time with 5 mph winds

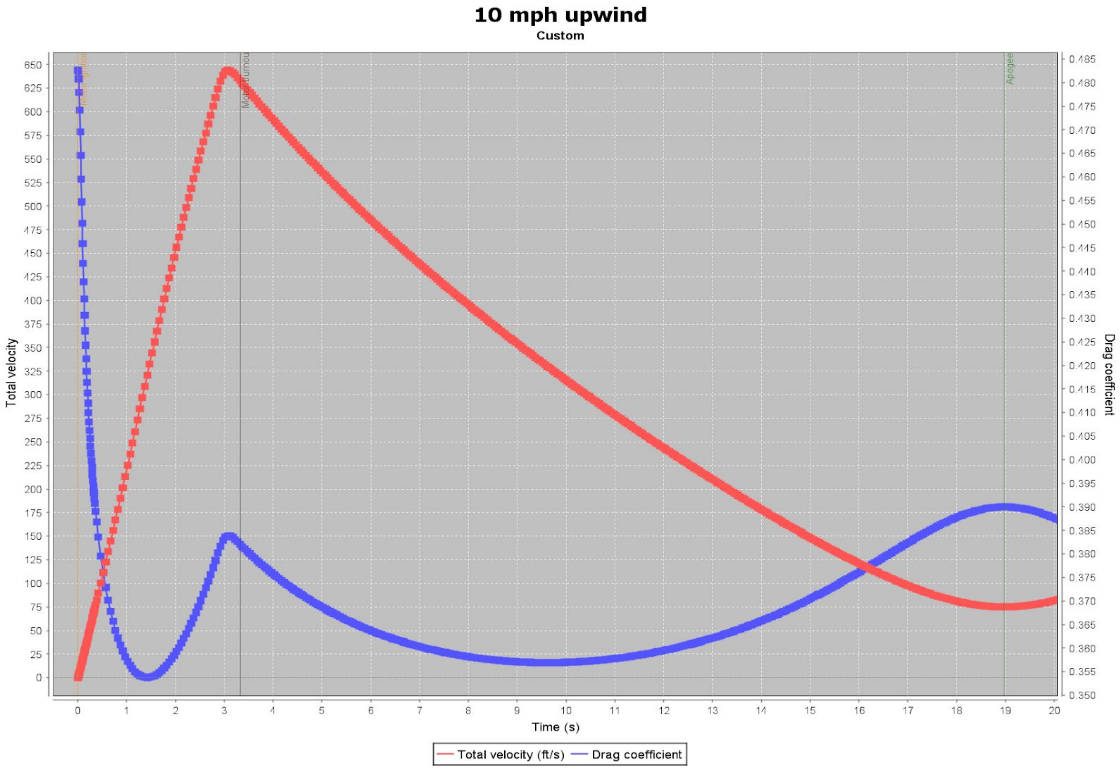


Figure 77: Drag Coefficient and Velocity vs. Time with 10 mph winds

Simulations conducted of the launch vehicle without flaps reveal that the coefficient of drag remains nearly constant throughout flight (~0.35) except at low speeds (less than 75 ft/s) (see Figure D). The coefficient also begins to deviate from 0.35 at high speeds, but the difference remains below 0.05 for the range of speed of the rocket which is, at most, high-subsonic and can therefore be neglected. Simulations also reveal that, in the region of operation of the ATS, the coefficient of drag will rise above 0.40, at most, 2 seconds before apogee. This decreases as the local wind speed increases (see Figures E-G). This is because, with increasing wind speed, the rocket weathercocks more, which means its horizontal speed at apogee increases, thus increasing the local minimum in total speed at apogee. As a result, we can assume that the coefficient of drag of the rocket will remain constant with velocity for a given flap extension within the ATS operating region. CFD simulations of the vehicle at different flap extensions will be conducted to provide the necessary data for the ATS prediction and control systems.

3.4.4 Prediction and Control Design

The ATS uses active prediction and control to ensure that airbrake system is optimized for the desired apogee of 5100 feet. This system is is made up of two components: a prediction algorithm that projects the launch vehicle's apogee given a current state, and a control algorithm which determines the correct amount of flap extension to meet the apogee goal based on the difference between predicted apogee and apogee goal. CMRC has carefully evaluated the advantages and disadvantages of different implementations of each of these two systems.

Prediction

CMRC is considering two different prediction strategies to project the launch vehicle's apogee given a current state.

Launch Vehicle Dynamics model (LVD)

The LVD model uses the known dynamics of the launch vehicle to make a prediction of apogee given a current state. Specifically, given a current altitude, attitude and axial speed, LVD will, after a small velocity step *dv*, calculate a change in height *dh* using the following equation:

$$dh = \frac{dv \cdot \cos\theta}{\frac{-g}{v} - \frac{A(v)}{m} - \frac{B(v,d)}{m}}$$

The launch vehicle's mass, axial speed and attitude from vertical are represented as *m, v* and Θ*,* respectively. *g* designates the gravitational constant. *A(v)* is a function approximating the force of drag on the launch vehicle without the flaps extended as a function of velocity. *B(v,d)* is a function estimating the additional drag force exerted by the flaps as a function of velocity and flap extension *d. A(v)* and *B(v,d)* can be expressed as follows:

$$A(v) = a_0 + a_1 \cdot v + a_2 \cdot v^2$$

$$B(v, d) = b_0 + b_1 \cdot v + b_2 \cdot v^2 + b_3 \cdot d + b_4 \cdot d^2$$

After each velocity step, the above equations will be used iteratively to extrapolate the current state to a prediction of apogee.

Linear Least Squares Regression model (LINR)

Like the LVD model, the LINR model uses the dynamics of the launch vehicle to make a prediction of apogee after each velocity step *dv.* LINR differs from LVD in that it is supports recursive updating of the predictive model. After each *dv,* a prediction of the state of the launch vehicle one *dv* step into the future is made. The next predictive cycle then compares this predicted state to the launch vehicle's actual state. The measured difference is then used to update the predictive model. Specifically, the functions *A(v)* and *B(v,d)* will be updated to improve future estimations of the drag forces acting on the launch vehicle.

This recursive updating process will work in three steps. The first step is to predict the drag force acting on the launch vehicle over the next velocity step. To accomplish this, a collection of some of the launch vehicle's states *u(v)* is multiplied by a weight matrix *W* where *u(v)* and *W* are defined as follows.

$$W(v) = \begin{bmatrix} a_0 & a_1 & a_2 & b_0 & b_1 & b_2 & b_3 & b_4 \end{bmatrix}$$

$$u(v) = \begin{bmatrix} 1 \\ v \\ v^2 \\ 1 \\ v \\ v^2 \\ d \\ d^2 \end{bmatrix}$$

Then,

$$F_{d'} = W(v) \cdot u(v)$$

where the prime symbol designates a prediction rather than a measured value.

The second step is a calculation of the actual drag force acting on the rocket over the last velocity step. This is expressed as

$$F_d = m \cdot \left[\frac{v^2 - (v - dv)^2}{2 \cdot dh} - g \right]$$

Finally, using recursive least squares updating, *W* is updated based on the difference between the predicted drag force and actual drag force acting on the rocket using the following algorithm:

$$k(v) = \frac{\lambda^{-1} P(v - dv) \cdot u(v)}{1 + \lambda^{-1} u^T(v) \cdot P(v - dv) \cdot u(v)}$$

$$\epsilon(v) = F_d - F_{d'}$$

$$W(v) = W(v - dv) + k(v - dv) \cdot \epsilon(v)$$

$$P(v) = \lambda^{-1} P(v - dv) - \lambda^{-1} k(v) \cdot u^T(v) \cdot P(v - dv)$$

Here, λ designates the model's forget factor, while *P* and *k* are intermediate matrices used to facilitate the update of the weight matrix *W*. By updating *W*, the expressions *A(v)* and *B(v,d)* are updated.

Comparing LVD and LINR

There are advantages and disadvantages associated with each of the models discussed above. Below is a table giving a brief overview of some of these considerations.

Table 31: Comparison of LVD and LINR

Method	LVD	LINR
Reliability	High: Due to its simplicity, the LVD model will be relatively easy to test, implement, and run	Unclear: Additional complexity of the recursive updating process will need further evaluation to determine reliability
Hardware Requirements	Low: LVD does not require sensor systems with any particular sampling rate or synchronization. It also generates little load on the flight computer.	High: Due to the nature of LINR's prediction cycle, it's required that sensor systems have a sampling rate significantly higher than the prediction rate.
Precision	Low: LVD is forced to make approximations of drag force that may be difficult to refine.	High: LINR will be able to improve state estimation throughout the course of the flight, leading to less error on apogee.

Control

Currently, CMRC plans to use a PI controller to enact control on predicted apogee values from the ATS prediction algorithm. Control output will be determined by the following equation. *v* designates the current velocity, while *K* and *I* are the gain parameters of the proportional and integral terms, respectively.

$$u(v) = K \cdot e(v) + I \cdot \int_0^v e(\underline{v})d\underline{v}$$

From preliminary control model simulations, we have found that the PI controller yields desirable critically damped behavior on apogee predictions. Included below are three figures displaying the response characteristics of a tuned PI controller acting on the ATS system, with simulated measurement noise. Each figure displays system response from a different initial condition, but with the same controller parameters. We expect that the launch vehicle's state at burnout will be within the range of initial conditions shown below. Specifically, the system's projected apogee is shown as the control cycle runs after each *dv*. Details are written in the table below.

Table 32: Preliminary Model Control Simulation Results

Test Number	**Burnout velocity**	**Burnout altitude**	**Simulated signal to noise ratio**
Test 1	560 feet/sec	1250 feet	1000
Test 2	580 feet/sec	1250 feet	1000
Test 3	600 feet/sec	1250 feet	1000

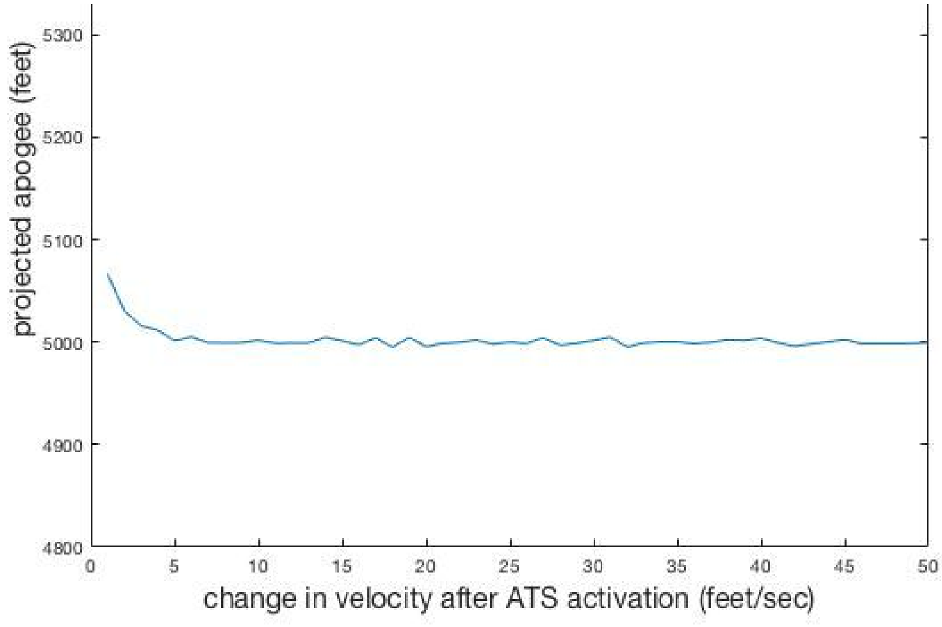


Figure 78: Simulated ATS Activation Test 1

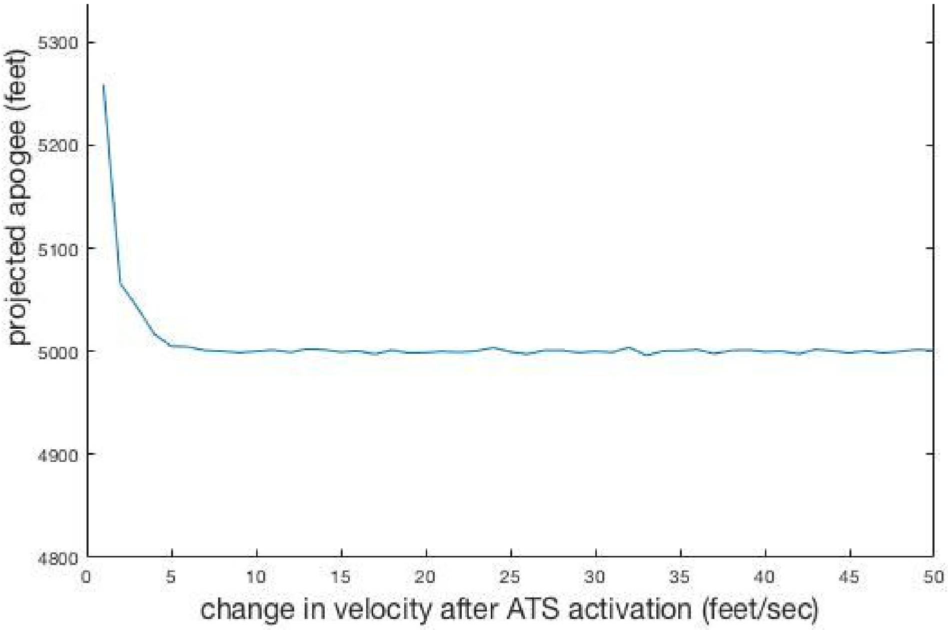


Figure 79: Simulated ATS Activation Test 2

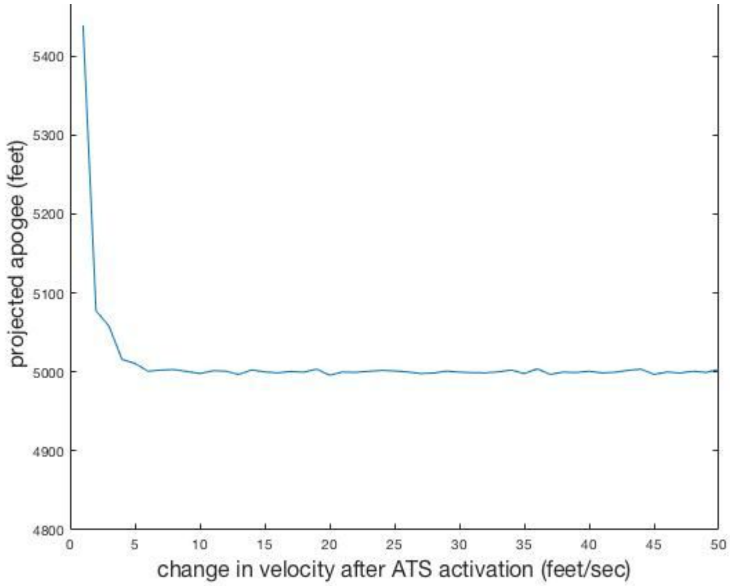


Figure 80: Simulated ATS Activation Test 1

As evident from the figures above, the PI controller responds well to a variety of initial conditions on the launch vehicle preceding ATS activation. In each case, projected apogee has stabilized to the desired apogee in only 5 to 10 control cycles, without overshooting.

3.4.5 ATS Electronics Bay

There are two main options for the ATS electronics, one using a modular architecture composed of several small, low power processors connected via serial over a standardized interface, and the other having just a Raspberry Pi controlling everything using breakout boards.

Modular

The ATS electronics will consist of the same central controller as the payload deployment system, and modules for batteries, motor control, coprocessor (if used), and the IMUs. The central controller will be run by teensy 3.6, with several RS-422 compatible asynchronous serial (UART) channels: two (one RX, one TX) for each module.

The motor control module with connect to the servo or stepper motor (still to be decided) that will deploy and retract the ATS fins. If a servo, it will just contain a microcontroller and any interface needed (a tristate buffer, for example, if using a dynamixel servo), if a stepper, this will contain the stepper driver. It will likely be designed agnostic to the specific motor used, and footprints for the unused servos/stepper drivers simply not populated. Current candidates for servos include the Dynamixel XM430-W210-T and the Hitec HS-7945TH.

Figure 81: Dynamixel XM430-W210-T (Left) and Hitec HS-7945TH (Right)

The exact model of IMU is currently undecided, but will likely be either a premade unit such as a VN-100 from vectornav, or a quadcopter flight controller. If using a flight controller, we will select one with open source firmware (most likely betaflight) and slightly modify it to do all of the sampling and low-level processing onboard (since this is already written), and send the processed data via UART to the central controller. Either of these solutions keep all complex and time-critical sampling and processing on a separate unit, keeping the code running on the central controller simple.

Figure 82: VectorNav VN-100

The central controller will include at least one barometer (instead of placing that on an external module, to reduce the number of modules). The outputs of the IMU and barometer will be combined with a Kalman filter to provide more accurate estimates of altitude and velocity than either could alone. Initial estimates suggest this should be sufficient for the ATS, but if higher accuracy is required, then another altitude/velocity sensor, such as a radar, lidar, or time-of-flight radio modules may be added.

The batteries will likely be two separate modules, each with two lithium-ion or lithium-polymer batteries in series, and 5V and 12V switching regulators, through a diode, to provide power redundancy. The 5V rail will be used to power low-power devices (sensors, microcontrollers, etc.) and the 12V rail to power high-power devices (motors and coprocessor).

If the computational power of the teensy is insufficient to run the ATS prediction algorithm and control loop, then a coprocessor (likely a raspberry pi compute module) will be added as a module which will be passed the processed IMU and barometer data, and return the desired motor position.

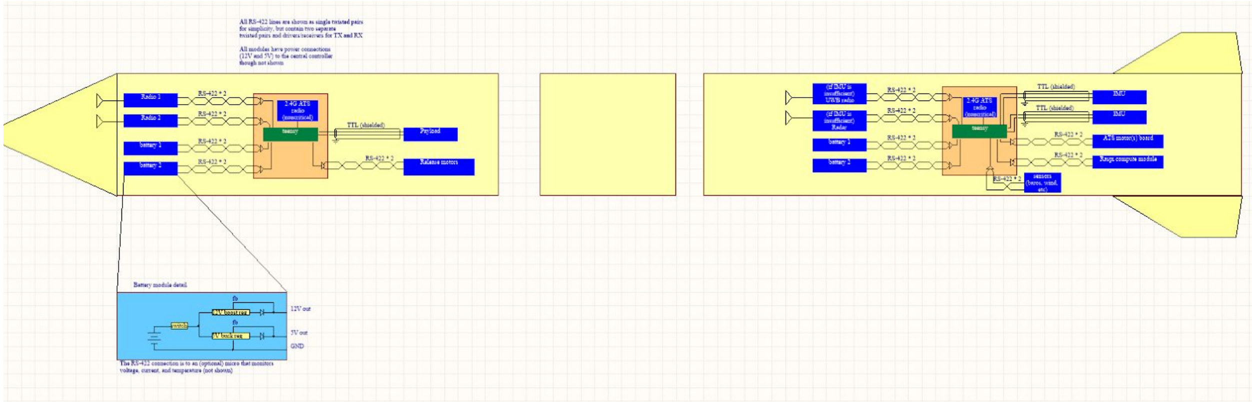


Figure 83: High Level ATS Schematic

Pi only

The ATS electronics bay will consist of the flight computer, a motor driver, motor, and battery to power the controller and the motor. Electronic hardware will be screwed down or zip tied to the structural support.

Currently, CMRC plans to use either a stepper or servo motor with an output torque much greater than 115.2 oz-in in order to account for the friction force required for the flaps to deploy. To accurately and quickly extend the flaps, the motor will have an angular speed of at least 60 rpm. Since stepper motors are much heavier, the current servo we're considering is a HS-7945TH, which has a stall torque of 250 oz-in and a speed of 83 rpm.

If using a stepper motor, we will either use a TB67S249FTG or TB6600 stepper motor driver, depending on the motor we select. Both boards are able to supply a current of over 1.5A, which is what the motors require to run.

The power source will most likely be a Glacier 30C 1000mAh 2S 7.4V LiPo Battery, which has enough power to keep the microcontroller and motor driver on while the rocket waits on the launch pad.

Below is a tentative layout of the ATS Bay. Currently, depicted is a Raspberry pi as the flight computer, a servo motor, and stand-in for the motor driver board. The layout of the board may change depending on if a stepper motor is used instead the servo motor.

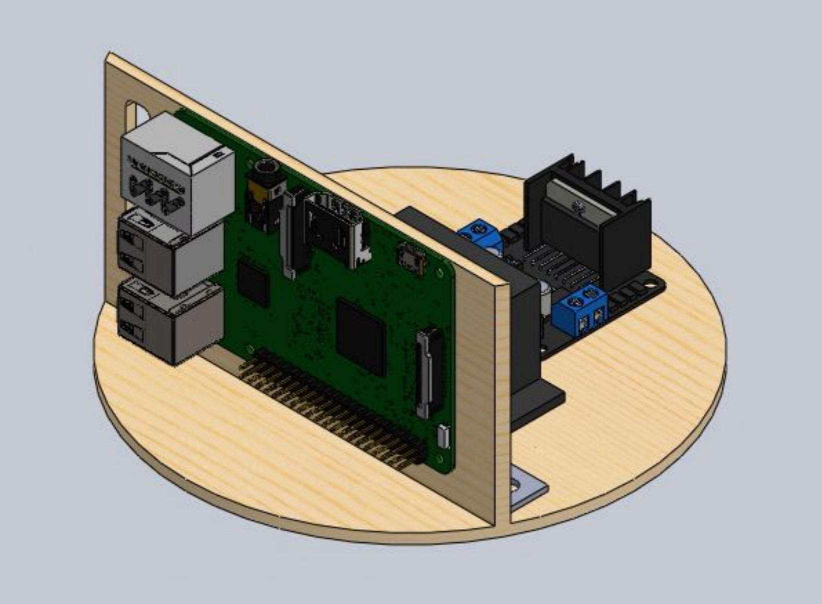
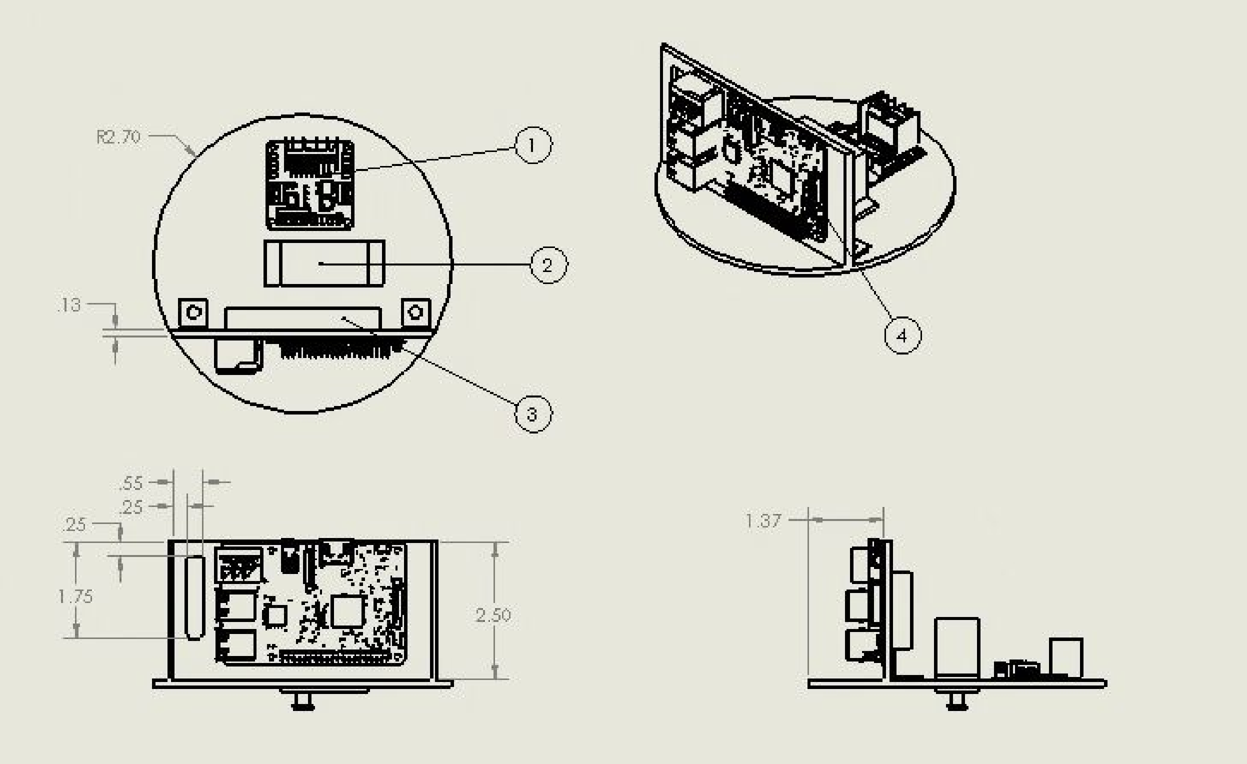


Figure 84: Isometric view of payload bay, including Raspberry Pi, battery, servo motor, and stepper motor driver



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	L298N.step		1
2	futaba s9452 rough		1
3	Glacier 30C 1000mAh 2S 7.4V LiPo Battery		1
4	Raspberry Pi 3 Light Version.step		1

Figure 85: Assembly Drawing of ATS E-bay

3.4.6 ATS Testing Plan

The ATS will undergo multiple levels of preliminary testing before SCOTTIE's first launch. The three most significant components to undergo testing are the ATS sensor suite, the ATS prediction and control process and the ATS flap deployment mechanism. Components to be tested within the ATS sensor suite include barometric altimeters and an inertial measurement unit. Besides for static testing of these sensors to measure drift and noise errors, CMRC plans to test a well developed prototype of this system during test launch of the subscale launch vehicle. We will continue to test prediction and control using MATLAB simulations, but as a next step, will additionally test prediction and control when running on of the ATS flight computer. Finally, the constructed ATS flap deployment system will be tested by simulating aerodynamic load during ATS operation using appropriate weights attached to the mechanism. Reliability, speed and precision of the flap extension and retraction process will all be evaluated.

3.5 Construction

3.5.1 Fins

After exploring multiple options for creating airfoiled fins we decided that buying beveled fins is the best option for now since we don't need the extra performance. Due to restrictions on cutting/sanding fiberglass with a school CNC machine our only option for precisely cutting fins is a jig, which turned out to be difficult to create. Other materials are either too weak or too expensive to be cut with a CNC.

One technique we will be exploring for future fin construction is 3D printing ABS or PCABS fins and reinforcing them with epoxy. ABS and PC/ABS are hard, semi-flexible materials capable of withstanding impact forces. Their hardness also makes them less susceptible to fin flutter. This is further enhanced by applying epoxy to the fin which also helps to reduce the surface roughness of the part that results from the 3D printing process and, consequently, reduces the drag force on the fin. This process will allow us to create a fully airfoiled fin for high aerodynamic performance at low cost and manufacturing complexity. Testing of these fins will reveal whether this process can be implemented in future launch vehicles.

We'll also be testing carbon fiber and fiberglass overwrapping with vacuum bagging for use in future years. Because of the fin's sharp leading and trailing edges we'll be testing loose weaves such as 8HS 3K carbon fiber. We hope to find out how multiple layers affects the accuracy of the airfoil. Testing epoxy with and without vacuum bagging will let us know how much of a difference vacuum bagging makes in the strength of the fin.

Our initial plan to test wrapping is to cut foam to an airfoil shape and wrap carbon fiber over it, making a nearly hollow fin. Single or multiple layers can be added then left to set. This should let us make a very light and still strong fin. The largest concern is ground impact rather than fin flutter at this scale.

3.5.2 Fin Slots

In order to cut fin slots at precise angles and lengths, we are fabricating a cutting jig. This jig will securely hold a range of body tube diameters, and provide a centered gap for inserting and linearly sliding a router over the top of the body tube in order to create perfectly square fin slots. To ensure that held tubes are centered, the jig’s support arms will be geared to all extend in unison. A compass-like angle overlay allows for accurate angles between cuts, and allows for the jig to be used on rockets of any number of fins. Symmetry about the x and y axes of the jig allow for exact cutting of 4 fins.

3.5.3 Motor Retention

Our current leading design for the motor retention system consists of a custom thrust plate interfaced with a mass produced 75mm motor retainer and cap from Apogee Components. In order to produce the thrust plate in house, we will be using the CNC mill located in Carnegie Mellon's makerspace. This CNC is capable of machining Aluminum 6061, which we intend to use.

3.5.4 Recovery Bay

The recovery bay will be constructed out of a variety of laser cut plywood bulkheads and 3D printed parts. The Tech Spark makerspace will be used for all of this construction process with their laser cutters and 3D printers. The other electronics and hardware components will be purchased from suppliers directly for use. These include threaded rods, nuts and bolts, altimeters, rotary switches, and the various electrical connectors.

3.5.5 Nose cone, Body Tubes, Couplers, and Bulkheads

The nose cone, body tubes, couplers, and bulkheads will all be purchased as from suppliers directly. Careful sanding and fitting will be required in order to make sure that all tubes and bulkheads fit together well. Couplers and body tubes will be cut to size using the CMRC jigsaw and then the edges will be power sanded smooth.

3.5.6 ATS Electronics Bay, Airbrake Deployment System, and Flaps

ATS Electronics Bay

Modular

The structure of the electronics bay is not entirely decided, but will likely be composed of several simple, 3D printed modules to house the electronics, and a laser cut wooden or plastic base (similar to the pi only design) to mount the motor.

Pi only

The structure of the electronics bay will be made with thin carbon fiber or plywood, lasercut to shape. With a Raspberry Pi as the flight computer, the ATS electronics bay will be two separate pieces mounted perpendicular to one another. To mount the electronics, we plan on screwing down all the components except the battery. The battery will be attached to the bay with velcro straps in order to be easily removable.

Airbrake Deployment System

The central turnpiece, connecting arm, brake guide, and brake support will be machined out of aluminum using a CNC router. The exact dimensions of each piece and the grade of aluminum are not entirely decided. The pin connecting the connecting arms and central turnpiece can be found on McMaster Carr. The thrust bearing supporting the central turnpiece and bulkhead can also be found on McMaster Carr. The thrust bearing will be connected rigidly to the bulkhead using either screws or epoxy. The brake guide will be rigidly connected to the bulkhead using epoxy and the bulkhead will be screwed to the rocket shell.

Flaps

The flaps will be machined out of ⅛” thick high-strength 7075 aluminum bar using a CNC router. The standoff, screw, and nut for the solid and gridded flap structures can be found in McMaster Carr. The female-ended clevis and single thread-ended rod for the pin flap are also available on McMaster Carr. While the exact dimensions of the connection system my vary with the dimensions of the fin and deployment system, the current selection is: a stainless steel 5/16” long, ⅛” outer diameter female threaded standoff with a 2-56 thread, a 2-56 stainless steel button head hex drive screw, a stainless hex nut, a clevis with a 3/16” jaw width and 10-32 female thread, and a connection rod with 10-32 thread endings. The connection rod can be cut to produce a single thread-ended rod using a band-saw.

4 Safety

4.1 Risk Assessment

The Risk Assessment Code (RAC) describes the qualifiers used in evaluating the risk associated with specific actions, events, or substances implemented/used throughout the execution of this project. It is borrowed from NASA's MWI 8715.15 directive. The four tables below define the RAC labels, levels of management approval required, associated severity, and probability of occurrence respectively. These are followed by a risk assessment of different aspects of this project.

Table 33: Risk Assessment Code

	Severity			
Probability	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 34: Level of Risk and Level of Management Approval

Level of Risk	**Level of Management Approval/Approving Authority**
High Risk	Highly Undesirable. Documented approval from the MSFC EMC or an equivalent level independent management committee.
Moderate Risk	Undesirable. Documented approval from the facility/operation owner's Department/Laboratory/Office Manager or designee(s) or an equivalent level management committee.
Low Risk	Acceptable. Documented approval from the supervisor directly responsible for operating the facility or performing the operation.
Minimal Risk	Acceptable. Documented approval not required, but an informal review by the supervisor directly responsible for operating the facility or performing the operation is highly recommended. Use of a generic JHA posted on the SHE Webpage is recommended.

Table 35: Severity Definitions

Description	Project Completion	Personnel Safety and Health	Facility/Equipment	Environmental
1 - Catastrophic	Project progress terminated	Loss of life or a permanent-disabling injury	Loss of facility, systems, or associated hardware.	Irreversible severe environmental damage that violates law and regulation
2 - Critical	Project Progress delayed beyond a month	Severe injury or occupational-related illness.	Major damage to facilities, systems, or equipment.	Reversible environmental damage causing a violation of law or regulation.
3 - Marginal	Project progress delayed beyond a week	Minor injury or occupational-related illness.	Minor damage to facilities, systems, or equipment.	Mitigatable environmental damage without violation of law or regulation where restoration activities can be accomplished.
4 - Negligible	Project progress delayed, but can be fixed within 2 days.	First aid injury or occupational-related illness.	Minimal damage to facilities, systems, or equipment.	Minimal environmental damage without violation of law or regulation.

Table 36: Probability Definitions

Description	Qualitative Definition	Quantitative Definition
A - Frequent	High likelihood to occur immediately or expected to be continuously experienced.	Probability is > 0.1
B - Probable	Likely to occur to expected to occur frequently within time.	0.1≥Probability>0.01
C - Occasional	Expected to occur several times or occasionally within time.	0.01≥Probability>0.001
D - Remote	Unlikely to occur, but can be reasonable expected to occur at some point within time.	0.001≥Probability> 0.000001
E - Improbable	Very unlikely to occur and an occurrence is not expected to be experienced within time.	0.000001≥Probability

4.1.1 Project Completion

Table 37: Project Completion Risk Assessment and Mitigation

Hazard	Cause	Effect	Pre-RAC	Mitigation	Verification	Post-RAC
Project fails to keep up with the projected timeline.	Unforeseen circumstances take time otherwise spent on completing the project.	Project is not completed within given deadlines; Members are unable to produce an acceptable and reusable final product.	**2C**	Project workload will be distributed among project members according to their areas of comfort and expertise; Progress will be monitored by project leads.	Hold weekly project assessment meetings in which teams report their progress as well as concerns and challenges; See Section 6.3.3 for Gantt Chart	**2E**
Budget is exceeded.	Funds are not allocated properly; The price of components is miscalculated.	Purchasing is halted/slowed down until funds are found; Inability to carry out projects elsewhere around the organization; Members required to cover some expense associated with the competition.	**2D**	Conduct thorough research on pricing of components; Budget for additional parts, unforeseen expenses and potential mishaps.	See Section 6.3.1 for budget that has been approved by treasurer. See Section 6.3.2 for funding to fully cover the budget	**2E**

Parts are damaged or no longer available.	Mishandling of tools or parts; Inability to purchase parts in sufficient quantity or time.	Inability to complete manufacturing of the rocket in a timely manner; Improvisation and deviation from the original design.	**2D**	Purchase additional parts for any component critical to the completion of the project.	See Section 6.3.1 for budget allocation. Some components, such as the motor, will be purchased in excess to mitigate this risk.	**2E**
Failure in communication between team members.	Deadlines and/or expectations are not met.	Inability to maintain a healthy and constructive work environment.	**2D**	CMRC will use a task schedule to assign sections of the project.	See 6.3.3 for GANTT chart that will be used during project. Club president has verified the completion of all tasks in a timely manner.	**2E**
Scheduled launches are delayed.	Poor weather conditions.	Inability to efficiently meet CDR and PDR requirements; Subscale and full scale launches may have to be delayed or cancelled.	**3C**	Alternative launch dates will be set up to ensure a decent number of test flights.	See 6.3.3 for GANTT chart with expected launch dates. Launch dates are well in advance of deadlines to allow for rescheduling due to weather	**3E**
Machine shops and workshops are not accessible.	Shops are closed due to construction on campus; Team's availability and shop hours do not coincide;	Scheduled work times will have to be moved or cancelled; Inability to complete project sections as	**3C**	Construction of the rocket will be scheduled with early deadlines to make room for unforseen closings.	See Section 6.3.3 for detailed construction schedule in Gantt Chart	**3E**

	Shops are closed due to unforeseen circumstances (i.e. accident, damage to facilities).	originally scheduled.				
Students and/or staff are not available.	Students are overburdened with school work; School holidays keep some staff/students from meeting to work on the project.	Sections of the project may not be completed on time; Some team members will have to take on a greater workload.	**3B**	Work on the project will be scheduled and implement early deadlines with some flexibility; Student/staff schedules will be examined to ensure availability on the necessary dates.	See Section 6.3.3 for GANTT Chart used for project. Sub team leads will discuss with team members about their work loads throughout the project.	**3D**

4.1.2 Personnel Hazard Analysis

Table 38: Manufacturing Risk Assessment and Mitigation

Hazard	Cause	Effect	Pre-RAC	Mitigation	Verification	Post-RAC
Accident occurs while operating workshop tools and/or machines.	Lack of training or supervision; No adherence to established safety protocols and techniques.	Members experience injury and/or maiming; Equipment and/or facilities are damaged.	**1D**	Training on all required tools and machines; Instruction on safe shop and work practices including the use of proper PPE;	CMRC-owned hand tools are used under the supervision of the safety officer or president.	**1E**

Mistake is made during manufacturing of rocket.	Improper use of machinery or tools; Lack of attention to instructions and rocket design.	Structural components are damaged; May lead to re-purchasing of parts; Project timeline is delayed; Improvisation and/or deviation from original design may be required.	**2C**	Follow safety procedures on all required tools and machines; Brief all manufacturing team members on rocket design and best practices.	Weekly team meetings will be held in which the design is discussed. A shared GrabCAD folder will be utilized throughout the year to ensure everyone is up to date on the rocket design and plan of fabrication.	**2E**
Accident occurs while using soldering iron/ assembling GPS system.	Lack of training or supervision; No adherence to established safety protocols and techniques; Exposed wire or power source.	Members experience burns; Equipment and/or facilities are damaged; Components are damaged; Fire can occur.	**3C**	Training on all required tools and machines; Instruction on safe shop and work practices including the use of proper PPE; Additional components will be purchased as backup.	All use of tools and/or a shop will be supervised by CMU facility personnel.	**3E**
Error in 3D printing payload and electronics bay components.	Lack of training and/or experience; Malfunction with equipment.	Components will not be fit for use; More time and money will be spent on re-printing.	**3C**	All students engaging in 3D printing should have prior training on the use of this process and proper tolerancing; Equipment will be inspected before use.	Inspection of printed components will be occur before installation and before launch, in order to ensure structural integrity.	**3E**

Table 39: Materials Handling, Risk Assessment and Mitigation

Hazard	Cause	Effect	Pre-RAC	Mitigation	Verification	Post-RAC
Black powder detonates unintentionally.	Safety protocol is poorly or not followed; Substance is exposed to fire, a hot surface or live electrical components; Substance experiences friction and or an impact force.	Members may suffer injury and/or maiming or death; Equipment and/or facilities may be damaged.	**1D**	Black powder will only be handled by mentor directly before launch.	MSDS; Work with black powder will be conducted by a level 3-certified mentor.	**1E**
Inhalation of chemical dusts and/or fumes.	Exposure of substances to fire or a hot surface; lack of ventilation for substance with low vapor pressures; Unforeseen reaction between components results in gas products; Exposure to vapors from 3D printing with ABS plastic.	Irritation of the respiratory tract; Shortness of breath, dizziness and/or fatigue; Prolonged exposure may lead to internal damage.	**2C**	Limit use of such substances to well-ventilated areas; Use of a fume hood when appropriate; Training on and enforcing of exposure time limitations.	MSDS; Work with hazardous substances will be performed in a designated shop/laboratory space supervised by trained personnel.	**2E**

Swelling/explosion of LiPo battery.	The battery is overcharged; One or more of the cells is punctured or the battery is dropped onto a hard surface; Batteries short when terminals come in contact with one another; Batteries are exposed to a heat source (only swelling, which affects performance).	Team members may suffer injuries or burns; Surrounding materials may be damaged and may catch fire if flammable.	**2C**	Batteries will be kept in their appropriate packaging until needed and handled with caution when removed; Batteries will be charged per the manufacturer's recommendations; Batteries will be kept away from any sources of excessive heat.	Routine inventory checks and oversight by safety officer during construction.	**2E**
Superficial exposure to hazardous chemical components.	Improper use of personal protective equipment (PPE); Accidental spill or unforeseen reaction between different substances.	Irritation of the skin; Irritation of the eyes; Burning and/or burning sensation.	**3C**	Training on proper use of PPE as described by a substance's MSDS; Training on hand-washing, eyewash stations, and emergency shower.	MSDS; Work with hazardous substances will be performed in a designated shop/laboratory space supervised by trained personnel.	**3E**

Explosion of 9V battery.	Batteries are shorted when both terminals come in contact with a common metal surface; Batteries become overheated when exposed to a heat source.	Team members may suffer a minor injury and/or burn; Surrounding materials may be damaged and may catch fire if flammable.	**3C**	Batteries will be kept in their appropriate packaging until needed; Batteries will be kept away from any sources of heat.	Routine inventory checks and oversight by safety officer during construction.	**3E**

4.1.3 Failure Modes and Effects Analysis

Table 40: Flight Risk Assessment and Mitigation

Hazard	**Cause**	**Effect**	**Pre-RAC**	**Mitigation**	**Verification**	**Post-RAC**
Recovery system fails to deploy or malfunctions during deployment.	Parachute becomes tangled; Ejection charge fails to ignite; Redundant altimeters malfunction.	Spectators may be injured; Rocket and internal components may become damaged upon landing.	**1C**	Perform ground testing of recovery system; Test the recovery system with a small-scale model.	Analyze recovery system deployment of small-scale model for the desired functionality.	**1E**
Unstable flight.	Weather cocking knocks rocket off its expected trajectory due to overstability; Improper exit velocity; Body of rocket is damaged	Spectators may be injured; Rocket may become damaged; Software may be incapable of detecting ground targets.	**2B**	Use simulation software to predict flight pattern; Test stability of airframe design with launch of a subscale model.	Simulations will be performed prior to flight to ensure that flight is stable in a variety of circumstances. Analyze the results of the subscale launch	**2D**

	during launch or improper construction.		🟥		flight to ensure stability.	🟨
Target altitude range is not reached or exceeded.	Miscalculation of net thrust needed by the rocket; Weather cocking lengthens upward trajectory; Inability to reach necessary exit velocity at launch pad.	Failure to meet minimum requirements set by competition; Possible disqualification of competition.	**2B**	Use simulation software to ensure proper motor choice; Accurately measure rocket mass and its CP and CG.	Simulations will be done with the specifications of the full-scale rocket to decide the motor to use in the launch. Test flight will allow real-world testing of simulation results.	**2D**
Not enough black powder is inserted into ejection charges.	Incorrect measurement or calculation of powder needed.	Parachutes will not deploy as shear pins will not break and the rocket will enter freefall; Team members and/or spectators could be injured.	**2B**	The amounts necessary will be calculated before the launch and measured out by our mentor.	A ground test will be performed to ensure that the ejection charge detonation is appropriate for rocket recovery.	**2E**
Fin flutter	The rocket experiences very strong forces on ascent; Construction of the fins fails to secure them to both the outer airframe and the motor mount.	Fins break during flight; Rocket veers off the expected flight trajectory.	**2C**	The speeds at which fin flutter becomes significant have been calculated using the NACA Flutter Boundary Equations; Robust construction of fins in adherence with	Analysis of simulation results will help guarantee that fin flutter will not occur. Materials testing of fin material will be done to ensure that the expected forces are within the	**2E**

				the proposed design.	material tolerances.	

Table 41: Vehicle Operation/Handling Risk Assessment and Mitigation

Hazard	Cause	Effect	Pre-RAC	Mitigation	Verification	Post-RAC
Power supplied to electronics is lost.	Hardware is damaged upon launch; Components shift or disconnect during handling and launching; Batteries run out of charge.	Inability to perform technical task; Ejection charges will not activate; Rocket may be damaged due to failure in recovery system deployment.	**1C**	Test power levels and activation of electronic components; Secure connections between power sources and electrical components.	Ground and flight testing; Change batteries between launches. Ensure batteries are properly stored and maintained.	**1E**
Ejection charge does not ignite.	Malfunction of ignition system; Poor choice of vendor.	Recovery system will not deploy and rocket may be damaged; Bystanders may be injured by falling rocket;	**1C**	Correctly use and set up tested ignition systems.	Verify reliability of component and of its vendor.	**1E**
Motor shifts or loosens within the mount tube.	Improper construction of motor mount; Structural damage occurs upon launch.	Motor may be ejected from the body of the rocket; Payload may not separate.	**1C**	Use a robust motor retention system; Robust manufacturing of motor mount and rocket body.	Run test flights; Check state of motor mount and/or body tube frequently. Calculate forces to ensure that they are within	**1E**

					tolerance for the components.	
GPS or tracker failure.	Nearby metal components block the signal transmission; Hardware is damaged during launch/handling; Power is lost.	Rocket may not be recovered.	**1D**	Test transmission of GPS data and RF capabilities.	Tests will be performed both on the ground and in flight to ensure validity of GPS measurements.	**1E**
Unintentional motor ignition.	Exposure to nearby flame, heat, or electric current.	Members and/or spectators may be injured; Fire may occur; Equipment and/or facilities may become damaged.	**1D**	Isolate the motor from possible sources of heat and from electric fields.	Supervision of safety officer and mentor or trained personnel when appropriate.	**1E**
Burning propellant damages the motor casing upon launching.	Improper assembly of motor set; Poor choice of vendor.	Equipment may become damaged and unusable.	**1D**	Use a certified motor from a reputable vendor.	Verify that the motor is certified.	**1E**
Unintentional ejection charge ignition.	Exposure to nearby flame, heat, or electric current.	Members and/or spectators may be injured; Equipment and/or facilities may be damaged.	**2D**	Isolate the ejection charges from possible sources of heat and from electric fields.	Supervision of safety officer and mentor or trained personnel when appropriate.	**2E**

Motor does not ignite.	Malfunction of ignition system; Poor component selection.	Rocket will not launch.	**3C**	Correctly use and setup tested ignition systems.	Flight testing of the launch vehicle will reveal any problems with motor ignition. Ensure that the motor is being used as recommended by vendor.	**3E**

4.1.4 Environmental Impact Analysis

Table 42: Environmental Concerns Risk Assessment and Mitigation

Hazard	**Cause**	**Effect**	**Pre-RAC**	**Mitigation**	**Verification**	**Post-RAC**
The rocket encounters strong winds on its ascent.	Weather conditions are not favorable	Unexpected launch trajectory; Possible injury to team members or spectators; Failure to reach the desired apogee.	**2C**	Construction will emphasize flight stability and structural integrity; Launch will be postponed and/or cancelled should conditions remain unfavorable.	Weekly team meetings will be held in which the design is discussed. Launch guidelines will be developed to ensure that launch will be cancelled if winds exceed tolerance.	**2D**
The rocket encounters strong winds on descent.	Weather conditions are not favorable.	The rocket will land outside of the predetermined landing radius; Team members or spectators may be harmed by falling rocket;	**2C**	The main parachute will be deployed so as to minimize drift while meeting the maximum allowed kinetic energy on landing; The rocket will carry a GPS	Simulations and flight tests will confirm the optimal deployment height for the main parachute under various circumstances.	**2D**

		The rocket may be hard or impossible to retrieve.		tracker for retrieval; Launch will be postponed and/or cancelled should conditions remain unfavorable.	GPS accuracy will be confirmed via ground and flight tests. Launch guidelines will be developed to ensure that launch will be cancelled if winds exceed tolerance.	
The UAV's camera's view is blocked or visibility is decreased.	Unforeseen cloud cover or presence of fog.	Navigation to the target may be impaired and may result in an inability to see the target with the camera.	**2C**	Camera system will be designed such that it can detect the colored target area through mild obscuring of the camera.	Tests will be performed on the ground before the final launch in order to confirm that the camera works in varied circumstances.	**2D**
High temperatures or strong light sources ignite flammable materials.	Improper storage of flammable material; Improper temperature control of flammable material.	Fire or explosion; Harm or injury to student team and/or personnel; Harm or injury to university students, faculty, or staff not associated with the project; Damage to materials and facility.	**1D**	All flammable materials will be stored in metal cabinets at room temperature; Brief all team members best storage practices	Routine inventory checks and oversight by safety officer during construction to ensure that flammable materials are properly stored.	**1E**

Rocket impacts the ground at a very high velocity.	Failure to model landing kinetic energy accurately; Parachute fails to deploy due to faulty ejection charges; Parachute fails to deploy due to shock cord tangling around the chute.	Area of impact is damaged; Materials from the rocket are scattered around impact site and threaten local flora and fauna.	**1C**	Rigorous landing simulations will be completed; Will use a parachute of a necessary size to ensure that a safe amount of drag force is created; Methodical and best practices will be used in construction to decrease likelihood of rocket coming apart.	Simulation results will be analyzed for accuracy and used to find tolerable landing velocities. Simulations and calculations will determine parachute size. Safety checks will be done pre-flight to ensure the integrity of the rocket.	**1E**
Wildlife is injured during launch and/or flight.	Wildlife approaches the launch pad at time of launch; The rocket collides with wildlife during flight or upon landing.	Wildlife may be wounded or killed; Rocket may be damaged and thrown off its trajectory if an air collision occurs.	**1D**	Launches will take place on sites that are in agreement with NAR and Tripoli regulations, and only when the site is deemed clear of any wildlife.	Launch guidelines will be developed to determine acceptable launch locations and conditions.	**1E**
The rocket lands in a body of water (lake, pond, creek, etc.).	Rocket drifts out further than the designated landing area coming down after either an early parachute deployment or the use of too large a parachute.	Electronics onboard the rocket are damaged; Body of the rocket becomes damaged; Rocket may no longer be retrievable due to the depth of	**1D**	Rigorous calculations of the drift distance will be used to optimize main parachute deployment; Will use fiberglass materials which are highly resistant to water damage.	Simulations will confirm the veracity of calculations. Small-scale and full-scale testing will additionally test calculations. Materials data regarding the fiberglass will be gathered.	**1E**

		the body of water.				
Recyclable or hazardous materials from rocket construction end up in the trash or an open container.	Inadequate recycling and disposal practices.	Negative impact on environment; Possible adverse health effects for university students, faculty and/or staff.	**2C**	Training on recommended recycling practices; Training on disposal of potentially hazardous substances.	Recycling and waste disposal guidelines will be developed and followed in accordance with local and federal laws.	**2E**
Parachute or shock cord is damaged upon landing.	Sharp objects, either natural or man-made, obstruct the rocket's landing.	Additional time and money will be spent on replacing the parachute and/or shock cord before another flight.	**2D**	Selection of robust shock cord and parachutes.	Materials testing of shock cord will be done to confirm its strength.	**2E**
Fins become damaged upon landing.	The rocket lands on a hard surface.	Additional time and money will be spent on replacing the fins before another flight.	**2D**	Robust construction of fins and use of G10 fibreglass.	Fin material will be tested to confirm that landing forces are within tolerance.	**2E**
Fumes and dust particles from rocket construction are vented out into the open air.	Improper or absent use of a filtration or capture system.	University students, faculty, and/or staff in the immediate vicinity may experience a lower air quality.	**3B**	Filters will be used on all ventilation fans; Painting will be completed in an enclosed and ventilated paint booth.	Construction will follow to-be-developed guidelines to prevent the spread of dust, paint, or other airborne particulates.	**3E**

4.2 NAR/TRA Personnel Duties

The CMRC mentor, John Haught, is the primary NAR/TRA personnel. With NAR Level 3 certification, the CMRC mentor will be responsible for all energetic device storage, handling, and use, as outlined in section 4.5

The CMRC president, Michael Messersmith, is the secondary NAR/TRA personnel. With NAR Level 1 certification, the CMRC president will work with the CMRC mentor and SO for the following responsibilities:

- Ensure the safety of launch vehicle and members during all ground tests and launches.
- Ensure that all members adhere to NAR/TRA regulations, as described in section 4.4.
- Ensure that NAR High Power Safety Code is maintained, as described in section 4.4.

4.3 Safety Plan Briefing

The SO will hold periodic safety briefings during the beginning of the project until all members have been briefed on all safety procedures, hazards, and policies outlined in Section 3. At the end of the briefing the SO will distribute the safety agreement for the members to sign. Before performing any manufacturing or work in the CMRC facilities, members must have attended a safety briefing and signed the safety agreement. The SO will be responsible for maintaining a list of all individuals who have received a safety briefing.

The safety plan will be openly available for all members to reference throughout the course of the project. Furthermore, warning stickers and safety memos will be fixed to all CMRC equipment that presents a safety hazard. Members will be able to see the proper safety procedures and PPE for each piece of equipment, such as the Dremel or power drill, before using it. The SO will be responsible for updating these safety procedures as needed during the course of the project, and including the updated procedures in all future working documents.

As part of the safety briefings, all members will also be made aware of the consequences for failing to comply with Section 3. Willful neglect of any procedure or policy described in Section 4 will result in the following:

1. Members who commit an offense without prior records of safety violations will be issued a warning and will be retrained on the appropriate safety protocol.
2. Members found guilty of a second offense will be removed from the NASA USLI project while remaining members of CMRC.
3. A third offense will result in permanent removal from the project team as well as from CMRC.

“Willful neglect” will be defined by the CMRC body when assessing each situation and an action will be labeled an “offense” via a majority vote involving all members of the body.

4.4 Safety Regulation Compliance

Table 43: NAR High Power Safety Code

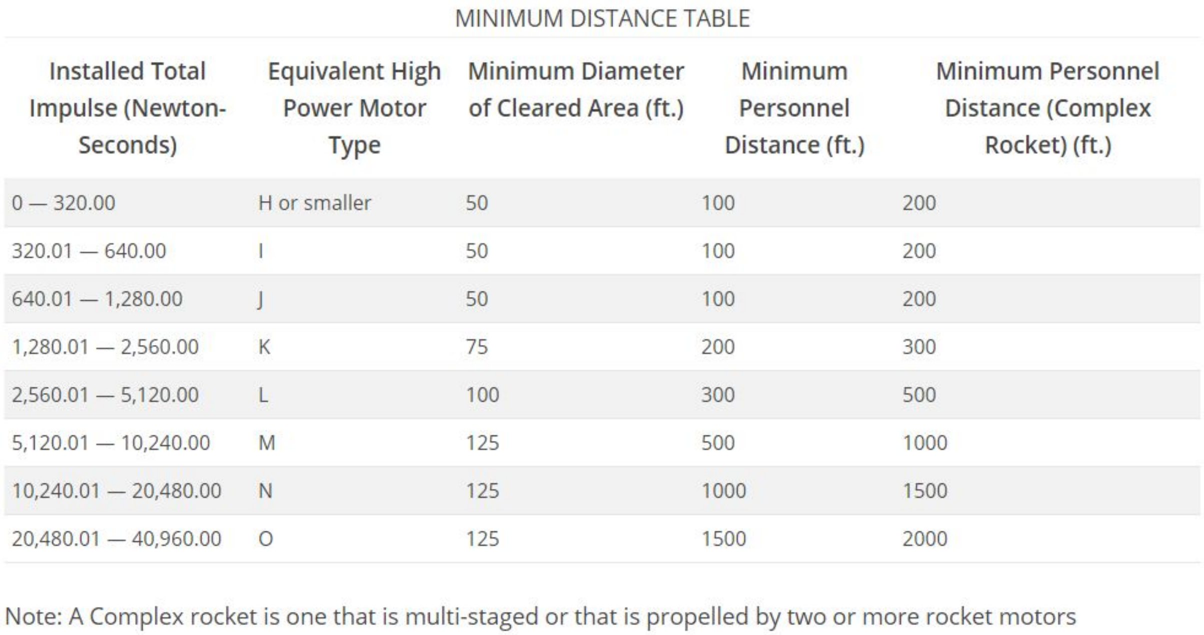
Section	Compliance
1. Certification	CMRC mentor, John Haught, has NAR Level 3 certification. He will be responsible for the possession of J-, K-, and L- impulse class motors. CMRC president, Michael Messersmith, NAR Level 1 certification. He will only possess I- impulse class motors or lower.
I will only fly high power rockets or possess high power rocket motors that are within the scope of my user certification and required licensing.	
2. Materials	The launch vehicle will be primarily constructed out of fiberglass, wood, and plastic. Metal, typically aluminum or alloyed steel, will only be used for various mounting hardware and possibly to increase strength in the nose cone.
I will use only lightweight materials such as paper, wood, rubber, plastic, fiberglass, or, when necessary, ductile metal, for the construction of my rocket.	
3. Motors	CMRC will only purchase certified motors such as from CTI, Loki, and AeroTech. These motors, if within CMRC's NAR certification scope, will be stored in a locked motor box which is kept in a locked cabinet. The room is climate controlled and smoking is prohibited.
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, or heat sources within 25 feet of these motors.	
4. Ignition System	CMRC is using electrical motor igniters compatible with our selected motor. These will be only installed on the launch vehicle on launch day, when the launch vehicle is on the launch pad or designating prepping area. The launch switch will be a horizontal spring switch that will return to "off" after release. The onboard electronics will be powered off until ready for launch. The onboard electronics will then be powered on using
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.	a screwdriver to activate a Schurter rotary switch. This will not have any impact on the ignition system.
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.	The CMRC SO will ensure that in the case of a misfire, the launcher's safety interlock will be removed and that 60 seconds will elapse before anyone is allowed to approach the launch vehicle.
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 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.	The CMRC SO will ensure that a loudspeaker is used to inform the nearby spectators that a launch will occur. The SO will ask for all spectators to move to a safe distance outlined by the Minimum Distance Table, to stand up, and to track the rocket during launch. The SO will then count down from 5 and launch the rocket. During descent, spectators are asked to shout when they see the rocket and point at it. This will ensure that all nearby spectators are aware of the trajectory of the rocket and can move out of the landing path. CMRC will analytically verify the stability of the launch vehicle using OpenRocket prior to launch. Simultaneous launches of more than one high power rocket will not be permitted by CMRC.

7. Launcher	CMRC has constructed a steel 12' launch pad which provides structural stability. The launch pad will be angles with 10 degrees of vertical, but NASA provided launch pads will be used during the competition launch in April. The launch pad has a blast deflector to prevent the exhaust from hitting the ground. Dry grass is always cleared around the launch pad.
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 of 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.	
8. Size	CMRC will not exceed an L-impulse class motor, a maximum of 5,000 Ns of impulse. This is below the allowable size. The thrust to weight ratio of the launch vehicle will be determined and mandated to be greater than 3:1.
My rocket will not contain any combination of motors that total more than 40,960 N-sec (9,208 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.	
9. Flight Safety	CMRC will only perform launches in FAA authorized airspace after submitting the proper FAA documentation and receiving approval. If there are low clouds, airplanes, or spectators in the path of the launch vehicle, the launch will be delayed until the obstruction has cleared.
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 when flying, and will ensure that my rocket will not exceed any applicable altitude limit in effect at that launch site.	
10. Launch Site	CMRC will only perform launches at the Tripoli Pittsburgh's Dragon Fire launch site, or at NAR's Weber Farm launch site. Both sites are in agreement with these specifications.
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 1,500 feet, whichever is greater, or 1,000 feet for rockets with a combined total impulse of less than 160 N-sec, a total liftoff weight of less than 1,500 grams, and a maximum expected altitude of less than 610 meters (2,000 feet).	
11. Launcher Location	CMRC will only perform launches at the Tripoli Pittsburgh's Dragon Fire launch site, or at NAR's Weber Farm launch site. Both sites are in agreement with these specifications.
My launcher will be 1,500 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.	
12. Recovery System	The launch vehicle is equipped with a dual deploy recovery system with a

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.	drogue chute deployed at apogee and a main parachute deployed at approximately 600-800 ft. All parachutes will be protected by flame shields prevent the charges from damaging the parachutes.
13. Recovery Safety	The CMRC SO will enforce safe launch vehicle recovery practices by preventing members from retrieving the rocket from dangerous places. The SO will also determine whether the launch location/weather is appropriate prior to the launch.
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.	



MINIMUM DISTANCE TABLE

Installed Total Impulse (Newton-Seconds)	Equivalent High Power Motor Type	Minimum Diameter of Cleared Area (ft.)	Minimum Personnel Distance (ft.)	Minimum Personnel Distance (Complex Rocket) (ft.)
0 — 320.00	H or smaller	50	100	200
320.01 — 640.00	I	50	100	200
640.01 — 1,280.00	J	50	100	200
1,280.01 — 2,560.00	K	75	200	300
2,560.01 — 5,120.00	L	100	300	500
5,120.01 — 10,240.00	M	125	500	1000
10,240.01 — 20,480.00	N	125	1000	1500
20,480.01 — 40,960.00	O	125	1500	2000

Note: A Complex rocket is one that is multi-staged or that is propelled by two or more rocket motors

Figure 86: NAR Minimum Distance Table

CMRC will also abide by all relevant state and federal regulations set forth by the Federal Aviation Association (FAA), National Association of Rocketry (NAR), Tripoli Rocketry Association (TRA), National Fire Protection Association (NFPA), and the Department of Transportation (DOT). Refer to Appendix 7 for more information.

4.5 Energetic Device Handling Plan

The CMRC mentor, John Haught, will be the only individual that handles the rocket motors and energetic devices such as black powder ejection charges. Since he is NAR Level 3 and TRA Level 3 certified, John is qualified to be handling the K- and L-impulse class motors that CMRC is expecting to use for the launch vehicle.

4.5.1 Motor Purchase

For H- and I- impulse class motors, CMRC will purchase the motors with the expressed permission of the CMRC President, Michael Messersmith, who is NAR Level 1 certified. He will use his certification to verify the validity of the purchase with the motor company in question. The motors will be shipped to Carnegie Mellon University and stored by CMRC under the supervision of the CMRC President.

For J-, K-, and L- impulse class motors, CMRC will purchase the motors with the expressed permission of our mentor, who is NAR Level 3 and TRA Level 3 certified. He will use his certification to to verify the validity of the purchase with the motor company in question. The motors will be shipped to Carnegie Mellon University, and held by CMRC until John is able to retrieve the motors.

4.5.2 Motor Storage

For H- and I- impulse class motors, the motors will be kept sealed inside their original packaging, stored inside the CMRC motor box, which is a flame resistant, locked metal box. This metal box will be kept inside the locked CMRC cabinets in Doherty Hall A200. Doherty Hall A200 is a climate controlled room, maintained at a cool temperature and low humidity, with smoking prohibited at all times.

For J-, K-, and L- impulse class motors, our mentor will store the motors. Until our mentor is available, the motors will be stored in the CMRC motor box. They will then be removed from the CMRC motor box, and transferred to our mentor’s motor box. Our mentor will then store the motor box in his privately owned, climate controlled storage room.

4.5.3 Motor Transportation

The CMRC mentor, John Haught, will handle all transportation of the motors and other energetic devices. The motor box will be located in his car, kept secure in a locked trunk. The motor box will be kept away from any potential electrical or heat sources. Our mentor will drive his car, containing the motor box, to all launches including sub-scale, full-scale, and the competition launch at Huntsville, Alabama.

In the event that our mentor is unable to drive to Huntsville, and instead flies, the purchased motors will be directly shipped to the NASA University Student Launch team representatives in Huntsville, to be retrieved by CMRC following our arrival during launch week.

4.5.4 Motor Use

The CMRC mentor, John Haught, will perform all handling of energetic devices, including rocket motors and the black powder ejection charges during the sub-scale launch, full-scale launch, and competition launch. Our mentor will prepare the reloadable motor, install it in the motor retention system, and install the ignition system. Our mentor will measure the black powder ejection charges, pour the charges into the canisters on the recovery bay, and seal the canisters.

4.5.5 Motor Disposal

Following launch, the motor will be retrieved from the launch vehicle. If there is any remaining fuel, it will be collected. According to NAR guidelines and engine manufacturer recommendations, and with the approval of the land site owner, we will dig a ditch to pour the excess fuel in, and remotely ignite it using the same ignition system as for the launch vehicle. Any leftover fuel must be soaked in water to render it inert, and then provided to EH&S for proper disposal.

4.5.6 Defective Motor Handling

If a motor fails to ignite on the launchpad, it will first be considered due to a defective igniter. The battery will be disconnected, and after 60 seconds John will go and replace the igniter. If after several attempts the motor still does not ignite, it will be considered a defective motor. These motors are under warranty by the vendor, so any defective motors will be returned to an onsite vendor by car and given to them for disposal.

4.6 Materials Safety

4.6.1 Composites

The fabrication of the launch vehicle will include cutting fiberglass in order to produce the slots for fins and other necessary modifications to the commercially available fiberglass tubes. The process of cutting fiberglass results in air contamination which can damage the eyes and lungs. Therefore, proper masks and eye protection will be used while cutting fiberglass. In addition, fiberglass will only be handled in proper locations equipped with an exhaust hood to expel the air contamination. Any injuries resulting from contact with the fiberglass will be reported to the safety officer and addressed immediately. Composites that CMRC is expected to use include:

- G12 Fiberglass
- G10 Fiberglass

In order to mitigate these risks, CMRC requires members to wear eye protection, dust mask, gloves, and to use the window air ventilation system in Doherty A200 when working with any composite material.

4.6.2 Chemicals

When handling chemicals, CMRC will keep in mind that there are many hazards associated with it. Some of these hazards include irritation to the skin, eye, and respiratory system from contact with or inhalation of the fumes of the material. Other risks can include exposure to chemical spills and destruction of the laboratory. Chemicals that CMRC is expected to use include:

- 5 Minutes Epoxy
- 20 Minute Epoxy
- 24 Hour Epoxy
- Epoxy Fillet
- Rubbing Alcohol
- Spray Paint
- Primer

In order to mitigate these risks, CMRC requires members to wear eye protection, dust mask, gloves, and to use the window air ventilation system in Doherty A200 when working with any hazardous chemicals

4.6.3 Lithium Polymer/Ion Batteries

Lithium ion and lithium polymer batteries present additional safety concerned beyond that of standard batteries. They may catch fire and explode if punctured, overcharged, or are otherwise damaged. As such, all LiPo and Li-Ion batteries will be labeled with brightly colored fire hazard markings.

LiPo and Li-Ion batteries will be charged and discharged using proper JST-connectors, balance board, and charger. A member must be present at all times during the charging and discharging process. LiPo and Li-Ion batteries will be stored at approximately 75% of their maximum voltage. During long term storage, LiPo and Li-Ion batteries must be periodically charged back to 75% voltage to prevent the battery from becoming depleted.

When a battery has lost its charge or value to the CMRC team, it will be disposed. To safely dispose the LiPo or Li-Ion battery, safely discharge it as much as possible. Then, deliver the batteries to the supplier or CMU Environmental Health & Safety (EH&S) for proper disposal.

4.6.4 Hazardous Material Disposal

When disposing of materials or components made up of hazardous substances, CMRC will comply with the recommendations stated by EH&S at CMU, namely

- Minimization of hazardous waste generation,
- Use of secondary containment,
- Use of certification tags detailing chemical makeup and concentration, name of SO, and date of use,
- Use of the EH&S hazardous waste pickup service,
- Hazardous waste training for SO and all members handling hazardous materials as determined by the SO.

4.6.5 Fire Safety Plan

In the case of a fire, the SO will ensure that all personnel are evacuated from the immediate area and that the fire alarm is triggered. All fire incidents will be reported to campus police. The SO will train members on how to react to a fire incident. It is required that members alert people in the immediate area if there is a fire incident and promptly proceed to evacuate the premises. Members will be made aware that they are not required to fight a fire if they see one and that they should not attempt to do so unless they have been trained, have the appropriate extinguisher class, and the fire has not grown beyond what is possible to fight with an extinguisher. The SO will be trained in the use of fire extinguishers and a CO2 fire extinguisher will be kept readily available in DH A200. All members will be instructed on the fire evacuation plan for Doherty Hall.

4.7 Facilities Safety

4.7.1 Overview

Table 44: Facilities and Available Equipment Summary

Facility	Equipment & Resources	Access
Doherty Hall A200	● Hand drills ● Dremel ● Vacuum and ventilation duct system ● Electric Sander ● Tool kits ● Assorted hardware (screws, nuts, etc)	Tues 4:30PM - 6:30PM Sat-Sun 24/7
Tech Spark Makerspace	● Epilog 50 wt. laser cutter/engraver ● Form 2 SLA printers ● Ultimaker 2 Extended FDM printers ● PCB Board CNC Mill ● Drill Presses ● Bandsaw ● Belt sander ● Soldering irons ● Hand drills ● Heat guns	Mon-Thurs 9:00AM - 11:59PM Fri-Sun 9:00AM - 9:00 PM

	● Tool kits ● Assorted hardware (screws, nuts, etc) ● Guidance from Makerspace staff	
IDeATe Workshop	● CNC Router with 3D axis capabilities ● Electronics room with a plethora of sensors and actuators ● 3 Laser Cutters ● 5 3D printers ● Guidance from IDeATe employees	Wood Shop: Mon-Thur 8:00AM - 4:30PM Makerspace: 24/7
Undergraduate Mechanical Engineering Machine Shop	● Sharp 3 axis knee mills w/ Readout ● 12” Knuth bench lathes w/ Readout ● Knuth gear drive drill presses ● Bandsaw ● MakerBot FDM rapid prototyping machines ● Stratasys Dimension Elite FDM Rapid Prototyping machines ● Haas 3 axis CNC Office mills ● Heat Guns ● Hand Tools ● Small stock of metals ● Guidance from 3 shop employees	Mon-Fri 8:00AM-4:30PM
CFA Fabrication Facility	● Ventilated spray paint room ● CNC router with 2D axis capabilities	Mon-Fri 8:00AM - 5:00PM
Morewood Gardens Makerspace	● Rabbit RL-60-9060 Laser Cutter ● Soldering irons ● Hand tools	Mon-Sun 8:00AM - 10:00PM
Scaife Hall Conference Rooms	● Audio teleconference capabilities ● Projector & Screens	Available if reserved

4.7.2 Doherty Hall A200

Doherty Hall A200 is the main workspace of CMRC. It is located on the A-level of Doherty Hall, and houses nearly all of CMRC owned tools and materials. It is equipped with eight long work tables, proper safety equipment, ventilation systems, and building materials. This is where CMRC general body meetings occur every Tuesday and Sunday.

Shop Manager: Kunal Ghosh
Contact: kunalghosh@cmu.edu
Required Training:

- Supervision of SO
- Respirator Training (when using respirator)

4.7.3 Tech Spark Makerspace

Located in the basement of Hammerschlag Hall on Carnegie Mellon's Pittsburgh campus, the Tech Spark Makerspace gives students access to 3D printing, laser cutters, CNC mills, CAD and simulation software, as well as many more.

Shop Manager: Diana Haidar
Contact: dhaidar@andrew.cmu.edu
Website: https://www.meche.engineering.cmu.edu/facilities/tech-spark.html
Required Training:

- 24-200 Machine Shop Practice (required for drill press, bandsaw, and belt sander) OR
- 24-302 Introduction to Manual and CNC Machines

4.7.4 IDeATe Workshop

This facility houses a standard wood shop and CNC router. The facility is new and does not have a class to authorize students but rather has multiple safety trainings provided by the school.

Shop Manager: John Antinitis
Contact: jantanit@andrew.cmu.edu
Website: https://resources.ideate.cmu.edu/spaces/woodshop/
Required Training:

- Student Shop Safety Training
- Fire Extinguisher Use Part 1 Training
- Fire Extinguisher Use Part 2 Training
- Hazard Communication Training
- Student Hazardous Materials Training
- Back and Lifting Safety Training
- Hand and Power Tool Safety Training

4.7.5 Undergraduate Mechanical Engineering Machine Shop

The Undergraduate Mechanical Engineering Machine Shop works with the school but is also regarded as an independent business. It assists students when constructing their components but also has high standards and requires students to take a class in order to be permitted inside during shop hours. This machine shop will be used for fabrication of custom components.

Shop Manager: Jim Dillinger
Contact: jimd@cmu.edu
Website: https://www.cmu.edu/me/facilities/machine-shop.html
Required Training:

- 24-200 Machine Shop Practice

4.7.6 CFA Fabrication Facility

The College of Fine Arts has a fabrication facility on the D-level of Doherty Hall. It is open for general student use given they adhere to the facility rules. The fabrication facility is equipped with a ventilated spray paint booth which is used to paint our rockets safely. In addition, there is CNC router for woodwork which has been used to fabricate various components for the organization.

Shop Manager: Steve Gurysh
Contact: sgurysh@cmu.edu
Website: http://www.art.cmu.edu/facilities/overview/
No Required Training

4.7.7 Morewood Gardens Makerspace

The Morewood Gardens dormitory has several workspaces, including a makerspace that houses laser cutters, soldering irons, and various hand tools. This is a convenient location for people living on campus to go to work on various parts for the project.

Shop Manager: Alex Peltier
Contact: apeltier@andrew.cmu.edu
Website: https://calm-cliffs-64729.herokuapp.com/
Required Training:

- Power Tool Training
- Fire Extinguisher Training

4.7.8 Scaife Conference Rooms

Students at Carnegie Mellon have access to the Scaife Hall Conference Rooms, provided that reservations are done in advance with the Department of Mechanical Engineering through 25Live.

Manager: Carnegie Mellon Computing Services
Contact: it-help@cmu.edu
Website:
https://www.cmu.edu/computing/services/teach-learn/tes/classrooms/locations/scaife.html

Reservation System: https://25live.collegenet.com/cmu

4.8 CMRC Safety Agreement

All CMRC NASA members will be required to sign the CMRC Safety Agreement (provided in Appendix 7.2). The Safety Agreement entails that all CMRC members handling the rocket in any way, shape, or form will uphold themselves to safety measures outlined above.

5 Payload

5.1 Overview of Payload

The payload system must successfully and autonomously deploy a 5in, impact-resistant drone from the landing site of the rocket. This deployed drone must fly and locate the 10ft x 10ft tarp and drop a small 1in x 1in beacon on top of the the tarp. The deployment system will move the UAV from inside of the coupler to outside of the rocket completely autonomously. Because the contained UAV features a rotating cage, the UAV will self right itself in order to be ready for takeoff. Next, the pilot will engage the UAV and begin liftoff for flight. This pilot will perform a search procedure in order to locate the tarp. Once the tarp has been discover and the drone is overtop said tarp, the pilot will deploy the previously mentioned beacon onto the tarp, and will proceed to land in a safe secondary area.

5.2 Deployment & Locking Mechanism

5.2.1 Mission Goals and Criteria

The following is a list of the goals and criteria of the UAV deployment mechanism:

- To secure the UAV within the payload bay until the deployment signal is received. This includes withstanding the loads of launch and parachute deployment.
- To clear the UAV from the body of the launch vehicle when instructed without causing damage to the UAV or the launch vehicle itself. The deployment system must be capable of overcoming any expected external resistance to deployment such as rocks, grass, and other vehicle sections.
- Conduct all deployment processes autonomously.

5.2.2 Design Concepts and Trade Study

5.2.2.1 Initial Designs

Two high-level payload deployment concepts were considered: airframe separation and bulkhead ejection.

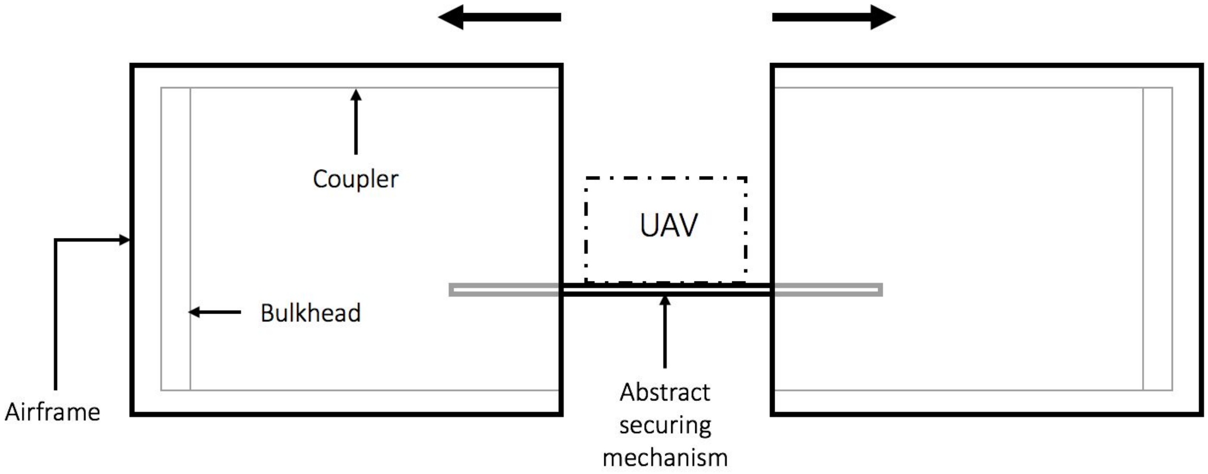


Figure 87: Airframe Separation Deployment

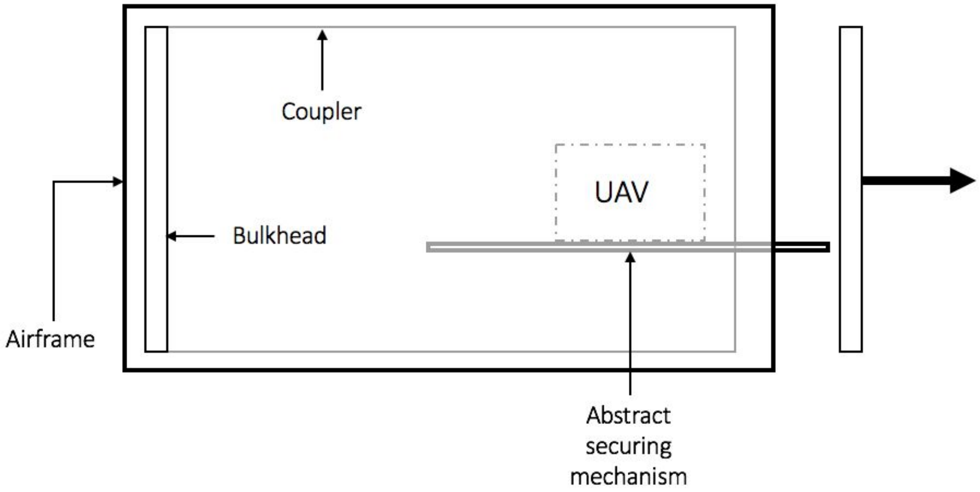


Figure 88: Bulkhead Ejection Deployment

The bulkhead ejection method was chosen due to the reduced complexity of the design, lower power requirements, and greater reliability. Bulkhead ejection requires less power because less mass has to be moved (entire airframe, coupler, and electronic hardware vs. just the bulkhead). Mounting a reliable locking mechanism to prevent accidental airframe separation during flight unto the curved inner surface of the payload coupler adds a lot of design, manufacturing, and assembly complexity which makes the probability of mission critical failure all the more likely.

Two bulkhead securing and ejection mechanisms were initially explored: explosive ejection (with blackpowder) and solenoid lock with reaction ejection. Along with the bulkhead ejection mechanisms, two concepts were initially explored for housing and displacing the UAV from the payload bay: a cart and track system with roller bearing supports and a spring loaded piston system with a mesh-enclosed UAV.

Explosive Ejection

The UAV is housed within a coupler that is suspended within the payload bay by two centering rings. The space between the internal coupler and payload bay (the interspace), and between the front bulkhead and centering ring houses a series of black powder charges that are ignited to eject the front bulkhead. This space can be made airtight such that the highly-energetic gas does not escape into the barrel before shearing the pins and losing most of its energy in the process. Since the volume of the interspace is so small compared to the volume of the barrel, the resulting pressure difference produced by expanding gas in the barrel will likely be negligible. Therefore, the primary concern is protecting the UAV from any black powder debris or soot, which can be accomplished by using a fire-resistant cloth like a parachute protector placed over the front of the UAV. The black powder will be stored in a similar manner to the recovery charges with the E-match wires routed through the front centering ring down the length of the coupler to a microcontroller mounted either behind the barrel bulkhead or external to the payload coupler itself.

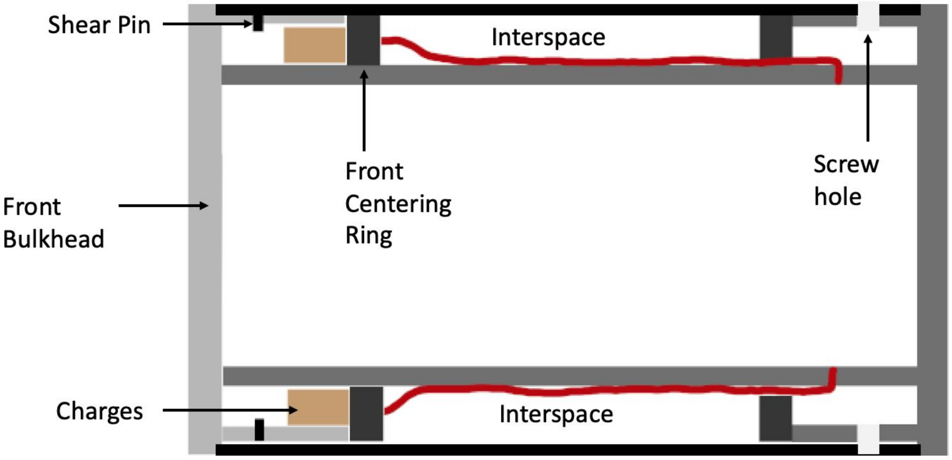


Figure 89: Ejection bulkhead schematic

Solenoid Lock and Reaction Ejection

A series of three push-pull solenoids are mounted on the inside face of the front bulkhead as shown in Figure 27. The solenoid shafts extend through holes in the bulkhead shoulder and payload coupler thus preventing the bulkhead from moving. They are connected to a microcontroller and power source via long wires packed within the payload compartment that will remain connected to the bulkhead after ejection. When the deployment signal is received, the solenoid shafts retract and the bulkhead is pushed out by the UAV deployment mechanism. The shoulder on the front bulkhead is meant to prevent soil and other debris from entering the payload coupler during landing. This method can still be used in conjunction with an internal coupler as in the explosive ejection method to route wires and house electronics or other systems for bulkhead ejection.

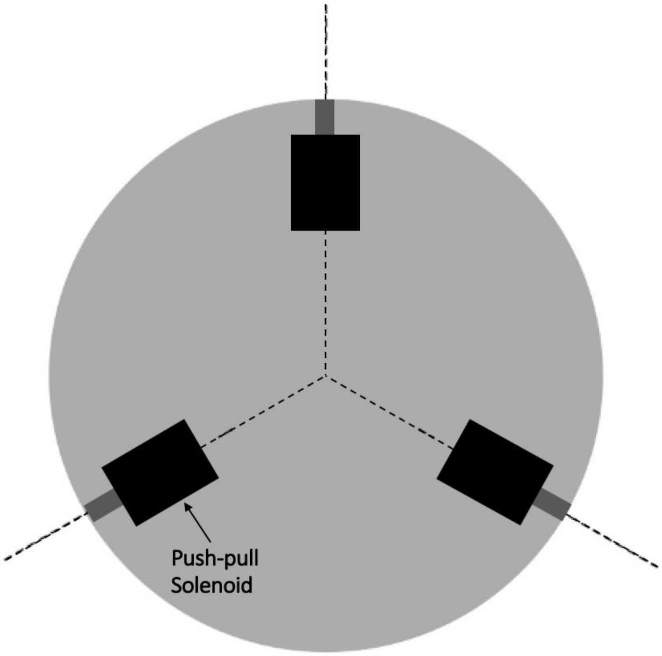


Figure 90: Solenoid Attachment Schematic

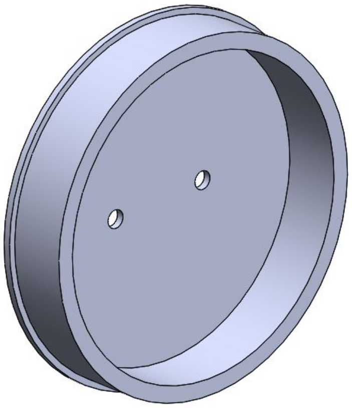


Figure 91: Isometric View of Front Bulkhead with Attached Shoulder

Cart and Track System

The first concept shown below has a cart which slides on a track that is fixed to the inner race of two separate roller bearings which are epoxied to the inner surface of the payload coupler. A push-pull solenoid with an extended shaft in its unpowered state is epoxied to the inner race of the aft bearing. The shaft of this solenoid is covered in high friction material that prevents rotation of the cart and track when in contact with the aft bulkhead. This is meant to reduce loads on the UAV and cart electronics during flight. When the solenoid is engaged, the shaft retracts and allows the bearings to rotate. This will level out the track with respect to the ground during deployment. Once the cart is level with the ground, the solenoid is once again disengaged to prevent further rotation of the cart. Information on the orientation of the cart is provided by an accelerometer mounted on the cart.

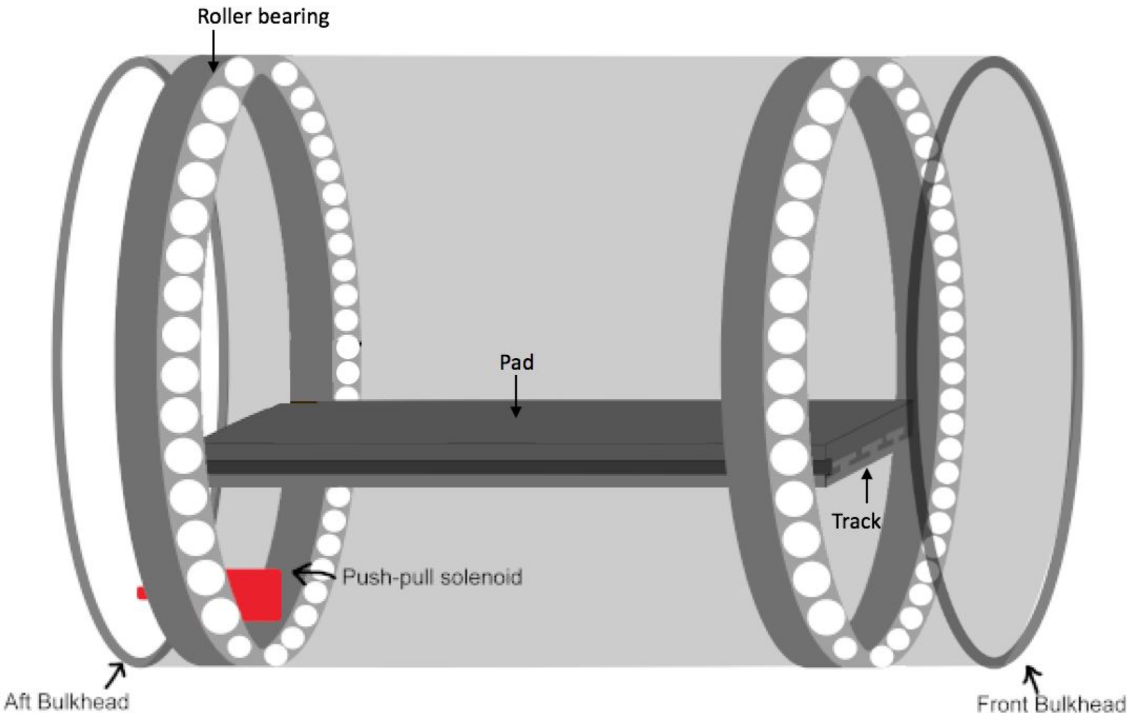


Figure 92: Perspective view of general cart and track concept.

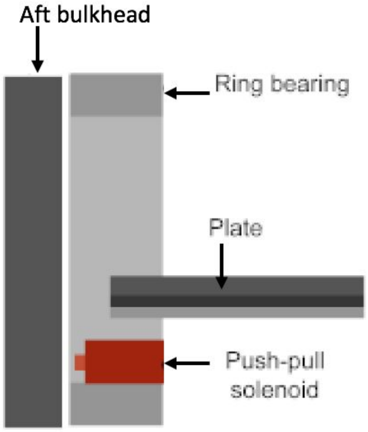


Figure 93: Longitudinal cross section view of aft bearing region.

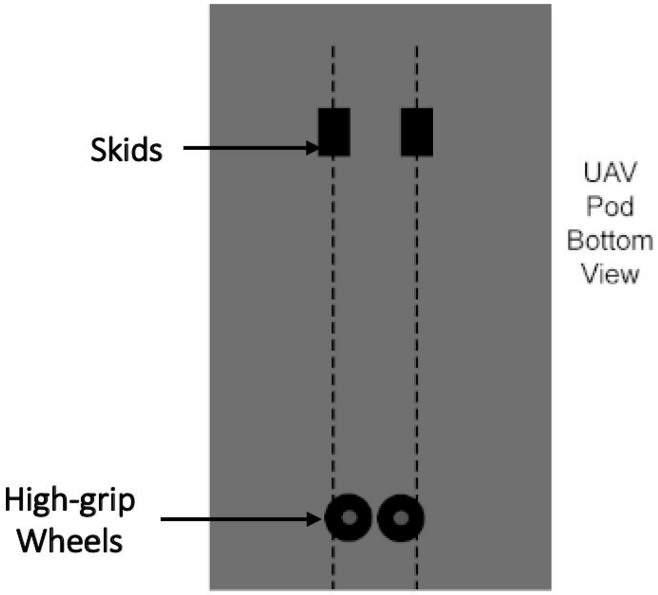


Figure 94: Cart bottom view

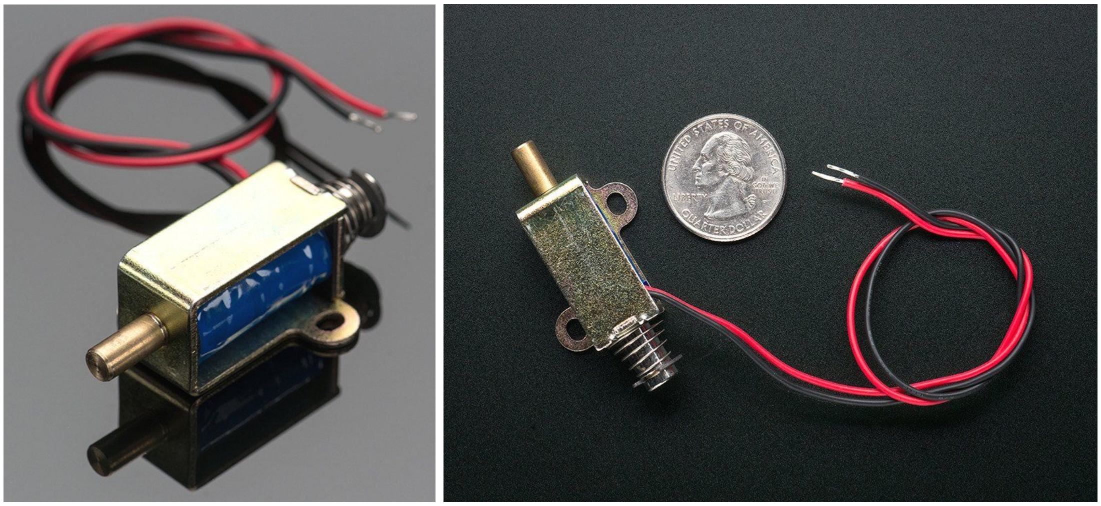


Figure 95: Adafruit Push-Pull Solenoid

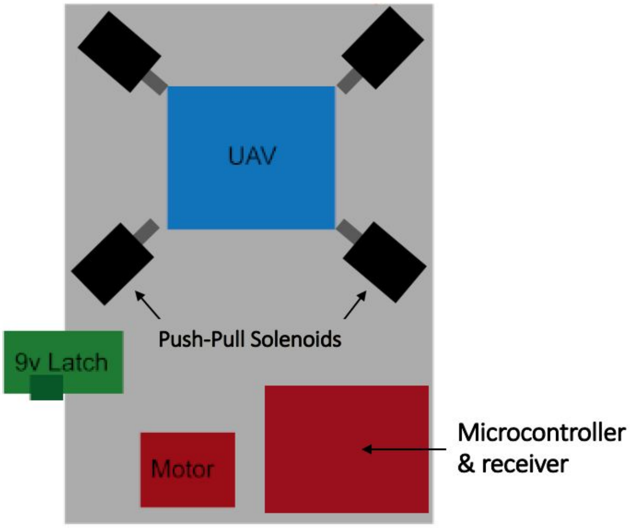


Figure 96: Pad top view for motorized cart

Figure 97: Top view of track for motorized cart configuration.

Figure 98: Cross section of track for motorized cart

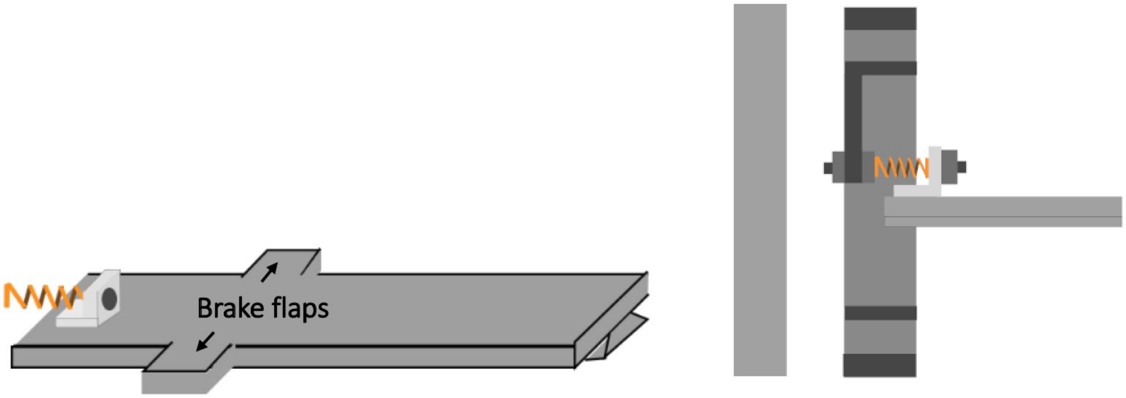


Figure 99: Perspective view of spring-propelled cart (left) and cross section view showing full spring attachment setup (right)

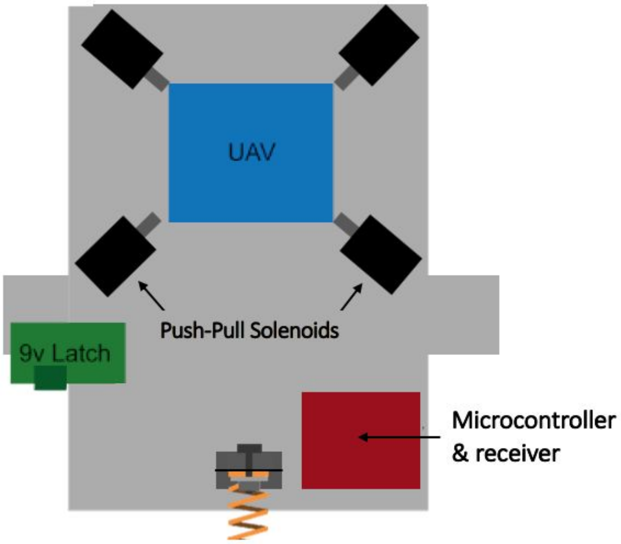


Figure 100: Top view of spring-propelled cart

Figure 101: Cross section of track for spring-propelled cart

There are two versions of the cart and track system. One has the cart propelled by a small DC motor which is connected to the shaft of one of the wheels on the underside of the cart. The wheels and two forward skids on the cart slide within a well-lubricated double-I-beam track. The track has a stopping block that allows the skids to pass but not the wheels which prevents the cart from sliding out altogether. The other configuration has a spring-damper system in place of the DC motor and full-length skid that slides within a trapezoidal track (also well-lubricated) shown in Figures 35-37. Two side-fins on the cart impact the front bearing once the cart has moved a certain distance to prevent the cart from sliding out of the track. These side-fins could potentially hold dashpots that will control the speed of the cart. Both configurations feature four small push-pull solenoids mounted on the cart that secure the UAV to the cart and a 9V rotary latch that connects to a U-bolt fastened to a small protrusion on the track below. The latch disengages once the deployment signal is received to allow the cart to slide. Alternatively, a downward-facing push-pull solenoid could be used for this purpose. Once the cart has reached a stop, the UAV solenoids disengage allowing the UAV to take-off. All electronics on the cart are connected to a microcontroller. The second configuration is preferred since it reduces power consumption. It is also easier to manufacture the cart and track for this configuration given that no wheels or moving parts need to be integrated on the underside of the cart.

Spring-Loaded Piston System

Alternatively, instead of using a cart and track system, it is possible to enclose the UAV in a spherical/cylindrical mesh like the one shown in Figure 38 with a rotational degree of freedom about a point above its CG. This degree of freedom allows the UAV to level off after ejection from the payload coupler.

Figure 102: Example of mesh-enclosed UAV

Ejection of the UAV can be accomplished using a spring-loaded piston (shown in Figure 39) where the front face of the piston head is machined to the curvature of the mesh. The same can be machined on a pad epoxied to the inside of the front bulkhead to more uniformly distribute the forces on the mesh. The UAV will also be positioned with the interface shaft collinear with the spring axis. This way the majority of compressive forces are exerted on the shaft rather than the mesh. The UAV is housed in an internal coupler (or barrel) within the payload compartment that provides the UAV with a smooth, un-intruded path for deployment and prevents excessive bouncing of the UAV within the payload compartment. The UAV mesh will protect the UAV from impact and debris when it hits the ground after deployment.

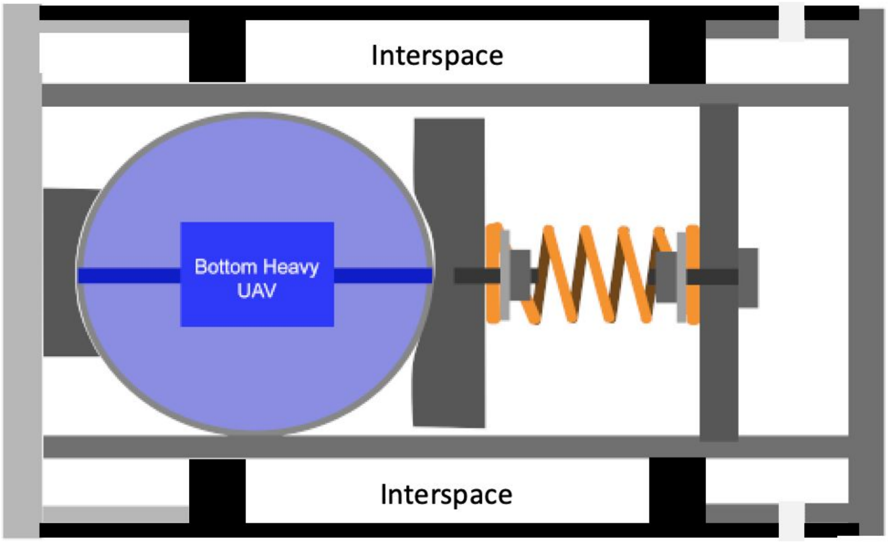


Figure 103: Longitudinal cross section of spring-loaded piston system

One of the disadvantages of this design is that it loads the UAV shaft in compression which risks failure in buckling. To counteract this would require a thicker shaft which would increase the mass of the UAV and, thus, reduce its operating range. Furthermore, it is difficult to ensure that the piston will not deflect in one direction and get jammed during deployment.

5.2.2.2 Trade Study of Initial Designs

🟩 = Excellent 🟨 = Fair 🟥 = Poor

Table 45: Trade Study Summary

Method	**Effectiveness and Performance**	**Reliability**	**Ease of Manufacturing**
Cart and Track	🟥 High power requirements even with a spring-propelled cart due to the high number of solenoid and/or electronic latch mechanisms, not to mention sensors and the microcontroller. These, in addition, consume a fair portion of the	🟥 The high complexity of this design increases the probability of mission failure.	🟥 Custom track and cart required. Various sensors and actuators are required to control movement of the cart, roller bearings, and UAV. Assembly of parts within the payload coupler will be a challenge.

	volume within the bay that would be used for the UAV. It may not even be possible to fit electronics such as the UAV securing solenoids on the cart. The cost of implementing this design will also be high.		
Spring-Loaded Piston	A purely mechanical system eliminating the need for electronic components and power supplies. The spring can be ordered to the necessary specifications to propel the UAV clear of the body tube. Can house a larger UAV which is important to the operating capacity of the UAV.	Current design does not prevent the piston from angling during deployment and thus experiencing high friction loads that could prevent successful deployment. Furthermore, compressive load on the shaft from the spring-loaded piston might induce buckling failure of the shaft. However, the low complexity of the design increases the probability of mission success.	Manufacturing will be easier with this design compared to the cart and track system. However, integration of the UAV and forward bulkhead, will be difficult as the spring will constantly be pushing against these components.

Table 46: Trade Study Summary Continued

Method	**Effectiveness and Performance**	**Reliability**	**Ease of Manufacturing**
Explosive Ejection	Will ensure clear ejection of bulkhead under high external resistive loads.	Might cause damage to UAV and payload bay. The shear pins might not withstand the sharp impulse of parachute deployment which could pose a safety hazard.	Creates fracture critical vessel which pushes up the design requirements on the payload bay.
Reaction Ejection	Ejection effectiveness depends on the	No harm caused to the UAV or payload	Requires mounting three solenoids to the

	deployment method.	bay. If used in combination with a spring-loaded piston system, the shafts might fail to retract due to friction between the solenoid shafts and the payload coupler or might not retract simultaneously which would also prevent ejection.	front bulkhead.

5.2.3 Overview of Leading Design

To address the issues identified above, a new design (shown in Figure 101) was proposed that utilizes a lead screw mechanism to eject the UAV and front bulkhead.

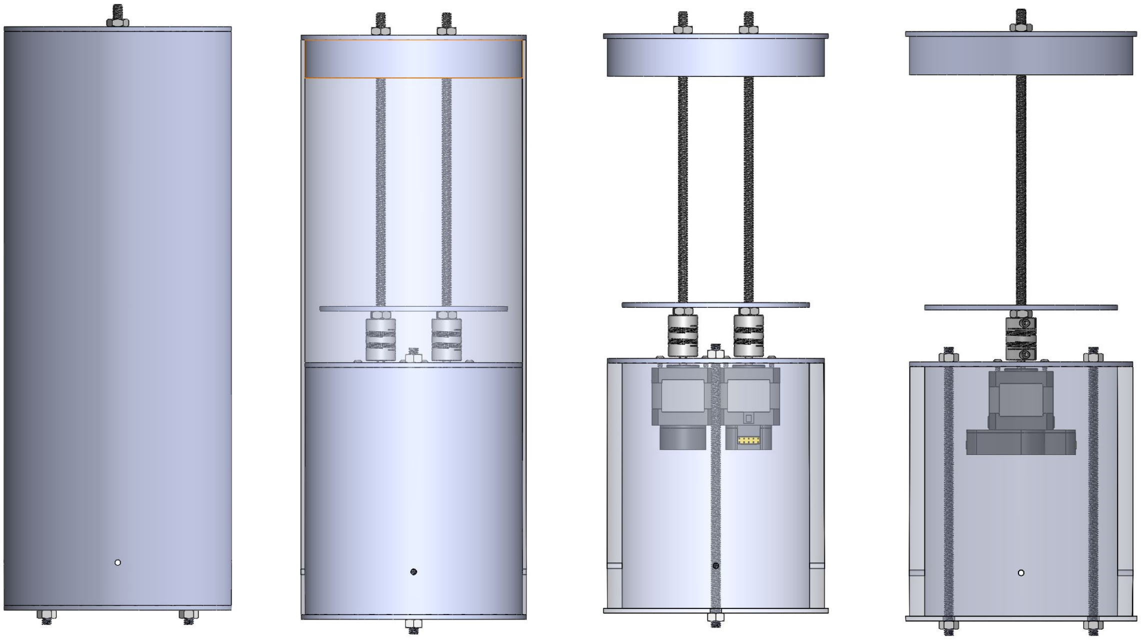


Figure 104: Leading Design for UAV Deployment

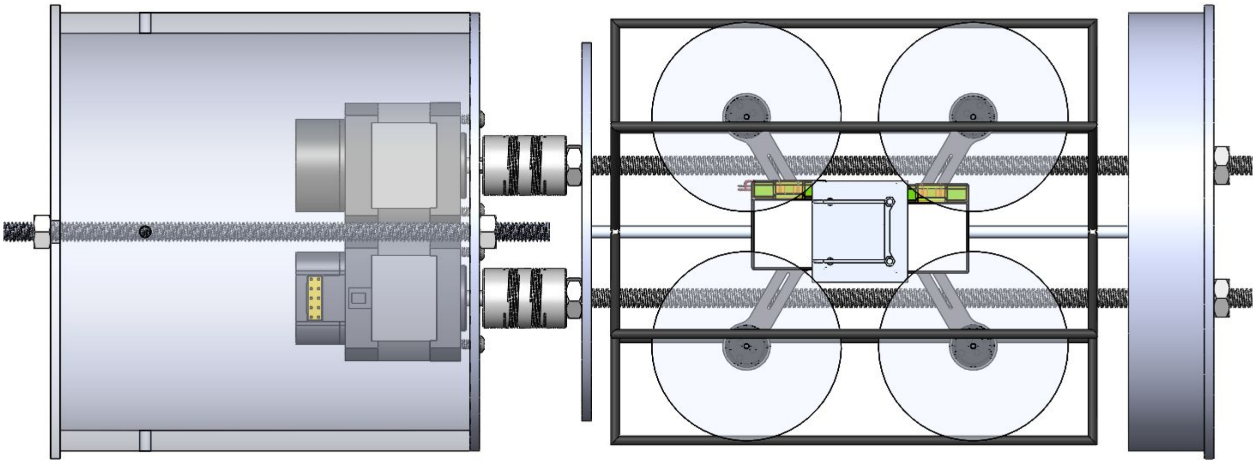
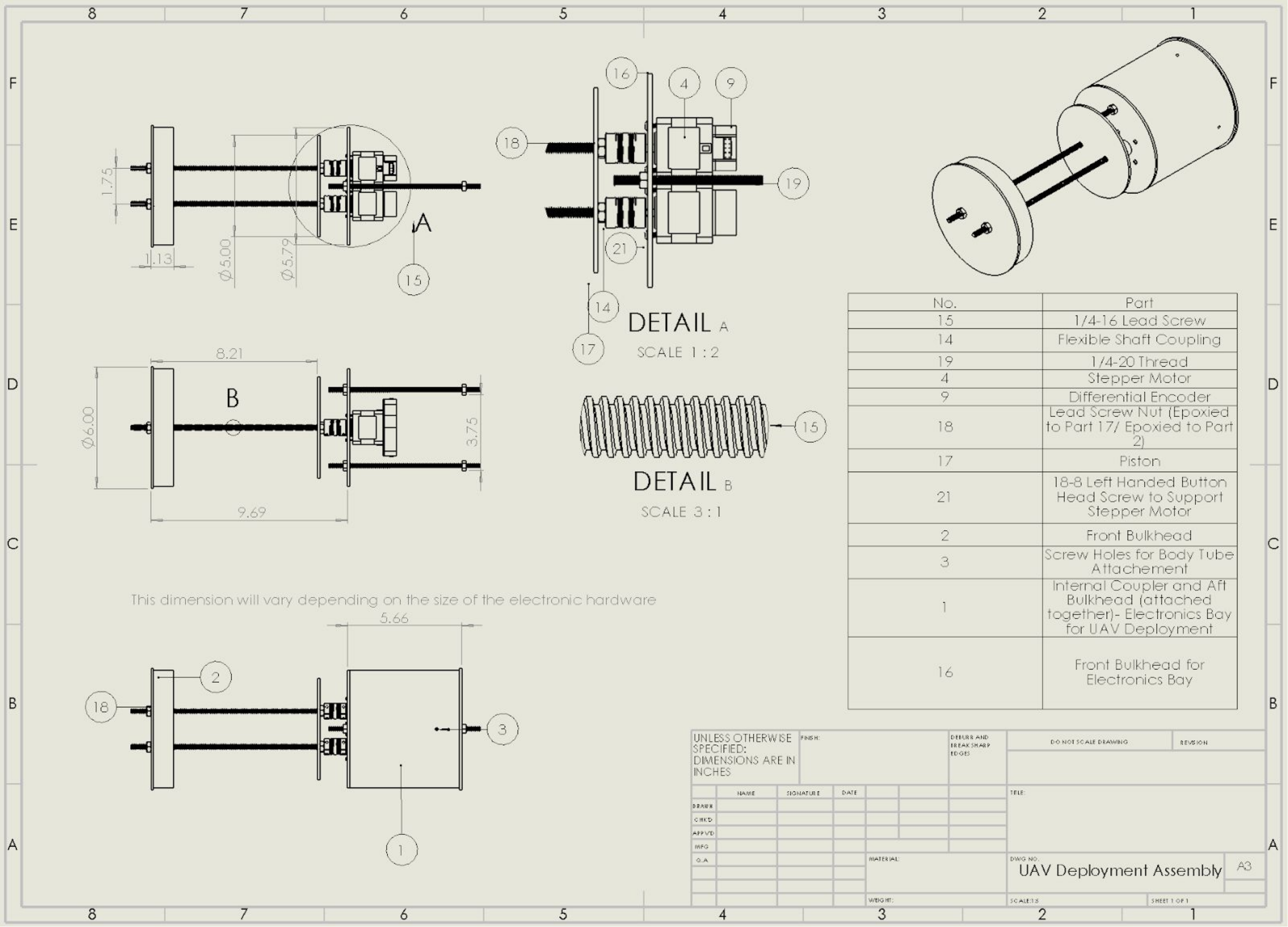


Figure 105: UAV Deployment System with UAV



No.	Part
15	1/4-16 Lead Screw
14	Flexible Shaft Coupling
19	1/4-20 Thread
4	Stepper Motor
9	Differential Encoder
18	Lead Screw Nut (Epoxied to Part 17/ Epoxied to Part 2)
17	Piston
21	18-8 Left Handed Button Head Screw to Support Stepper Motor
2	Front Bulkhead
3	Screw Holes for Body Tube Attachement
1	Internal Coupler and Aft Bulkhead (attached together)- Electronics Bay for UAV Deployment
16	Front Bulkhead for Electronics Bay

Figure 106: Dimensional Drawing of Leading Design for UAV Deployment

Lead screws have great mechanical advantage between input torque and output force that is directly proportional to the lead of the screw and its mean diameter. The following equation relates the input and output in terms of these variables.

$$\tau = \frac{F d_m}{2}\left(\frac{l + \pi f d_m sec\ \alpha}{\pi d_m - f l sec\ \alpha}\right)$$

where f is the coefficient of friction between the screw and nuts, F is the force on the nuts, d_m is the mean diameter, l is the lead, and τ is the applied torque. They can provide a large force at small input torques which is desired to overcome any external obstacles to deployment. Furthermore, by using two lead screws, not only does this increase the force that can be exerted on the UAV for deployment, but this also prevents the bulkhead and piston from being back driven by external forces. Furthermore, as long as the two stepper motors are actuated simultaneously and at the same angular speed, the piston will remain flat with the face of the UAV's cylindrical mesh. The differential encoder on the stepper motor will allow the implementation of feedback control to ensure the two lead screws are properly actuated.
The flexible shaft couplers will connect the motor shaft with a corresponding lead screw. The benefit of using these couplings is that they are capable of handling some amount of error in the distance between lead nuts on the piston and the distance between the lead nuts on the front bulkhead. In other words, they can handle some misalignment due to tolerances. Since these couplings are flexible they cannot withstand the high axial stresses that would be generated by forces exerted during parachute deployment. Therefore, to avoid exerting those forces on the forward bulkhead (which would be directly transmitted to the couplings), the forward bulkhead will be facing the nose cone and will be epoxied to it. The aft bulkhead will be fixed to the upper airframe using four screws and it will be connected to the main parachute via an eyebolt. Therefore, when the main parachute deploys, the force will be exerted on the button head screws rather than the couplings. During UAV deployment, the nose cone along with the front bulkhead will be pushed off. The screws connecting the payload bay to the airframe are 18-8 stainless steel button head screws, which have a tensile strength of 70,000 psi corresponding to an approximate shear strength of 35,000 psi. The peak force on the payload bay will be ~580 lbs at main parachute deployment, which will produce a shear stress on each screw of ~10,948 psi. Since the shear stress is much less than the shear strength of these screws, they should hold the payload bay in place.

The components of the system will consist of 2 stepper motors (NEMA-17 size) driven by the Adafruit DC Motor + Stepper FeatherWing add on board that will provide the necessary driving signal to control both stepper motors at 9V (powered by a standard 9V battery). This motor controller will be operated by the main controller, the Adafruit Feather M0. This compact main controller will be the board that will be directly programmed (over native micro USB from the computer) and features a built in 900 MHz LoRa Radio that will communicate directly to the ground station. In addition, the board will be powered by a secondary Lithium Polymer battery as the motors have higher power requirements than the main controller.

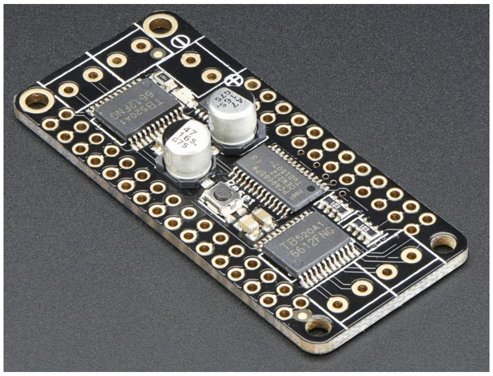


Figure 107: Adafruit Stepper Motor Controller for Feather Board

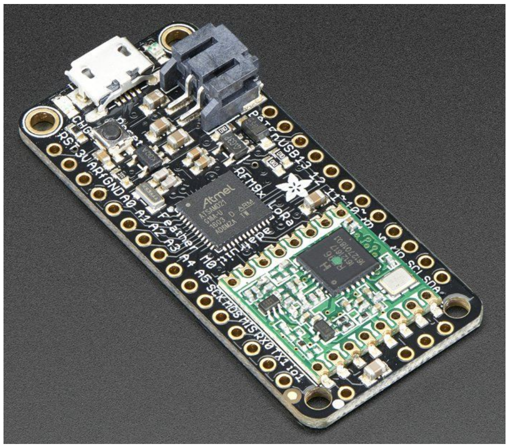


Figure 108: Adafruit Feather Control Board and 900MHz Radio

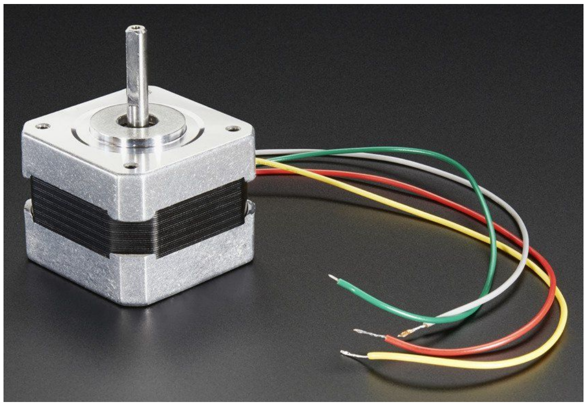


Figure 109: Stepper Motor NEMA-17

Figure 110: Lithium Ion Polymer Battery

🟩 = Excellent 🟨 = Fair 🟥 = Poor

Table 47: Trade Study Summary of Leading Design

Method	Effectiveness and Performance	Reliability	Ease of Manufacturing
Lead Screw Mechanism	🟩 The large mechanical advantage possible using lead screws will ensure that the UAV can be evacuated from the payload bay. The control systems are not complex (motor driver + a microcontroller such as an Arduino + receiver + power source is all that is needed).	🟩 The simplicity of the design makes it more compact and reliable than the initial design concepts. Avoids exerting large forces on the UAV when driving against external forces since the forward bulkhead is driven independently of the UAV (not reaction driven).	🟩 Not any more complex than the manufacturing process for a typical recovery bay.

5.3 Drones Overview of Selection Criteria

5.3.1 Fixed-wing Drone

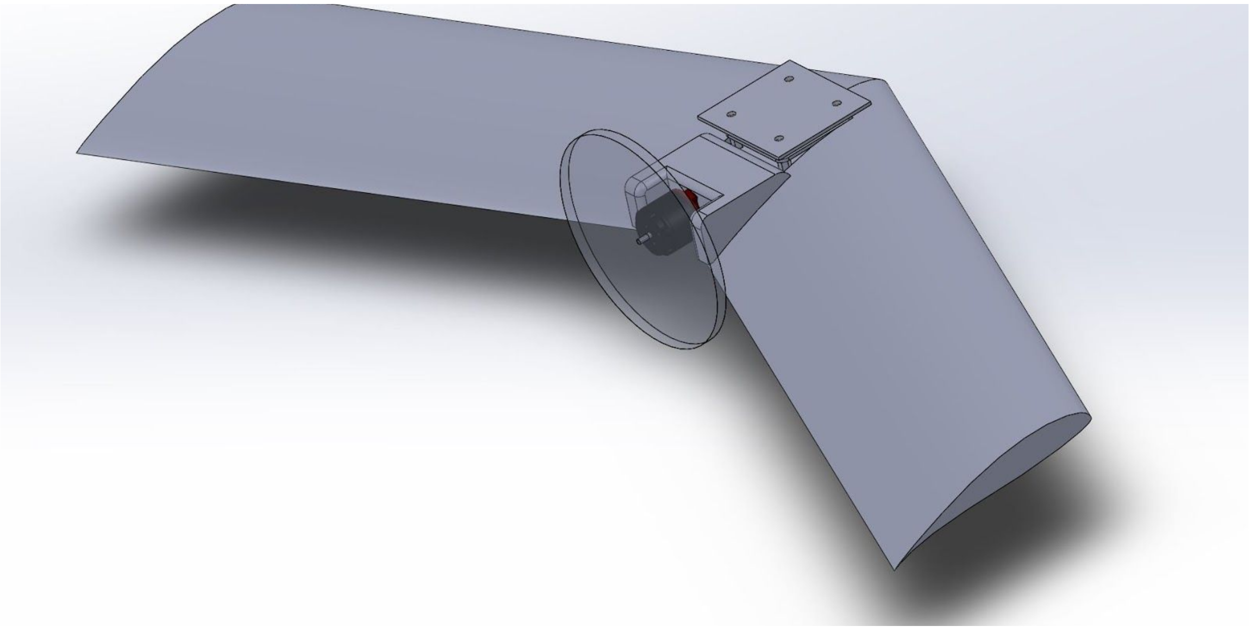


Figure 111: CAD Model of Fixed Wing Drone

Summary of Design

This drone design can utilize hinges to lengthen its wingspan. Ideally, there will be hinges/servo motors located some distance from the center on each side, allowing the wings to fold up during rest position, conserving space. The flight controller and electronics are located at the back of the drone along with the main rotor, which may be supplemented by smaller rotors placed around the rest of the central frame. The airfoil of the drone is similar to that of a glider, where the thickness of the airfoil increases for about 1/3rd of the wing, before decreasing to a fine edge at the back of the wing.

Advantages

- One advantage of this drone design is that it is more efficient, in that it requires less battery power. Therefore, we can potentially add more rotors and other thrust mechanisms as deemed necessary, increasing the speed and range of the drone.
- In the case that we lose control of the motors, the fixed-wing drone will still be able to fly due to its glider-like properties.

Disadvantages

- Unfortunately, this design does not allow for a vertical takeoff. Therefore, an ejection mechanism must be developed that propels the plane at a speed that enables it to start flying, which requires more planning.
- Another potential disadvantage is that fixed-wing drones are not particularly good at flying non-linear paths. This could be a problem depending on the direction that the drone is deployed.

- The fixed wing drone would also require the deployment mechanism to be relatively advanced or controlled by an experienced pilot, as the drone lacks the ability to hover in place. Therefore, the pilot would need to take the plane's velocity and potential air resistance when determining when to drop the beacon.

5.3.2 Design 2: Spreadable Drone

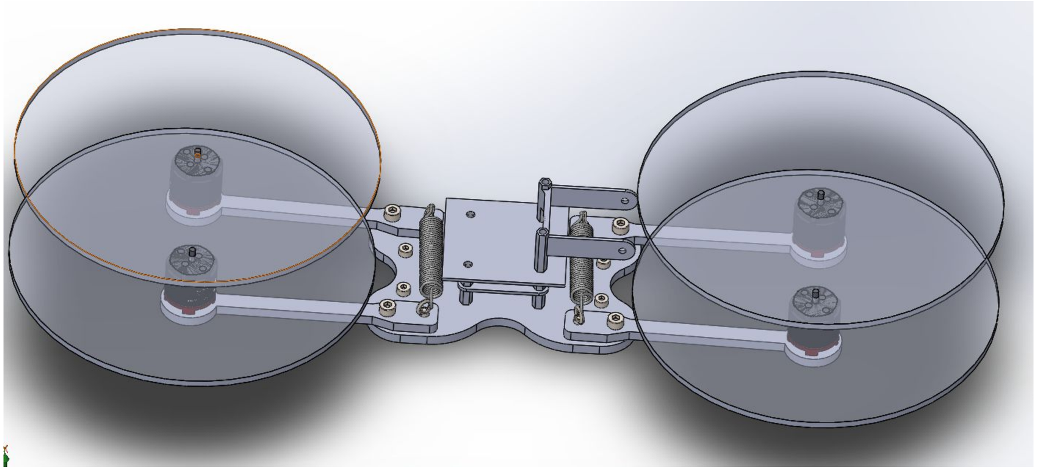


Figure 112: Retracted Position

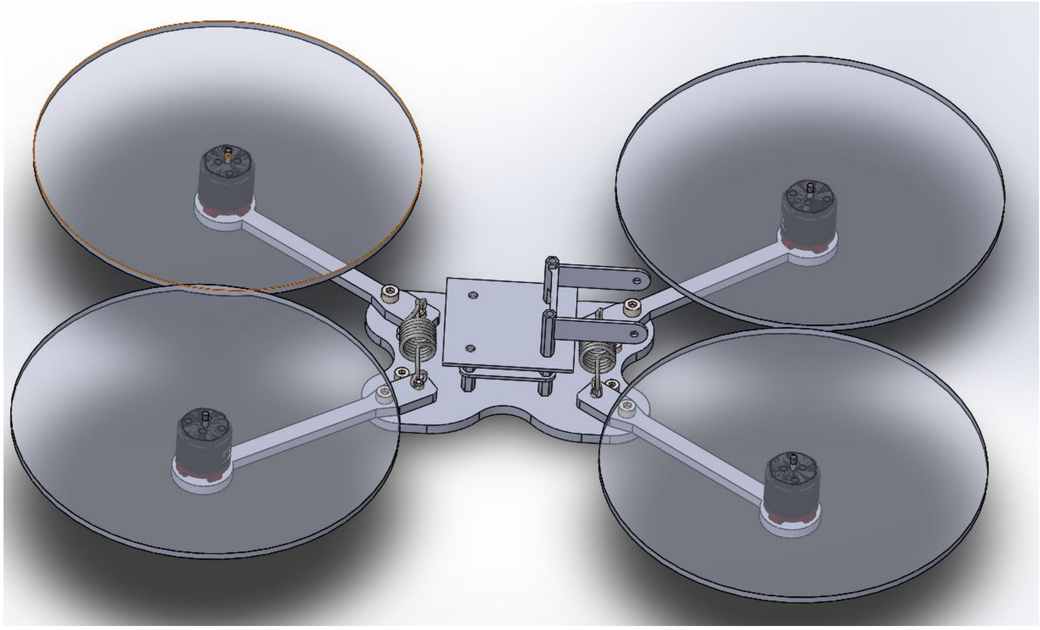


Figure 113: Retracted Position

Summary of Design

The arms of this drone will be in retracted position (parallel to rocket body) when it is inside the rocket. An extended spring is linked between two arms in each side, linked by two eye bolts on the inside of each arm. The drone uses two bladed propellers (shown as a translucent plate in the picture) instead of three, so that the blades do not directly push against rocket's inner wall or each other. When the rocket lands and the drone is pushed out by the deployment system, the arms will each spread about 45 degrees into their take-off position. The arms will then lock in place with the force exerted by the spring and will be stopped by screws screwed in to the frame.

Advantages

- This design allows us to utilize the full width of the rocket, since the arms will not take up space in the width direction of the rocket. This lets us make the entire drone bigger
- Longer arms allow the drone to have longer propellers which will give increased thrust and control of the drone, as well as payload and battery carrying capacity.
- Betaflight is already optimized for quadcopter designs.
- Quadcopter designs allow the drone to suspense in air. Easier to drop the beacon.

Disadvantages

- The arms push against the rocket's inner wall, so a harsh landing may damage the arms.
- We need a mechanism to ensure the drone is oriented upright after launch, most likely a tube-mounted design.
- A failure in any of the springs or arm locking mechanics would result in the drone being unable to reach take-off position or rendering the blades hitting each other.
- Sudden acceleration or deceleration may cause the arms to swing if the springs are not strong enough. This may make the drone hard to maneuver.

5.3.2 Design 3: Cylindrical Cage Drone

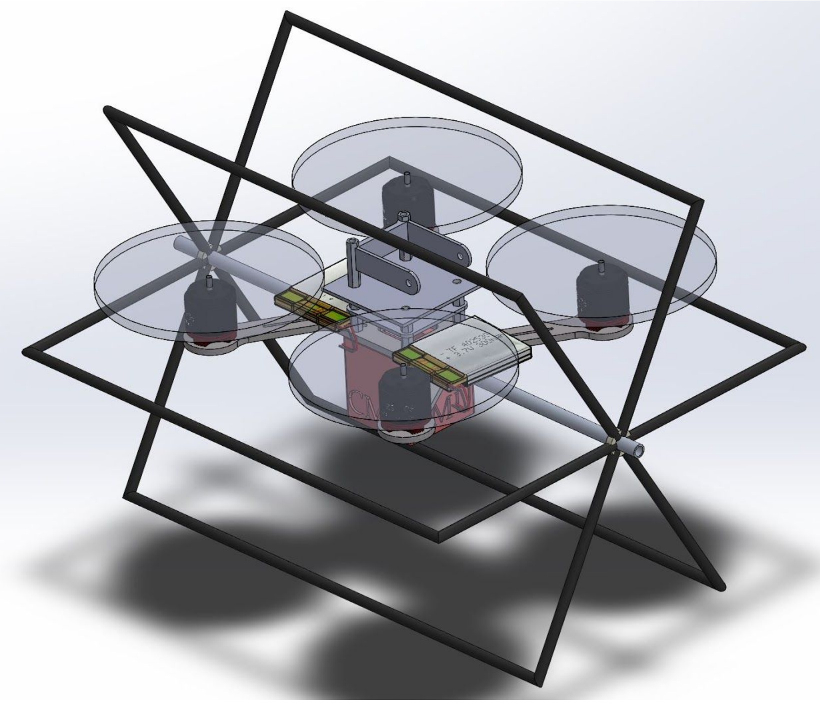


Figure 114: Cylindrical Cage Drone Schematic

Summary of Design

This drone has a reduced width to accommodate a wire frame cage around its propellers. After the drone exits the body of the rocket, the cage keeps the drone off the terrain. To ensure that it is oriented correctly as it exits, there is a tube running lengthwise through the frame of the drone. The tube along with the drone can rotate around its mount inside the rocket bay. To be sure the the drone is oriented correctly as it exits, the center of mass is below the tube, pulling it right side up.

Advantages

- Less moving parts during deployment increases reliability.
- The orientation upon exit problem is resolved.
- The cage reduces the chance of objects blocking the drone from taking off, like rocks, plants, or irregularities in the terrain.

Disadvantages

- The cage reduces the size of the frame, propellers, and motors, reducing thrust, forcing the selection of smaller batteries.
    - Shorter flight time means it is harder to complete the mission.
    - Carrying the payload and the release mechanism becomes more difficult.
- The cage adds extra weight.
- The cage partially obscures the camera’s view.

5.4 Flight Controller and Electronics

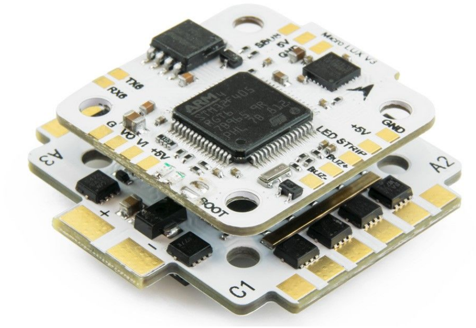


Figure 115: Lumenier MICRO LUX FC with 30A BLHeli 32 4-in-1 ESC

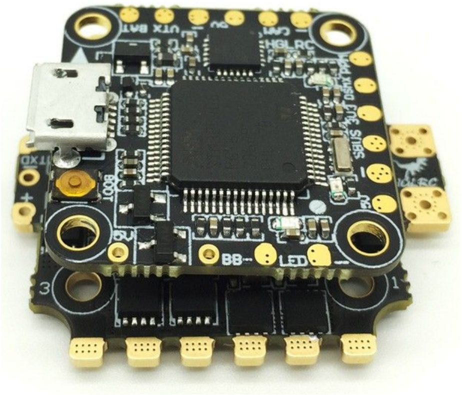


Figure 116: HGLRC F440 FC with 40A BLHeli 32 4-in-1 ESC

Table 48: Payload Flight Controller Options Comparison

Option	Lumenier MICRO LUX V3 F4 + 30A BLHeli_32 4in1 Stack (FC + ESC Combo)	HGLRC XJB F440 V2 Stack - F4 Flight Controller - 40A Blheli32 ESC
Voltage	5V or 3.3V	Not Specified (5V or 3.3V standard)
Ampage	30A ESC	40A ESC
Overall FC size	27x27mm	25x25mm
Overall ESC size	33x36mm	32x34mm
Mounting	20x20mm	20x20mm
Battery Support (FC/ESC)	2-4S LiPo/2-4S LiPo	2-4S LiPo/3-4S LiPo
Firmware	Betaflight OSD (F4)	Betaflight OSD (F4)
BEC (Battery Elimination Circuit aka Voltage regulator)	No (Would need external UBEC)	Yes BEC output on FC: 5V@3A
Weight	12g	9.2g
# of UART Ports	3	2
Price	$ 64.99	$ 77.99

Summary of Comparison

Options 1 and 2 are compatible with 20x20mm mounting holes. However, Option 1 provides an ESC that can provide a constant current of 40A, a current that is 10A higher than that provided by the ESC of Option 1. These options are equally supported by the community through tutorials and instruction manuals. Both Options include Betaflight, a lightweight operating system that allows for the configuration of parameters and controls such as PID preferences.

Option 2 has an integrated Battery Elimination Circuit (BEC) that can contribute to weight savings in our build. Because the ESC of Option 2 supports batteries with a minimum of 3 cells, the use of a three cell LiPo battery will be needed if Option 2 is to be used. While this means that Option 2's battery will have to be a little bigger and therefore heavier than Option 1's, this slight increase in weight will be offset by the presence of the BEC. Option 2 has smaller total dimensions than Option 1 and this could potentially make all the difference when going over proposed drone frames.

Conclusion/Decision

There aren't a lot of online vendors selling boards with 20x20mm mounting holes. However, out of the two Options outlined above, it seems that Option 2 will best suit the needs of this project, and is worth the higher cost. Both Options weigh about the same yet Option 2 will give the team more leeway in component selection throughout the rest of the process. Additionally, should we opt for autonomous navigation for our UAV, we can adapt and upload Pixhawk 4 firmware, which is both open source (and therefore well-documented and easily accessible) and supports autopilot, to Option 2, since both Option 2 and the Pixhawk 4 run in ARM processor.

5.5 Ground Support Hardware (Communication)

5.5.1 Ground Support Hardware

The ground support hardware will consist of three radio links, the remote control link (for controlling the drone in flight), the first-person view (FPV) link (a video link from the drone camera(s) to the operator), and the deployment link, which will allow the payload to be deployed when it is deemed safe to do so. Each of these links will have some level of redundancy. The remote control link will be established by an off the shelf 2.4GHz remote control system (a Spektrum DX8), with an EZUHF transmitter for redundancy. Since the EZUHF transmits at 600mW (28dBm) by default, it will be fitted with a 4dB attenuator, bringing it down to 24dBm (250mW). Since this lies within an amateaur radio band (433MHz), it will be operated by a team member with a proper license.

The UAV will be fitted with the transmitters for the FPV link. One of these will be a 5.8GHz COTS video transmitter (which will remain under 250mW). The other will again be a UHF transmitter (the exact frequency has not been decided, further review of the relevant rules and laws is required), operated by an appropriately licensed team member. The ground station will have only receivers for both of these, and will thus not generate any significant emissions in these bands.

The payload deployment link will consist of either one or two radios, one if it is determined to be feasible to connect the payload UAV flight controller to the deployment system while it is still in the payload bay, and forward auxiliary channels from the remote control link to it, two if this is not feasible. The radio that will certainly be used will be a 915MHz transceiver, a hoperf

RFM69HCW, with a PA/LNA on the rocket and ground station (to bring the power up to 23dBm, 200mW up from 20dBm by default, in both cases). The second radio will be the same radio module, but fitted with a mixer (and filter for the sum, any necessary matching/amplifiers) to bring it near 150MHz (the exact frequency will again depend on the relevant laws and rules), once again, operated by a licensed team member.

5.5.2 Pilot Assistance System Software

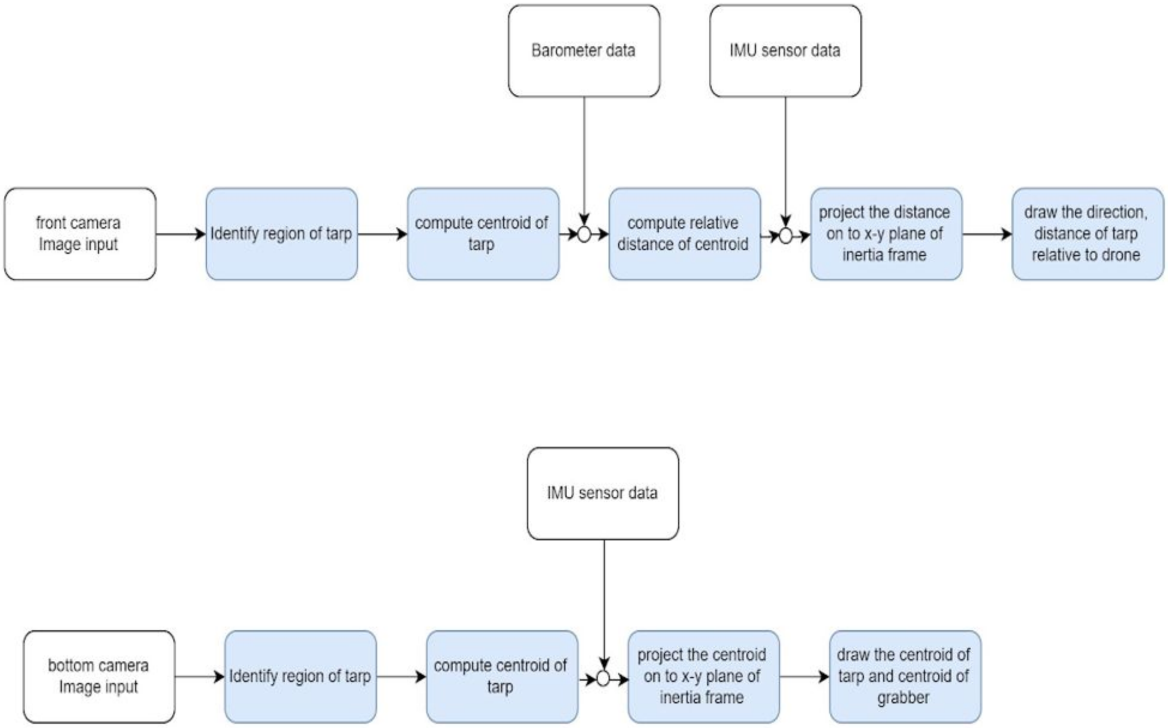


Figure 117: Pilot Assistance System Overview

The assistance system shall overlay on the imaging feedback to the human pilot, and it shall provide relative distance from current position to the tarp goal; as well as alignment assistance during dropping cargo. The system shall be consisted of frontal camera and bottom camera for relative distance and alignment respectively. The region of interest (tarp) shall be identified and the centroid shall be calculated in both cases. In the frontal camera case, the information will be further used to calculate the relative distance between the camera frame and tarp. In addition, this distance shall be transformed into inertia frame via IMU sensory data so that they can make sense to human pilot.

5.6 Beacon Delivery

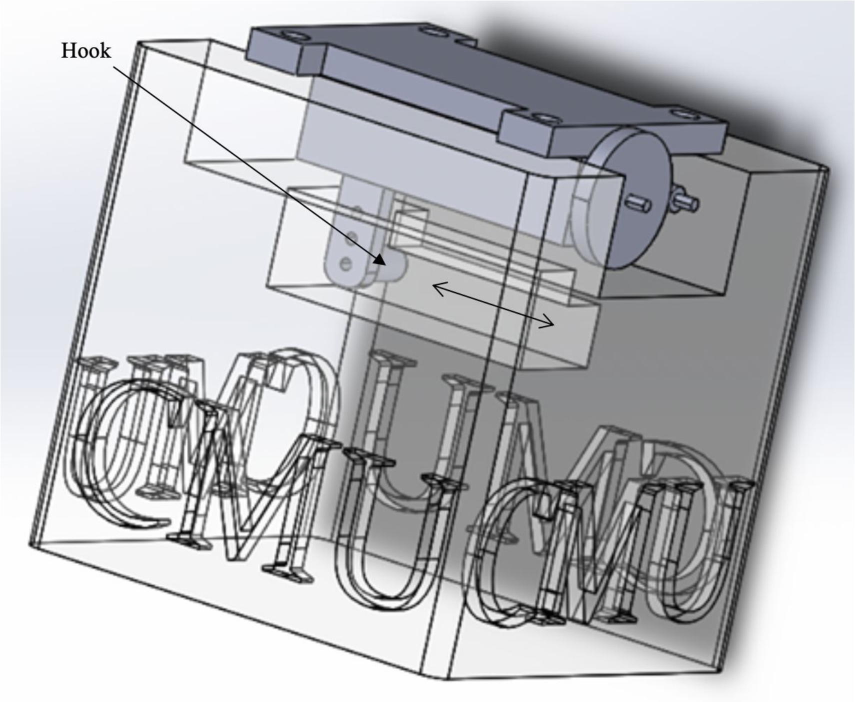


Figure 118: Beacon cube with servo and hook

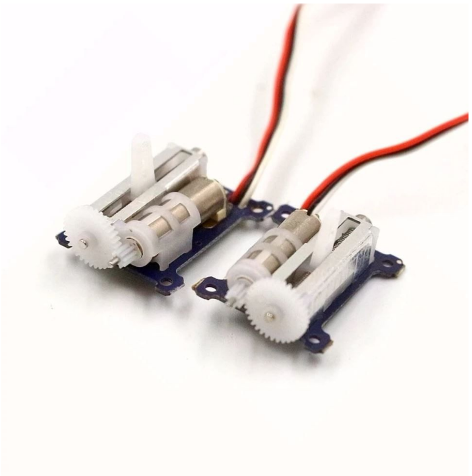


Figure 119: Micro Linear Servo

The beacon will be 3D printed using ABS plastic. It is connected to the drone by a micro-linear servo motor. The beacon will have a cut-out that will prevent it from being released while in rest position. However, when the drone is above the tarp, the servo motor will actuate the hook so that it is free from the overhang. This will result in the beacon no longer being connected to the drone, and therefore it will be released.

5.7 Test Plan

In order to validate the success of our drone, we must test various aspects of the drone and modify accordingly. The first major test will be a “duration of flight test”, where the drone is continuously flown (simulating searching for a tarp) until the battery drops below 10% capacity from full. This will indicate the efficiency of the drone and indicated if battery capacity must be increased. The next major test will be the “range” test where we will power on all systems (except the motors), and continuously move the transmitter until the drone disconnects. The third test will be the “impact test”, where we will drop the drone at various heights (from 1 ft to 10 ft) to simulate failures and crashes. We will observe any cracks or damage to the subframe and reinforce those areas. The fourth test will be the “beacon drop test” where we will hover/fly the drone 5-10 ft above the ground and actuate the servo to test success of the beacon drop.

6 Project Plan

6.1 Requirements Verification

6.1.1 NASA Derived Requirements

Table 49: General Requirements

NASA Subsection	NASA Requirements	Report Explanation	Report Reference
1.1	Students on the team will do 100% of the project, including design, construction, written reports, presentations, and flight preparation with the exception of assembling the motors and handling black powder or any variant of ejection charges, or preparing and installing electric matches (to be done by the team's mentor).	CMRC team will ensure that student members will do all work surrounding the rocket construction, and will only seek counsel from mentors and adult educators.	Section 1.1 & Section 6.3.3
1.2	The team will provide and maintain a project plan to include, but not limited to the following items: project milestones, budget and community support, checklists, personnel assignments, STEM engagement events, and risks and mitigations.	CMRC will provide and adhere to updated project plans. The finance team will ensure that budgets are up to date, while the Media and Outreach team will ensure that STEM Engagement events are carried out on schedule.	Section 6.3
1.3	Foreign National (FN) team members must be identified by the Preliminary Design Review (PDR) and may or may not have access to certain activities during launch week due to security restrictions. In addition, FN's may be separated from their team during certain activities.	CMRC has identified and reported all Foreign National members for the CMRC team.	--
1.4	The team must identify all team members attending launch week activities by the Critical Design Review (CDR).	CMRC will have a roster of team members attending launch week by CDR.	--

1.5	The team will engage a minimum of 200 participants in educational, hands-on science, technology, engineering, and mathematics (STEM) activities, as defined in the STEM Engagement Activity Report, by FRR. To satisfy this requirement, all events must occur between project acceptance and the FRR due date and the STEM Engagement Activity Report must be submitted via email within two weeks of the completion of the event. A sample of the STEM Engagement Activity Report can be found on page 33 of the handbook.	CMRC has identified a preliminary plan for educational engagement.	Section 6.2
1.6	The team will establish a social media presence to inform the public about team activities.	CMRC has a website that will be used for purposes for informing about our activities: https://cmrocketcommand.wordpress.com/	--
1.7	Teams will email all deliverables to the NASA project management team by the deadline specified in the handbook for each milestone. In the event that a deliverable is too large to attach to an email, inclusion of a link to download the file will be sufficient.	The CMRC team president, Michael Messersmith, will email all project deliverables to the NASA project management team by the deadlines.	--
1.8	All deliverables must be in PDF format.	Project deliverables will be emailed and posted to the website in PDF format.	--
1.9	In every report, teams will provide a table of contents including major sections and their respective sub-sections.	A Table of Contents will be after a list of tables and figures	See page 1
1.10	In every report, the team will include the page number at the bottom of the page.	Page numbers will be at the bottom center of every page	See page numbers at bottom

1.11	The team will provide any computer equipment necessary to perform a video teleconference with the review panel. This includes, but is not limited to, a computer system, video camera, speaker telephone, and a sufficient Internet connection. Cellular phones should be used for speakerphone capability only as a last resort.	CMRC will aim to use one of the Scaife conference rooms that has teleconference capabilities.	Section 4.7.8
1.12	All teams will be required to use the launch pads provided by Student Launch's launch services provider. No custom pads will be permitted on the launch field. Eight foot 1010 rails and 12 foot 1515 rails will be provided. The launch rails will be canted 5 to 10 degrees away from the crowd on launch day. The exact cant will depend on launch day wind conditions.	CMRC will use the Student Launch's provided 12 ft 1515 rails.	Section 3.3.3
1.13	Each team must identify a "mentor."	John Haught will be our mentor.	Section 1.1

Table 50: Vehicle Requirements

NASA Subsection	NASA Requirement	Report Explanation	Report Subsection
2.1	The vehicle will deliver the payload to an apogee altitude between 4,000 and 5,500 feet above ground level (AGL). Teams flying below 3,500 feet or above 6,000 feet on Launch Day will be disqualified and receive zero altitude points towards their overall project score.	Official apogee goal is 5100 ft. Max apogee (without ballast, no wind, no ATS) is 5618 ft, well within the allowed limits.	Section 3.3.2
2.2	Teams shall identify their target altitude goal at the PDR milestone. The declared target altitude will be used to determine the team's altitude score during Launch Week.	Apogee goal is 5100 ft.	Section 3.3.2
2.3	The vehicle will carry one commercially available, barometric altimeter for recording the official altitude used in determining the Altitude Award winner.	Of our two onboard altimeters, CMRC will identify one as the altitude award altimeter. Both altimeters are Stratologger CF's, which are commercially available.	Section 3.2.3
2.4	Each altimeter will be armed by a dedicated mechanical arming switch that is accessible from the exterior of the rocket airframe when the rocket is in the launch configuration on the launch pad.	Two Schurter rotary switches will be used, one for each altimeter. Two access holes will be drilled to allow a screwdriver to turn the switches on and off.	Section 3.2.2
2.5	Each altimeter will have a dedicated power supply.	Each altimeter will be powered by an individual 9V.	Section 3.2.2
2.6	Each arming switch will be capable of being locked in the ON position for launch (i.e. cannot be disarmed due to flight forces).	Schurter rotary switches will be used to ensure that arming switches are locked in the ON position.	Section 3.2.2
2.7	The launch vehicle will be designed to be recoverable and reusable. Reusable is defined as being able to launch again on the	Robust design will ensure survivability and reusability of launch vehicle. Full scale test launch will verify the	Section 3.1

	same day without repairs or modifications.	design.	
2.8	The launch vehicle will have a maximum of four (4) independent sections. An independent section is defined as a section that is either tethered to the main vehicle or is recovered separately from the main vehicle using its own parachute.	The launch vehicle will have three (3) independent sections.	Section 3.1
2.8.1	Coupler/airframe shoulders which are located at in-flight separation points will be at least 1 body diameter in length.	All couplers at in flight separation points are at least 6 inches (1 body diameter) in length.	Section 3.1
2.8.2	Nosecone shoulders which are located at in-flight separation points will be at least ½ body diameter in length.	Nosecone shoulder is not at an in-flight separation point.	Section 3.1
2.9	The launch vehicle will be limited to a single stage.	The launch vehicle will use one motor, a CTI L1350, to ensure a single stage flight.	Section 3.3.2
2.10	The launch vehicle will be capable of being prepared for flight at the launch site within 2 hours of the time the Federal Aviation Administration flight waiver opens.	The launch vehicle will be assembled within 2 hours during full scale test launch to verify the time required for preparation.	--
2.11	The launch vehicle will be capable of remaining in launch-ready configuration on the pad for a minimum of 2 hours without losing the functionality of any critical on-board components.	Batteries will be appropriately sized for all systems. All powered systems will tested prior to launch to ensure functionality after 2 hours of standby.	Section 3.2 & Section 3.4 & Section 5.2
2.12	The launch vehicle will be capable of being launched by a standard 12-volt direct current firing system. The firing system will be provided by the NASA-designated launch services provider.	Leading motor choice is an CTI L1350, which uses a standard electric ignition system.	Section 3.3.2

2.13	The launch vehicle will require no external circuitry or special ground support equipment to initiate launch (other than what is provided by the launch services provider).	Leading motor choice is a CTI L1350, which uses a standard electric ignition system.	Section 3.3.2
2.14	The launch vehicle will use a commercially available solid motor propulsion system using ammonium perchlorate composite propellant (APCP) which is approved and certified by the National Association of Rocketry (NAR), Tripoli Rocketry Association (TRA), and/or the Canadian Association of Rocketry (CAR).	Leading motor choice is a CTI L1350, which uses APCP propellant and is properly approved/certified by NAR, TRA, and CAR.	Section 3.3.2
2.14.1	Final motor choices will be declared by the Critical Design Review (CDR) milestone.	Leading motor choice is a CTI L1350. This will be updated and restated in CDR.	Section 3.3.2
2.14.2	Any motor change after CDR must be approved by the NASA Range Safety Officer (RSO) and will only be approved if the change is for the sole purpose of increasing the safety margin. A penalty against the team's overall score will be incurred when a motor change is made after the CDR milestone, regardless of the reason.	The CMRC Mechanical Design and Calculations subteams will work in conjunction to make sure a final motor selection will be reached by the Critical Design Review.	--
2.15	The minimum factor of safety (Burst or Ultimate pressure versus Max Expected Operating Pressure) will be 4:1 with supporting design documentation included in all milestone reviews.	No pressure vessels will be used.	--
2.16	The total impulse provided by a College or University launch vehicle will not exceed 5,120 Newton-seconds (L-class). The total impulse provided by a High	The leading motor choice is an CTI L1350, with an impulse of 4,263 Ns, which is below the allowed limit.	Section 3.3.2

	School or Middle School launch vehicle will not exceed 2,560 Newton-seconds (K-class).		
2.17	The launch vehicle will have a minimum static stability margin of 2.0 at the point of rail exit. Rail exit is defined at the point where the forward rail button loses contact with the rail.	The launch vehicle has a minimum static stability margin of 2.20.	Section 3.3.4
2.18	The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit.	The launch vehicle exits the rail at 72.2 ft/s.	Section 3.3.3
2.19	All teams will successfully launch and recover a subscale model of their rocket prior to CDR.	CMRC has plans to launch the subscale model on December 1st to 2nd.	Section 6.3.3
2.20.1	Vehicle Demonstration Flight - All teams will successfully launch and recover their full-scale rocket prior to FRR in its final flight configuration.	CMRC has plans to launch the full-scale model from February 16th to 17th.	Section 6.3.3
2.20.2	Payload Demonstration Flight - All teams will successfully launch and recover their full-scale rocket containing the completed payload prior to the Payload Demonstration Flight deadline.	CMRC has plans to launch the full-scale model with payload from February 16th to 17th.	Section 6.3.3
2.21	An FRR Addendum will be required for any team completing a Payload Demonstration Flight or NASA required Vehicle Demonstration Re-flight after the submission of the FRR Report.	CMRC will submit complete the Payload Demonstration Flight before the submission of the FRR	Section 6.3.3
2.22	Any structural protuberance on the rocket will be located aft of the burnout center of gravity.	The ATS bay is located aft of the burnout center of gravity.	Section 3.3.4
2.23	The team's name and launch day contact information shall be in or on the rocket airframe as well as in or on any section of the vehicle	Carnegie Mellon University and team contact information will be clearly labeled on the exterior of the rocket, after it	--

	that separates during flight and is not tethered to the main airframe. This information shall be included in a manner that allows the information to be retrieved without the need to open or separate the vehicle.	has been painted.	
2.24.1	The launch vehicle will not utilize forward canards. Camera housings will be exempted, provided the team can show that the housing(s) causes minimal aerodynamic effect on the rocket's stability.	The launch vehicle will not use forward canards.	--
2.24.2	The launch vehicle will not utilize forward firing motors.	CMRC will only use a CTI L1350.	Section 3.3.2
2.24.3	The launch vehicle will not utilize motors that expel titanium sponges (Sparky, Skidmark, MetalStorm, etc.)	CMRC will only use a CTI L1350. This utilizes a C-Star propellant which does not expel titanium sponges.	Section 3.3.2
2.24.4	The launch vehicle will not utilize hybrid motors.	CMRC will only use a CTI L1350 which uses APCP, a non-hybrid motor.	Section 3.3.2
2.24.5	The launch vehicle will not utilize a cluster of motors.	CMRC will only use a single CTI L1350.	Section 3.3.2
2.24.6	The launch vehicle will not utilize friction fitting for motors.	CMRC will only use a motor mounting system comprised of a thrust plate and motor retention rings in order to hold the motor in place during flight.	Section 3.1.5
2.24.7	The launch vehicle will not exceed Mach 1 at any point during flight.	The maximum velocity is 594 ft/s, Mach 0.53	Section 3.3.3
2.24.8	Vehicle ballast will not exceed 10% of the total unballasted weight of the rocket as it would sit on the pad.	Maximum ballast is 64.45 oz, 9.2% of the total mass.	Section 3.3.2

2.24.9	Transmissions from onboard transmitters will not exceed 250 mW of power.	Eggfinder GPS and UAV transmatter are both under 250 mW of power.	Section 3.2.4 & Section 5.2
2.24.10	Excessive and/or dense metal will not be utilized in the construction of the vehicle. Use of lightweight metal will be permitted but limited to the amount necessary to ensure structural integrity of the airframe under the expected operating stresses.	CMRC is using limited metal for structural components such as eye-bolts, metal tipped nose cones, motor retainers, and recovery bay hardware.	Section 3.1

Table 51: Recovery System Requirements

NASA Subsection	NASA Requirement	Report Explanation	Report Subsection
3.1.1	The main parachute shall be deployed no lower than 500 feet.	Main parachute will deploy at 500 ft.	Section 3.2.1
3.1.2	The apogee event may contain a delay of no more than 2 seconds.	Backup apogee charge will have a 2 second delay	Section 3.2.1
3.2	Each team must perform a successful ground ejection test for both the drogue and main parachutes. This must be done prior to the initial subscale and full-scale launches.	Ground tests will be performed before launch.	Section 6.3.3
3.3	At landing, each independent section of the launch vehicle will have a maximum kinetic energy of 75 ft-lbf.	Maximum landing kinetic energy is 56.03 ft-lbf.	Section 3.3.5
3.4	The recovery system electrical circuits will be completely independent of any payload electrical circuits.	CMRC has separate recovery and payload bays.	Section 3.1
3.5	All recovery electronics will be powered by commercially available batteries.	CMRC intends to use commercially available 9 volt batteries.	Section 3.2.1
3.5	The recovery system will contain redundant, commercially available	The altimeters will be powered with two separate	Section 3.2.1

	altimeters. The term “altimeters” includes both simple altimeters and more sophisticated flight computers.	circuits.	
3.7	Motor ejection is not a permissible form of primary or secondary deployment.	CMRC will not utilize motor ejection as deployment.	Section 3.2.1
3.8	Removable shear pins will be used for both the main parachute compartment and the drogue parachute compartment.	Removable shear pins will be used.	Section 3.2
3.9	Recovery area will be limited to a 2,500 ft. radius from the launch pads.	Open Rocket simulation predicted a maximum drift of 2152 ft.	Section 3.3.6
3.10	Descent time will be limited to 90 seconds (apogee to touch down).	The descent time was calculated to be 89.4 s.	Section 3.3.3
3.11.1	Any rocket section or payload component, which lands untethered to the launch vehicle, will contain an active electronic tracking device.	CMRC will ensure that all rocket sections and payload components that land untethered to the launch vehicle will contain active electronic tracking devices.	Section 3.2.4
3.11.2	The electronic tracking device(s) will be fully functional during the official flight on launch day.	GPS systems will be tested along with the full scale flight to ensure functionality on launch day.	Section 3.2.4
3.12.1	The recovery system altimeters will be physically located in a separate compartment within the vehicle from any other radio frequency transmitting device and/or magnetic wave producing device.	The recovery bay will be separated from the GPS, which will be housed in an isolated container affixed to the inside of the airframe.	Section 3.2.4
3.12.2	The recovery system electronics will be shielded from all onboard transmitting devices to avoid	The recovery bay will be coated in aluminum RF shielding tape.	Section 3.2.2

	inadvertent excitation of the recovery system electronics.		
3.12.3	The recovery system electronics will be shielded from all onboard devices which may generate magnetic waves (such as generators, solenoid valves, and Tesla coils) to avoid inadvertent excitation of the recovery system.	The recovery bay will be coated in aluminum RF shielding tape.	Section 3.2.2
3.12.4	The recovery system electronics will be shielded from any other onboard devices which may adversely affect the proper operation of the recovery system electronics.	The recovery bay will be coated in aluminum RF shielding tape.	Section 3.2.2

Table 52: Payload Requirements

NASA Subsection	NASA Requirement	Report Explanation	Report Subsection
4.2	College/University Division – Each team will choose one experiment option from the following list. ● Rover/Soil Sample ● UAV/Beacon Delivery	CMRC will perform the UAV/Beacon Delivery experiment	Section 5
4.2.1	An additional experiment (limit of 1) is allowed, and may be flown, but will not contribute to scoring.	CMRC will not fly an additional experiment.	Section 5
4.4.1	Teams will design a custom UAV that will deploy from the internal structure of the launch vehicle.	CMRC will design a custom deployable UAV.	Section 5.2
4.4.2	The UAV will be powered off until the rocket has safely landed on the ground and is capable of being powered on remotely after landing.	UAV will be placed into a low power state with the motors turned off during the duration of flight. It will only be activated by a remote signal sent by the team with the permission of the RSO.	Section 5.1

4.4.3	The UAV will be retained within the vehicle utilizing a fail-safe active retention system. The retention system will be robust enough to retain the UAV if atypical flight forces are experienced.	The deployment and locking mechanisms will fully constrain the UAV even during atypical flight forces.	Section 5.1
4.4.4	At landing, and under the supervision of the Remote Deployment Officer, the team will remotely activate a trigger to deploy the UAV from the rocket.	CMRC will comply.	Section 5.1
4.4.5	After deployment and from a position on the ground, the UAV will take off and fly to a NASA specified location, called the Future Excursion Area (FEA). Both autonomous and piloted flight are permissible but all reorientation or unpacking maneuvers must be autonomous.	CMRC will comply.	Section 5.1
4.4.6	The FEA will be approximately 10 ft. x 10 ft. and constructed of a color which stands out against the ground.	CMRC will comply.	--
4.4.7	One or more FEA’s will be located in the recovery area of the launch field. FEA samples will be provided to teams upon acceptance and prior to PDR.	CMRC will comply.	--
4.4.8	Once the UAV has reached the FEA, it will place or drop a simulated navigational beacon on the target area.	CMRC will drop the simulated beacon onto the cube and then land the UAV next to the FEA..	Section 5.5
4.4.9	The simulated navigational beacon will be designed and built by each team and will be a minimum of 1 in W x 1 in H x 1 in D. The school name must be located on the external surface of the beacon.	The simulated beacon meets the required dimensions and has the name “CMU” written on the outside surface.	Section 5.5

4.4.10	Teams will ensure the UAV’s batteries are sufficiently protected from impact with the ground.	The UAV housing and deployment system will withstand the forces of launch, turbulence, deployment and landing.	Section 5.1
4.4.11	The batteries powering the UAV will be brightly colored, clearly marked as a fire hazard, and easily distinguishable from other UAV parts.	All LiPo and Lion batteries will be labeled with brightly colored fire hazard markings.	Section 5.3
4.4.12	The team will abide by all applicable FAA regulations, including the FAA’s Special Rule for Model Aircraft (Public Law 112-95 Section 336; see https://www.faa.gov/uas/faqs).	CMRC will abide by all relevant state and federal regulations set forth by the FAA.	Section 4.4
4.4.13	Any UAV weighing more than .55 lbs. will be registered with the FAA and the registration number marked on the vehicle.	CMRC will abide by all relevant state and federal regulations set forth by the FAA.	Section 4.4

Table 53: Safety Requirements

NASA Subsection	**NASA Requirement**	**Report Explanation**	**Report Subsection**
5.1	Each team will use a launch and safety checklist. The final checklists will be included in the FRR report and used during the Launch Readiness Review (LRR) and any launch day operations.	Safety checklist will be provided in FRR and used during LRR and launch day.	--
5.2	Each team must identify a student safety officer who will be responsible for all items in section 5.3.	Fabian Aristizabal is the CMRC SO.	Section 1.1
5.3.1	Monitor team activities with an emphasis on safety during: ● Design ● Construction ● Assembly	SO will monitor all activities to ensure safe practices.	Section 4

	● Ground testing ● Sub-scale launch ● Full scale launch ● Recovery ● STEM Engagement		
5.3.2	Implement procedures developed by the team for construction, assembly, launch, and recovery activities.	SO will ensure that all procedures are followed during all activities.	Section 4.3
5.3.3	Manage and maintain current revisions of the team’s hazard analyses, failure modes analyses, procedures, and MSDS/chemical inventory data.	SO will oversee all safety documentation and ensure that it is up to date.	Section 4.1
5.3.4	Assist in the writing and development of the team’s hazard analyses, failure modes analyses, and procedures.	SO will be active member in developing all hazard/failure modes analyses and procedures.	Section 4.1
5.4	During test flights, teams will abide by the rules and guidance of the local rocketry club’s RSO. The allowance of certain vehicle configurations and/or payloads at the NASA Student Launch does not give explicit or implicit authority for teams to fly those vehicle configurations and/or payloads at other club launches. Teams should communicate their intentions to the local club’s President or Prefect and RSO before attending any NAR or TRA launch.	CMRC will abide by the rules and guidance of Pittsburgh Space Command (PSC) and Tripoli Pittsburgh, depending on the launch site.	Section 4.4
5.5	Teams will abide by all rules set forth by the FAA.	CMRC will review all relevant FAA rules and SO will ensure compliance.	Section 4.4

6.1.2 Team Derived Requirements

Table 54: Team Derived Vehicle Requirements

Req. Number	Requirement	Verification Method	Verification Status
1	The inner diameter of the airframe will be no smaller than 6” in order to accommodate the size of the drone.	Demonstration: Drone will be fully assembled and mounted in the payload bay to verify that there are no size constraints.	Met
2	The launch vehicle will not exceed 50 lbs. This will ensure that we will have access to parachutes that will be sufficiently sized in order to reduce our landing kinetic energy to below the 75 ft-lb maximum set by NASA requirement 3.3	Analysis: OpenRocket will be used to model the rocket and all of the internal subsystems. This will produce a weight estimate which we can use to verify whether or not a current design is at risk of exceeding the weight limit. Inspection: All components will be weighed using a digital scale in order to determine accurate weights for the Open Rocket model. The completed rocket will also be weighed to determine the actual weight and ensure that it agrees with the predicted value.	Met
3	The ATS IMU will be appropriately tuned in order to ensure accurate velocity readings during launch.	Test: The IMU will be be tested extensively prior to the subscale launch in order to determine approximate scaling and correction factors, as well as identify whether the IMU is worth pursuing. The leading choice of IMU will be placed on the subscale rocket and record data during each flight. The correction factors will be tuned in order to match the flight profile recorded by the altimeters. Finally, the	In progress

		completed ATS system will be tested during both the full scale launch and payload launch.	
4	The stability margin is not to be lower than 2.20 cal or higher than 3.5 at launch. This will provide an additional factor of safety against both unstable flight and weathercocking	Analysis: OpenRocket will be used to assess the static stability margin of the launch vehicle.	Met
5	All motors must be be from either CTI or AeroTech in order to ensure reliability and availability.	Analysis: The motors tested in OpenRocket and selected for use will only be from CTI or AeroTech	Met

Table 55: Team Derived Recovery Requirements

Req. Number	Requirement	Verification Method	Verification Status
1	The maximum acceleration of the rocket will not exceed 1000 ft/s^2. This will ensure a factor of safety of 2 on the shock cords.	Analysis: Open Rocket flight simulations will provide the acceleration during flight, including the sharp increase in acceleration when the main parachute deploys. The maximum acceleration predicted by a nominal flight simulation will be used for our factor of safety calculation on the shock cord.	Met
2	The GPS system will be kept isolated for major metal objects such as threaded rods and motors. This will prevent the signal from getting distorted	Test: The GPS will be tested in the final configuration in order to verify that the signal has not been distorted.	In progress

Table 56: Team Derived Payload Requirements

Req. Number	Requirement	Verification Method	Verificatio n Status
1	The UAV must fly from landing site to the tarp with 30% battery remaining	Real world prototype testing where the pilot with fly on a designated course (of a specific	In progress

		distance) to measure distance flown until 30% battery. That distance must be at least 1.5 times the average distance from the tarp to the land site	
2	The UAV must successfully deploy from the rocket and reorient itself	Using the full scale coupler and UAV, success will be based on the correct reorientation and deployment of drone on a simulated landing site	In progress
3	The beacon must successfully fall from the flying UAV on to the tarp	While hovering/flying the UAV above the tarp the pilot will actuate the servo. Success will be based on the distance from the final beacon to the expected beacon landing location	In progress

6.2 STEM Engagement

CMRC has, and will continue to, foster the spirit of interest and excitement of STEM related fields within the Pittsburgh area. We have two primary target audiences for our engagement activities: local students in grades 1-12, and Carnegie Mellon students.

For students in grades 1-12, our goal is to demonstrate what is possible in the fields of STEM by discussion our rocketry projects and bringing in parts for people to look at and interact with. By teaching them about the opportunities that exist, our goal is that some students may be swayed to pursue a career in STEM later in their lives.

For Carnegie Mellon students, we have different goals. There is a large amount of interest in the aerospace industry on campus, but relatively few outlets for students to engage in aerospace related projects. By promoting our organization at university events throughout the year, we aim to attract new members and provide the opportunity for them to participate on a technical aerospace project. This may provide the experience that Carnegie Mellon students need to get into aerospace related careers straight out of school.

Table 57: Educational Outreach Summary

Event	Expected Number of Students	Actual Number of Students
YMCA of Greater Pittsburgh	15	In progress
Burrell High School & Huston Middle School	75	In progress
Environmental Charter School	60	In progress
CMU Children's School	45	47
CMU Homecoming	25	10
Moon District Elementary School	200	In progress
Total	**430**	**57**

YMCA of Greater Pittsburgh

CMRC has developed a relationship with the YMCA of Greater Pittsburgh after several members volunteered to teach some students about rocketry and perform fun science activities. This year, we plan to further this relationship by returning to the YMCA of Greater Pittsburgh for our STEM engagement activities. We can expect to interact with a small classroom of 10 - 20 students in elementary to middle school.

Burrell High School and Huston Middle School

CMRC has also developed a relationship with Burrell High School and Huston Middle School through Rod Schafer, who was an adult educator for the CMRC team during the 2017-2018 NASA USLI competition. Rod invited CMRC to come speak to engineering and science students at the two schools. This year, CMRC is coordinating with Rod to return to the schools and do more STEM exercises and teach the students more about rocketry. We can expect 50 - 100 students in middle to high school.

Environmental Charter School

CMRC has made a connection to the Environmental Charter School in Pittsburgh through a teacher Mark Williams, who invited us to speak to his class of fourth graders. We performed some rocketry exercises and gave a presentation on our team and the NASA competition. This year we are coordinating with Mark to come and work with his class again, performing more STEM exercises and assisting with school activities. We can expect 50 - 70 elementary school students.

CMU Children's School

There is a pre-school and kindergarten run by the psychology department at CMU, which CMRC has been in contact with. During the year, our members will assist various classes in the Children's School with math and science activities as a part of their curriculum. We will also perform small rocket launches and give presentations on rocketry to get the students excited about STEM. Throughout the year, we can expect to engage 40 - 50 elementary school students.

CMU Homecoming

During CMU Homecoming weekend in late October, a science activity tent is set up for children attending the event. CMRC members will be volunteering to help run the STEM activities and engaging young students who visit the tent. We can expect to engage 20 - 30 elementary to middle school students.

Moon District Elementary School

CMRC has been invited to provide a rocketry presentation to the 1st-4th grade classes of Moon District Elementary School. We will teach the students about basic physics and principles of rocketry as well as the ways that they can get involved in the with model rockets. We can expected to engage 200 elementary school students.

6.3 Budgeting and Timeline

6.3.1 Budget Plan

Table 58: Budget Overview

Category	Amount	Percent Total
Launch Vehicles	$3,323.78	29.7
Payload	$2,065.00	18.4
Recovery	$475.23	4.2
Travel	$3,890.00	34.7
Avionics	$1,053.92	9.4
Reserve	$400.00	3.6
Total	**$11,207.93**	**100%**

Table 59: Launch Vehicle Itemized Budget

Item	Unit Cost	Quantity	Unit Total	Company
3" Diam G12 Tube 8ft	$164.32	1	$164.32	Wildman
3" Diam G12 Coupler 1ft	$27.72	2	$55.44	Wildman
3" Diam G10 Coupler Bulkheads	$5.00	6	$30.00	Wildman

3" Diam G10 Airframe Bulkheads	$5.00	6	$30.00	Wildman
3" Diam G12 4:1 Ogive Nosecone	$59.95	1	$59.95	Madcow
1/8" G10 Fiberglass Plate 1'x1'	$18.00	4	$72.00	Wildman
6" Diam G12 Tube 8ft	$370.00	1	$370.00	Wildman
6" Diam G12 Coupler 12" Long	$58.68	2	$117.36	Wildman
6" Diam G10 Coupler Bulkheads	$9.00	6	$54.00	Wildman
6" Diam G10 Airframe Bulkheads	$9.00	6	$54.00	Wildman
6" Diam G12 4:1 Ogive Nosecone	$149.95	1	$149.95	Madcow
3/32" G10 Fiberglass Plate 1'x1'	$28.00	4	$112.00	Wildman
G5000 RocketPoxy - 2 Quarts	$65.00	1	$65.00	Wildman
Fibre Glast 2000 Resin (1 gal)	$129.95	1	$129.95	Fibre Glast
FIbre Glast 2060 Hardner (1/2 pt)	$24.95	1	$24.95	Fibre Glast
JB Weld	$5.27	1	$5.27	Amazon
Loctite 5 Minute Epoxy - 8 oz	$17.42	2	$34.84	Amazon
Rubbing Alcohol	$2.00	1	$2.00	Amazon
Bondo Filler	$17.49	1	$17.49	Amazon
Spot Putty	$18.98	1	$18.98	Amazon
Primer	$3.47	3	$10.41	Amazon
Spray Paint	$12.31	4	$49.24	Amazon
Adhesive Vinyl	$7.25	1	$7.25	Amazon
Fine grit polish/buff	$21.95	1	$21.95	Amazon
Wax or polymer wax sealant	$16.99	1	$16.99	Amazon
Scratch/defect remover	$8.04	1	$8.04	Amazon
Painter's Tape	$35.53	1	$35.53	Amazon
Drop Cloth	$11.95	1	$11.95	Amazon
Tack Cloth	$5.91	1	$5.91	Amazon
1'x1' Plywood	$2.00	5	$10.00	Amazon
Mixing Cups	$5.59	1	$5.59	Amazon
Mixing Sticks	$9.99	1	$9.99	Amazon
Plastic Rivets	$3.71	1	$3.71	Apogee
Nylon Shear Pins	$3.10	1	$3.10	Apogee

#6 Screws	$11.03	1	$11.03	McMaster-Carr
#8 Screws	$11.03	1	$11.03	McMaster-Carr
#10 Screws	$11.03	1	$11.03	McMaster-Carr
PEM nuts	$11.00	1	$11.00	McMaster-Carr
Weld nuts	$12.70	1	$12.70	McMaster-Carr
6" 75mm Thrust Plate	$65.05	1	$65.05	Apogee
Aeropack 75mm Flanged Retainer	$55.56	1	$55.56	Apogee
AeroTech RMS 75/6400 Motor Casing	$449.40	1	$449.40	Apogee
Sub Scale Motor (CTI I470-15A-15)	$49.95	3	$149.85	TBD
Full Scale Motor (AeroTech L1170FJ)	$259.99	3	$779.97	TBD
Total	**$3,323.78**			

Table 60: Payload Itemized Budget

Item	Unit Cost	Quantity	Unit Total	Company
AIO Flight Controller	$90.00	3	$270.00	Amazon
Transmitter	$40.00	3	$120.00	HobbyKing
Receiver	$20.00	3	$60.00	HobbyKing
Antenna	$20.00	3	$60.00	HobbyKing
Camera	$50.00	3	$150.00	Amazon
DC Brushless Motor	$20.00	10	$200.00	HobbyKing
Mounting hardware	$20.00	1	$20.00	HobbyKing
RC Transmitter	$100.00	1	$100.00	HobbyKing
Video Transmitter 2.4g	$60.00	1	$60.00	HobbyKing
Video Receiver 2.4g	$120.00	1	$120.00	HobbyKing
Video Receiver 5.8Ghz	$75.00	1	$75.00	HobbyKing
Monitor	$100.00	1	$100.00	Amazon
Batteries	$20.00	5	$100.00	Amazon
Associated Hardware	$50.00	1	$50.00	Amazon

Patch Ant	$30.00	2	$60.00	HobbyKing
Omnidirectional Antenna	$20.00	3	$60.00	HobbyKing
Telemetry TXVRS	$40.00	4	$160.00	HobbyKing
Miscellaneous	$300.00	1	$300.00	Amazon
Total	**$2,065.00**			

Table 61: Recovery Itemized Budget

Item	**Unit Cost**	**Quantity**	**Unit Total**	**Company**
SkyAngle Cert 3 XXL	$239.00	1	$239.00	SkyAngle
SkyAngle Classic II 44"	$66.00	1	$66.00	SkyAngle
SkyAngle Classic II 32"	$33.00	1	$33.00	SkyAngle
SkyAngle Classic II 20"	$22.00	1	$22.00	SkyAngle
Schurter Rotary Switch	$4.67	1	$4.67	Apogee
9V batteries (8 pack)	$9.49	1	$9.49	Amazon
JST Connectors	$1.00	1	$1.00	Amazon
12" Chute protector	$8.95	1	$8.95	Apogee
18" Chute protector	$10.95	1	$10.95	Apogee
1/4-20 SS threaded rod	$5.84	2	$11.68	
1/4" SS eye bolts	$4.00	1	$4.00	
Kevlar Shock Cord	$48.50	1	$48.50	
Nomex Shock Cord Protector	$15.99	1	$15.99	
Total	**$475.23**			

Table 62: ATS Itemized Budget

Item	**Unit Cost**	**Quantity**	**Unit Total**	**Company**
SB2282SG Servo Motor	$135.99	1	$135.99	Amazon
Pololu Micro USB Servo Controller	$19.95	1	$19.95	Pololu
Raspberry Pi 3B	$34.99	1	$34.99	Amazon
Venom 35C 2000 mAh 2S LiPo Battery	$32.99	1	$32.99	Amazon

VN-100 IMU	$530.00	1	$530.00	VectorNav
Raw Material	$300	1	$300	TBD
Total	**$1,053.92**			

Table 63: Travel Itemized Budget

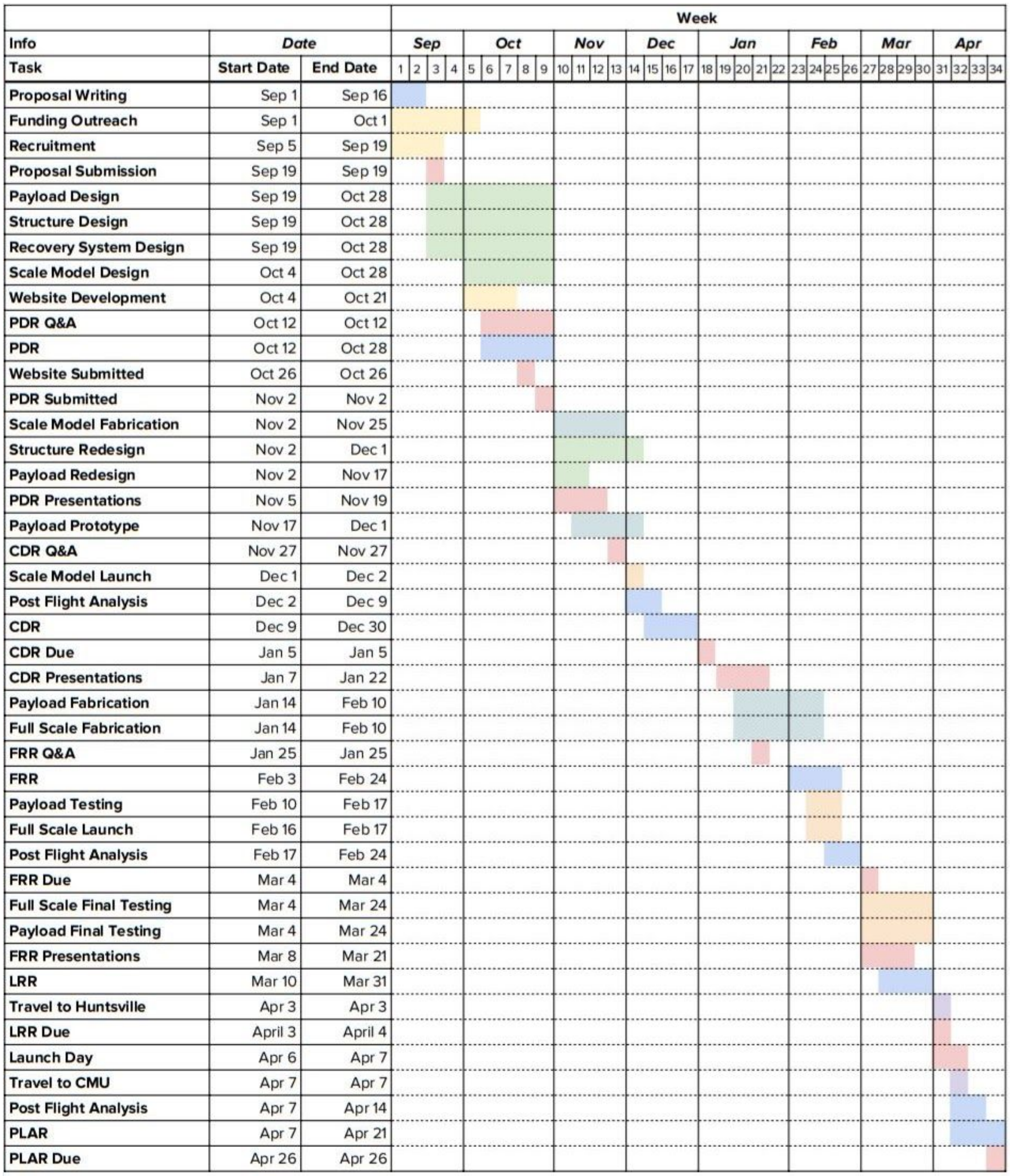
Item	Unit Cost	Quantity	Unit Total	Company
Rental Cars	$430.00	3	$1,290.00	TBD
Hotel Room	$500.00	4	$2,000.00	TBD
Gas	$300.00	1	$300.00	TBD
Food	$300.00	1	$300.00	TBD
Total	**$3,890.00**			

6.3.2 Funding Plan

Table 64: Funding Overview

Funding Plan	Amount	Status
Allocated Organization Budget	$5,837	Received
CMU Mechanical Engineering Department	$1,000	In Process
CMU Physics Department	$500	In Process
CMU Crowdfunding	$5,000	In Process
CMU College of Engineering	$2,500	In Process
Sponsorships	$500	In Process
Drone Club	$750	In Process
Member Dues	$750	In Process
Total Funding Opportunity	**$16,837**	

6.3.3 Project Timeline



Info	Date	
Task	Start Date	End Date
Proposal Writing	Sep 1	Sep 16
Funding Outreach	Sep 1	Oct 1
Recruitment	Sep 5	Sep 19
Proposal Submission	Sep 19	Sep 19
Payload Design	Sep 19	Oct 28
Structure Design	Sep 19	Oct 28
Recovery System Design	Sep 19	Oct 28
Scale Model Design	Oct 4	Oct 28
Website Development	Oct 4	Oct 21
PDR Q&A	Oct 12	Oct 12
PDR	Oct 12	Oct 28
Website Submitted	Oct 26	Oct 26
PDR Submitted	Nov 2	Nov 2
Scale Model Fabrication	Nov 2	Nov 25
Structure Redesign	Nov 2	Dec 1
Payload Redesign	Nov 2	Nov 17
PDR Presentations	Nov 5	Nov 19
Payload Prototype	Nov 17	Dec 1
CDR Q&A	Nov 27	Nov 27
Scale Model Launch	Dec 1	Dec 2
Post Flight Analysis	Dec 2	Dec 9
CDR	Dec 9	Dec 30
CDR Due	Jan 5	Jan 5
CDR Presentations	Jan 7	Jan 22
Payload Fabrication	Jan 14	Feb 10
Full Scale Fabrication	Jan 14	Feb 10
FRR Q&A	Jan 25	Jan 25
FRR	Feb 3	Feb 24
Payload Testing	Feb 10	Feb 17
Full Scale Launch	Feb 16	Feb 17
Post Flight Analysis	Feb 17	Feb 24
FRR Due	Mar 4	Mar 4
Full Scale Final Testing	Mar 4	Mar 24
Payload Final Testing	Mar 4	Mar 24
FRR Presentations	Mar 8	Mar 21
LRR	Mar 10	Mar 31
Travel to Huntsville	Apr 3	Apr 3
LRR Due	April 3	April 4
Launch Day	Apr 6	Apr 7
Travel to CMU	Apr 7	Apr 7
Post Flight Analysis	Apr 7	Apr 14
PLAR	Apr 7	Apr 21
PLAR Due	Apr 26	Apr 26

Administrative	🟨
Documentation	🟦
NASA	🟥
Design	🟩
Fabrication	⬜
Testing	🟧
Travel	🟪

Figure 120: Project Gantt Chart

7 Appendix

7.1 Applicable Laws and Regulations

7.1.1 FAA Regulations, Title 14, Chapter 1, Part 101, Subpart C - Amateur Rockets

101.21 Applicability.

(a) This subpart applies to operating unmanned rockets. However, a person operating an unmanned rocket within a restricted area must comply with §101.25(b)(7)(ii) and with any additional limitations imposed by the using or controlling agency.

(b) A person operating an unmanned rocket other than an amateur rocket as defined in §1.1 of this chapter must comply with 14 CFR Chapter III.

101.22 Definitions.

The following definitions apply to this subpart:

(a) *Class 1—Model Rocket* means an amateur rocket that:

(1) Uses no more than 125 grams (4.4 ounces) of propellant;

(2) Uses a slow-burning propellant;

(3) Is made of paper, wood, or breakable plastic;

(4) Contains no substantial metal parts; and

(5) Weighs no more than 1,500 grams (53 ounces), including the propellant.

(b) *Class 2—High-Power Rocket* means an amateur rocket other than a model rocket that is propelled by a motor or motors having a combined total impulse of 40,960 Newton-seconds (9,208 pound-seconds) or less.

(c) *Class 3—Advanced High-Power Rocket* means an amateur rocket other than a model rocket or high-power rocket.

101.23 General operating limitations.

(a) You must operate an amateur rocket in such a manner that it:

(1) Is launched on a suborbital trajectory;

(2) When launched, must not cross into the territory of a foreign country unless an agreement is in place between the United States and the country of concern;

(3) Is unmanned; and

(4) Does not create a hazard to persons, property, or other aircraft.

(b) The FAA may specify additional operating limitations necessary to ensure that air traffic is not adversely affected, and public safety is not jeopardized.

101.25 Operating limitations for Class 2-High Power Rockets and Class 3-Advanced High Power Rockets.

When operating *Class 2-High Power Rockets* or *Class 3-Advanced High Power* Rockets, you must comply with the General Operating Limitations of §101.23. In addition, you must not operate *Class 2-High Power Rockets* or *Class 3-Advanced High Power* Rockets—

(a) At any altitude where clouds or obscuring phenomena of more than five-tenths coverage prevails;

(b) At any altitude where the horizontal visibility is less than five miles;

(c) Into any cloud;

(d) Between sunset and sunrise without prior authorization from the FAA;

(e) Within 9.26 kilometers (5 nautical miles) of any airport boundary without prior authorization from the FAA;

(f) In controlled airspace without prior authorization from the FAA;

(g) Unless you observe the greater of the following separation distances from any person or property that is not associated with the operations:

(1) Not less than one-quarter the maximum expected altitude;

(2) 457 meters (1,500 ft.);

(h) Unless a person at least eighteen years old is present, is charged with ensuring the safety of the operation, and has final approval authority for initiating high-power rocket flight; and

(i) Unless reasonable precautions are provided to report and control a fire caused by rocket activities.

101.27 ATC notification for all launches.

No person may operate an unmanned rocket other than a Class 1—Model Rocket unless that person gives the following information to the FAA ATC facility nearest to the place of intended operation no less than 24 hours before and no more than three days before beginning the operation:

(a) The name and address of the operator; except when there are multiple participants at a single event, the name and address of the person so designated as the event launch coordinator, whose duties include coordination of the required launch data estimates and coordinating the launch event;

(b) Date and time the activity will begin;

(c) Radius of the affected area on the ground in nautical miles;

(d) Location of the center of the affected area in latitude and longitude coordinates;

(e) Highest affected altitude;

(f) Duration of the activity;

(g) Any other pertinent information requested by the ATC facility.

101.29 Information requirements.

(a) *Class 2—High-Power Rockets.* When a Class 2—High-Power Rocket requires a certificate of waiver or authorization, the person planning the operation must provide the information below on each type of rocket to the FAA at least 45 days before the proposed operation. The FAA may request additional information if necessary to ensure the proposed operations can be safely conducted. The information shall include for each type of Class 2 rocket expected to be flown:

(1) Estimated number of rockets,

(2) Type of propulsion (liquid or solid), fuel(s) and oxidizer(s),

(3) Description of the launcher(s) planned to be used, including any airborne platform(s),

(4) Description of recovery system,

(5) Highest altitude, above ground level, expected to be reached,

(6) Launch site latitude, longitude, and elevation, and

(7) Any additional safety procedures that will be followed.

(b) *Class 3—Advanced High-Power Rockets.* When a Class 3—Advanced High-Power Rocket requires a certificate of waiver or authorization the person planning the operation must provide the information below for each type of rocket to the FAA at least 45 days before the proposed operation. The FAA may request additional information if necessary to ensure the proposed operations can be safely conducted. The information shall include for each type of Class 3 rocket expected to be flown:

(1) The information requirements of paragraph (a) of this section,

(2) Maximum possible range,

(3) The dynamic stability characteristics for the entire flight profile,

(4) A description of all major rocket systems, including structural, pneumatic, propellant, propulsion, ignition, electrical, avionics, recovery, wind-weighting, flight control, and tracking,

(5) A description of other support equipment necessary for a safe operation,

(6) The planned flight profile and sequence of events,

(7) All nominal impact areas, including those for any spent motors and other discarded hardware, within three standard deviations of the mean impact point,

(8) Launch commit criteria,

(9) Countdown procedures, and

(10) Mishap procedures.

7.1.2 FAA, Title 14, Chapter I, Subchapter F, Part 107: Small UAV

For brevity, the full documentation of these regulations will not be included. Refer to the FAA website for full documentation. CMRC will register any UAV developed for the payload that exceeds 0.55 lbs. All of the regulations outlined in Part 107 will be followed at all times by all members. The SO will enforce these regulations.

7.1.3 CFR 27 Part 55: Commerce in Explosives

For brevity, the full documentation of these regulations will not be included. Refer to the CFR website for full documentation. CMRC will abide by all regulations outlined in Part 55. This will include the purchase and transport of any energetic devices throughout the duration of this project. The SO will enforce these regulations.

7.1.4 NAR High Power Rocket Safety Code

For brevity, the full documentation of these regulations will not be included. Refer to the NAR website for full documentation. CMRC will abide by all regulations outlined in the High Power Rocket Safety Code.

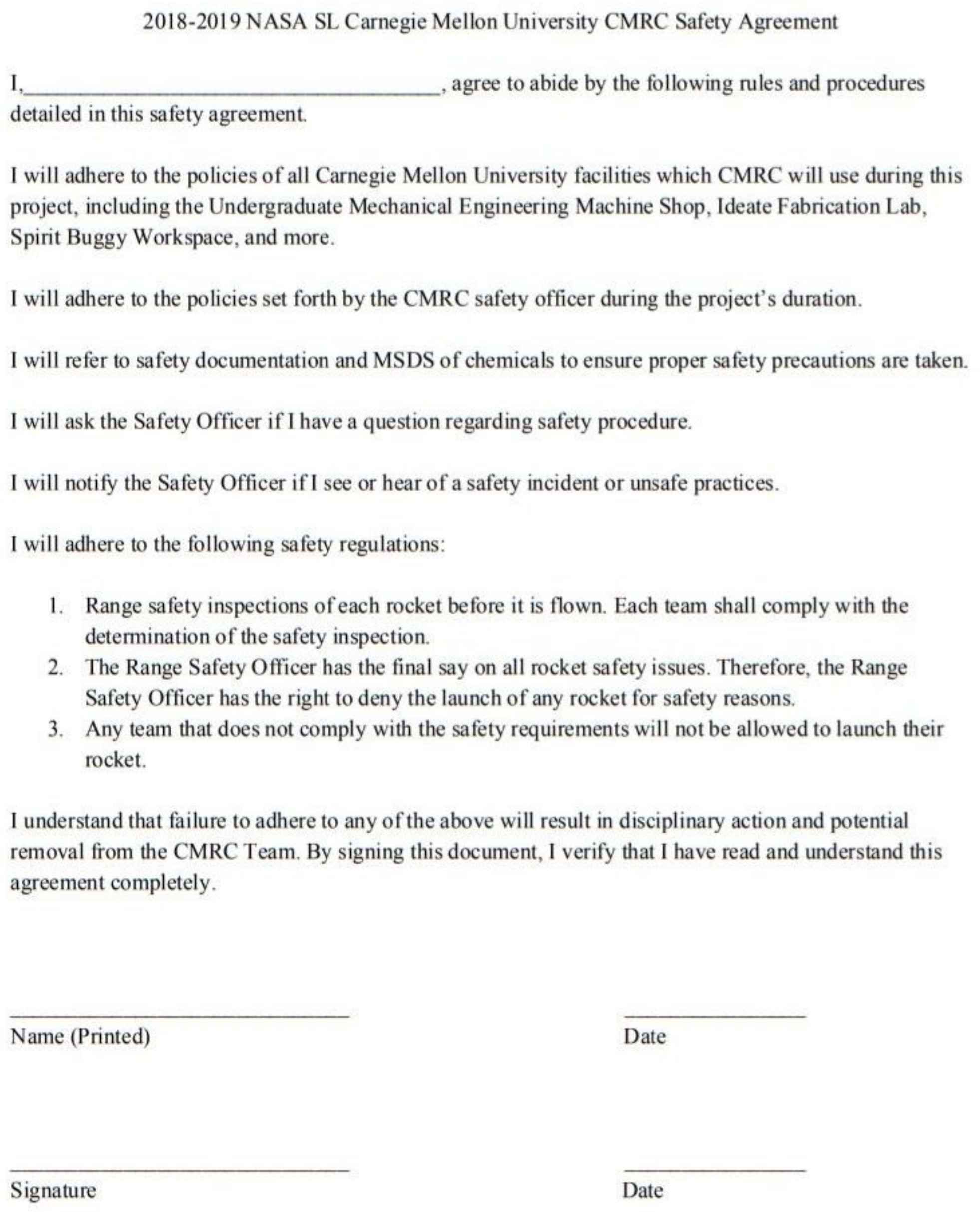
7.1.5 NFPA 1122: Code for Model Rocketry

For brevity, the full documentation of these regulations will not be included. Refer to the NFPA website for full documentation. According to the NFPA 1122 Code for Model Rocketry, 'model rockets' weight less than 1500 grams, contain less than 125 grams of total fuel, have a motor will less than 62.5 grams of fuel or less than 160 S of total impulse, use pre-manufactured solid propellant motors, and do not use metal body tubes, nose cones, or fins. The safety code specified in NFPA 112 is the same as the NAR safety code.

7.1.6 NFPA 1127: Code for High Powered Rocketry

For brevity, the full documentation of these regulations will not be included. Refer to the NFPA website for full documentation. According to the NFPA 1127 Code for High Powered Rocketry, 'high power rockets' exceed the total weight, propellant, or impulse restrictions of model rockets, but only use pre-manufactured rocket motors and don't use metal body tubes, nose cones, or fins. Metal components may be used for structural integrity. While there is no upper weight limit, there is a single motor limit of an 40,960NS of total impulse or a 81,920 NS of total impulse between all motors. The safety code specified in NFPA 1127 is the same as both the NAR and TRA safety codes.

7.3 Safety Agreement



2018-2019 NASA SL Carnegie Mellon University CMRC Safety Agreement

I,____, agree to abide by the following rules and procedures detailed in this safety agreement.

I will adhere to the policies of all Carnegie Mellon University facilities which CMRC will use during this project, including the Undergraduate Mechanical Engineering Machine Shop, Ideate Fabrication Lab, Spirit Buggy Workspace, and more.

I will adhere to the policies set forth by the CMRC safety officer during the project's duration.

I will refer to safety documentation and MSDS of chemicals to ensure proper safety precautions are taken.

I will ask the Safety Officer if I have a question regarding safety procedure.

I will notify the Safety Officer if I see or hear of a safety incident or unsafe practices.

I will adhere to the following safety regulations:

1. Range safety inspections of each rocket before it is flown. Each team shall comply with the determination of the safety inspection.
2. The Range Safety Officer has the final say on all rocket safety issues. Therefore, the Range Safety Officer has the right to deny the launch of any rocket for safety reasons.
3. Any team that does not comply with the safety requirements will not be allowed to launch their rocket.

I understand that failure to adhere to any of the above will result in disciplinary action and potential removal from the CMRC Team. By signing this document, I verify that I have read and understand this agreement completely.

________________________________ Name (Printed)	________________ Date
________________________________ Signature	________________ Date

7.3 Pre-Flight Checklist

7.3.1 Recovery Preparation

The following is a breakdown of what needs to be done before the rocket gets placed on the launchpad to ensure that everything is in its place and properly functioning. Each subsection should be followed for a successful launch.

Parachute Preparation

- ☐ Ensure that all the shock cords, parachutes, and harness equipment are accounted for.
  - ☐ drogue parachute
  - ☐ main parachute
  - ☐ nylon shock cord with sleeve
  - ☐ kevlar shock cord
  - ☐ (2) Nomex chute protectors
  - ☐ 1” forged eyebolts

Note: The nylon shock cord and main chute go on the upper airframe. The kevlar shock cord and drogue chute go on the lower airframe.

Make sure to check each of the listed components for any damage such as rips, tears, and burn holes.

Procedure for each parachute:

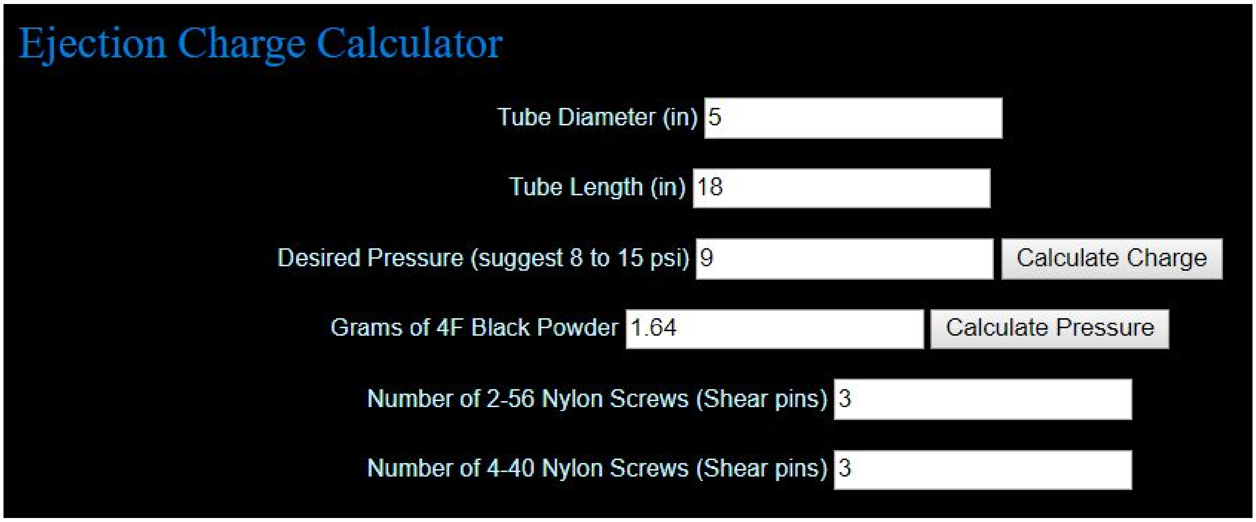
- ☐ Connect the main parachute to the nylon shock cord using a quick link.
- ☐ Connect the main shock cord ends to the eye bolts on the airframe using the quick links.
- ☐ Check the integrity of the bulk plates connected to the recovery harnesses.
- ☐ Have the safety officer check that the eyebolts and quick links are intact with the eye bolts securely attached to their respective bulkheads and the quicklinks securely connected to the shock cord and shroud lines.
- ☐ Lay the parachute out flat, folded in half to a semi-circle.
- ☐ Hold the top of the parachute and let it dangle. Use a z-fold. Press down and roll edges toward the inside.
- ☐ Wrap shroud lines around parachute bundle.
- ☐ Use a burrito fold to encase the parachute with the Nomex protector.
- ☐ Feed the shock cord into the airframe.
- ☐ Insert the parachute into the airframe. If it doesn’t fit, re-fold it and press down more firmly.

Charge Preparation

- ☐ BEFORE LAUNCH DAY: The mechanical lead will use an online calculator to determine the amount of black powder required for successful rocket separation. This

resource can be found at
http://www.rimworld.com/nassarocketry/tools/chargecalc/index.html
All these values should be known from the dimensioning the rocket or calculations from requirements that we have defined in previous sections pertaining to the rockets performance. Make sure to check with the team adviser so that this is the correct amount needed.
The backup charges will hold 25% more black powder than the primary charges to ensure separation of the rocket despite primary charge failure.
The black powder quantities are: **M1: XX g; M2: XX g; D1: XX g; D2: XX g**

The following is an example of the values that the calculator can output.



Ejection Charge Calculator

Tube Diameter (in) 5
Tube Length (in) 18
Desired Pressure (suggest 8 to 15 psi) 9
Grams of 4F Black Powder 1.64
Number of 2-56 Nylon Screws (Shear pins) 3
Number of 4-40 Nylon Screws (Shear pins) 3

Sample Calculator Results

- ☐ Make sure that the team advisor is always present for this portion. He will be in charge of handling the black powder and anyone around him should be alert of the situation as to avoid any safety hazards.
- ☐ The team advisor attaches (4) electronic matches to the (4) terminal blocks.

The following procedures should be done one charge at a time:

- ☐ The team adviser will measure the specified amount of black powder and pour it into the charge canister.
  - ☐ Ensure black powder is placed back in a safe location where fire hazards are not present such as igniters, matches, heat sources, cigarettes.
- ☐ The mechanical lead will ensure no power is connected to the recovery bay.
- ☐ The team advisor will place the end of the electronic match into the black powder.
- ☐ The mechanical lead will place a small chunk of wadding into the charge canister containing the black powder.
  - ☐ NOTE: Ensure supervision by the team adviser at all points in time.
- ☐ The mechanical lead will cover the charge canister with electrical tape.

- ☐ Finally have the safety officer and team adviser have a final look and verify that everything has passed their inspection.

Ground Parachute Charge Testing

- ☐ Always have the team adviser present as they will be overseeing the whole procedure, since it involves black powder.
- ☐ Following the procedure from charge preparation section, the charge will be ready to be activated.
- ☐ Verify that the voltage of the altimeter 9V batteries is 9V.
- ☐ Have a charge test ignition device available to attach leads onto the terminals of the charge system. Make sure that the ignition key is not placed into the device so that no incident can occur.
- ☐ Place the rocket on an elevated surface, usually chairs or table, and in an isolated area 100ft away from uninvolved individuals
- ☐ The safety officer alerts everyone in the area of the test charge being implemented and to have visual of the rocket
- ☐ The safety officer places the ignition key into the ignition device and gives a countdown to ignite the charge and eject the parachute from the lower and upper airframe systems.
    - ☐ If the igniter does not go off, wait 60 seconds and consult the troubleshooting section and have the safety officer try again but still alerting everyone in the vicinity.
    - ☐ Remove key if troubleshooting or igniter went off correctly
- ☐ Have the team adviser and safety officer inspect the area for residue
- ☐ Remove the rocket from the area with all its components and place it in a safe location.
- ☐ Complete section charge preparation section once again as to have the rocket ready for the actual flight

GPS

- ☐ Place the GPS Lithium Polymer battery onto the back side of the GPS sled, and cover with foam
- ☐ Tighten in place with three zip ties
- ☐ Screw the Eggfinder GPS onto the GPS sled using 4-40 screws, and fix in place using nuts
- ☐ Screw the GPS sled onto the exposed thread of the forward bulkhead for the nose cone coupler
- ☐ Tighten GPS sled in place with a nut
- ☐ Connect the JST-RCY connector of the Eggfinder to the corresponding JST-RCY connector on the wire running off the Schurter rotary switch in the nose cone
- ☐ Connect the JST-RCY connector of the battery to the corresponding JST-RCY connector on the wire running off the Schurter rotary switch in the nose cone
- ☐ Insert nose cone coupler into nose cone such that the GPS is enclosed in the nose cone

- ☐ Insert pem nuts into the forward three holes
- ☐ Insert shear pins to the aft three holes
- ☐ While on the launch pad, turn the rotary switch on the nose cone using a screwdriver
- ☐ Power on the receiver module and wait until the signal is locked
- ☐ If a signal cannot be locked, remove the pem nuts and check all wire connections
- ☐ Tighten pem nuts once more when the signal has been locked

Recovery Electronics Preparation

- ☐ Fasten altimeters to Electronics Bay sled with screws
- ☐ Insert power and ground wire leads into the two slots on the altimeters marked as "Negative"
    - ☐ Black wire must be closest to "NEG" marker
- ☐ While inserted, use a small screwdriver to screw in the screw above the slot until the leads are clamped down
- ☐ Connect all the male and female JST-RCY connectors between the Schurter rotary switch wires and the corresponding wires running off the altimeters
- ☐ Insert wire leads for the drogue parachute into the two slots on the altimeters marked as "Drogue". Order does not matter.
- ☐ While inserted, use a small screwdriver to tighten the screw above the slot until the leads are clamped down
- ☐ Connect all the male and female JST-RCY connectors between the drogue charge wires and the corresponding wires running off the altimeters
- ☐ Insert wire leads for the main parachute into the two slots on the altimeters marked as "Main". Order does not matter.
- ☐ While inserted, use a screwdriver to tighten the screw above the slot until the leads are clamped down
- ☐ Connect all the male and female JST-RCY connectors between the main charge wires and the corresponding wires running off the altimeters
- ☐ Slide electronics bay into the coupler and seal the loose bulkhead using ¼-20 hex nuts
- ☐ Ensure switches can be accessed with a screwdriver
- ☐ Prepare the ejection charges as detailed in section 7.2.
- ☐ When rocket is on launch pad, insert a small screwdriver through each of the two holes in the switchband of the electronics bay, and turn the rotary switch for each hole
- ☐ Listen to the beeping signal given by the altimeters. At the end of the sequence, a successful setup will result in a series of 3 beeps, repeated over and over.

7.3.2 Motor Preparation

- ☐ Before assembly have the safety officer inspect the motor retainer base and thrust plate for any cracks or defects.

- ☐ Our team adviser will be supervising the motor assembly along with the safety officer. Fire hazards such as people smoking, lighters, potential ignition sources, will be removed from the immediate surroundings during motor preparation.
- ☐ Please reference the Pro54 motor retention instructions that can be followed in great detail on how to place the motor into the retention ring properly.

7.3.3 Launch Pad Procedure

While the preparation stages are underway, a group of two people should inspect and clear the launch pad. The following is assumes the launch pad meets basic functions and has no debris from previous launches.

- ☐ Gather a step ladder and two team members
- ☐ Inspect the launch rail to have no visible flaws such as cracks or bends
- ☐ Check the rocket for any exterior defects
- ☐ Count that there are 3 screws for the nose cone
- ☐ Count that there are 3 screws in the lower airframe connecting the ATS bay
- ☐ Count that there are 3 shear pins in the mid-airframe connecting the ATS bay
- ☐ Count that there are 3 screws in the upper airframe connecting the electronics bay
- ☐ Count that there are 3 screws in the mid-airframe connecting the electronics bay
- ☐ Lower rail on the launch pad to a horizontal position so that it is easy to load the rocket
- ☐ Slide it into the 1515 series rail by putting the rail mounts into the slots, but do not erect yet
- ☐ Use a screwdriver and turn on the switches for the electronics bay, altimeter systems, and GPS system
- ☐ Listen for the beeps in the altimeter system until they are armed
    - ☐ A single beep means drogue ematch continuity is OK, two beeps means main ematch continuity is OK, three beeps means both drogue & main have good continuity.
    - ☐ If issues occur for these previous two steps make sure to refer to troubleshooting section.
- ☐ Rotate the launch rail to a vertical position and lock in place
- ☐ Other than the safety officer, mechanical lead, and team advisor, the rest of the assisting team members should exit the area and be 300 ft from the launch pad

7.3.4 Ignitor Installation

- ☐ The rocket must be properly installed on the launch pad system, tilted vertically, e-bays activated and properly functioning
- ☐ The motor igniter can now be placed on the motor itself. Make sure to inspect the igniter for any imperfections, cracks, and proper electrical resistance.

- ☐ Feed the igniter carefully into the motor cavity until a hard stop against the propellant grain is felt
- ☐ Make sure to mark the point where the bottom of the motor touches the igniter.
- ☐ Take the igniter out and make a loop at that marked point. Afterwards, reinsert the igniter in motor.
- ☐ Place the cap of the motor container.
- ☐ When properly cleared with the safety officer and NASA officials for the launch, place the launch lead clips onto the igniters. Make sure to maximize amount of contact on the leads by wrapping the wire around a couple times to reduce the chance of ignition failure from bad contact.
- ☐ For more instructions look at instructions from the manufacturers of the motor retainer.

7.3.5 Launch Procedure

This launch procedure encompasses the rocket's journey starting from the launch vehicle being on the launch pad until the rocket lands and needs locating which can be found in the post-launch sections of the report.

- ☐ Prior to launch assign two team members to be in charge of the GPS tracking to find be able to retrieve the rocket.
- ☐ Make sure that all personnel are at a minimum of 300 ft away from the launch pad once the rocket is setup and ready to go.
- ☐ Alert team members and anyone else around that the launch is imminent, so they should have visual of the rocket from this point on until landing. They should also be standing, this makes them more aware and allows them to react.
- ☐ The safety officer must check the situation and launch the rocket when deemed safe and ready.
- ☐ Once the rocket has been launched, wait for the safety officer to give the all clear so that the designated retrieval team may safety track down the rockets location with the GPS module.
- ☐ Retrieve the rocket and proceed to perform post-flight inspection.

7.3.6 Troubleshooting

During the preparation phase of the rocket there are points where systems do not act as intended. This holds true for when the rocket is on the launch pad and some for at any point in time. This troubleshooting has possible causes for the most likely issues scenarios found during the different stages.

In accordance to the NAR Safety Code number 5, if the rocket misfires, CMRC members will wait 60 second before troubleshooting the rocket. From there, the following procedure will be used to diagnose and fix problems relating to the rocket launch:

Troubleshooting Solutions

Issue	Stage	Possible Cause	Possible Solutions
Ground parachute Charge not igniting	Preparation Phase	-Key is not properly in ignition switch -Leads are not properly connect -Battery for the ignition device is low or dead	-Place key properly into the ignition switch by pressing down or shifting key around -Inspect the leads and see if they are connected to terminals of the charges -Replace the battery system with a new battery or charge it
Recovery Electronics are not connecting to receiver	Preparation Phase	-Transmitter or receiver is inside building having poor connection -Antenna is damaged -Battery is dead or too low	-Make sure that both modules are outside in a clear area so the signals do not get blocked -Make sure the antenna is the proper length and straight or replace the antenna but make sure it has the same specifications -Make sure that the battery is charged or switched out with another
Recovery Electronics is not getting GPS connected	Preparation Phase	-GPS is indoors and takes too long to connect -Battery is low	-Go outside to an open area such as a field -Replace battery or charge battery to provide proper power
Cracks or faults in the rocket body	Any	-Getting damaged from transportation	-If non essential then try and epoxy system but if not then try and postpone launch to a later date and time.

Charge electronics system not arming	Any	-Battery is dead -electronics are not properly connected to the terminals of the igniter charges	-Replace or charge battery -Check the connections and ensure that they are contacting the terminals
Igniter for motor not going off	Launch pad	-Battery for ignition device is dead -Leads are not properly connected	-Replace or charge battery -Check the leads on the igniter and see if they are making contact with the igniter ends or if the leads have material that blocks good continuity

7.3.7 Post Flight Recovery and Inspection

The following are post-flight inspection procedures that will cover what to do once the rocket has landed and been retrieved.

- ☐ After obtaining the rocket from a safe, retrievable area, make sure that all the sections of the rocket have been found
- ☐ Make sure that the rocket is in a safe location for inspection: no high density population and in a clean area so that the tools and inspections can be done without hindrance.
- ☐ The safety officer will examine the rocket for any hazards such as sharp edges, unintended loose parts, battery damage, electronic damage, and other possible form of safety hazard that could hurt an individual
- ☐ Access the altimeters by unscrewing the recovery bay cap.
    - ☐ The data of the apogee can be extracted but also heard as long as there is auditory feedback system capabilities. Show these live results to a NASA official so they can be present and verify our results as legitimate
- ☐ Have the mechanical lead check each system of the rocket. Have another teammate to double check the work and have the team adviser check as well.
    - ☐ Check body tube system for cracks and failures
    - ☐ Motor section of rocket for cracks and failures
    - ☐ Drogue parachute performance and status
    - ☐ Main parachute performance and status

☐ Have the safety officer remove the motor casing from the rocket and properly dispose of it in a marked bag to be placed in the correct disposal system that should be provided by NASA officials.

7.3.8 Safety Verification

CMRC safety officer, Fabian Aristizabal, or CMRC president, Michael Messersmith, certifies that all the items on the above checklists have been completed in accordance with CMRC, NAR, TRA, and NASA SL safety regulations.

Signature: ____