Rose Rocketry

Project Kirkpatrick
Preliminary Design Review

Rose-Hulman Institute of Technology
October 26, 2022

500 Wabash Ave, Terre Haute, IN 47803

Contents

Table of Acronyms

Acronym	Definition
VDF	Vehicle Demonstration Flight
VCS	Version Control System
USB	Universal Serial Bus
TNC	Terminal Node Controller
STEM	Science, Technology, Engineering, and Mathematics
STDIN/STDOUT	Standard input/Standard output
SNR	Signal to Noise Ratio
SL	Student Launch
SGA	Student Government Association
SDR	Software-Defined Radio
SDK	Software Development Kit
SBC	Single Board Computer
RTL-SDR	RealTek Software-Defined Radio
RSO	Range Safety Officer
RRC	Rocket Recovery Controller
RR-SL	Rose Rocketry - Student Launch
RF	Radio Frequency
PPE	Personal Protective Equipment
PLAR	Post-Launch Assessment Review
PDR	Preliminary Design Review
PDF	Payload Demonstration Flight
OS	Operating System
OpenCV	Open Computer Vision
NASA	National Aeronautics and Space Administration
NAR	National Association of Rocketry
ME	Mechanical Engineering
MBC	Merit Badge Counselor
MATLAB	Matrix Laboratory
LCD	Liquid-crystal Display
HTD	High-torque drive
HPR	High Powered Rocketry
HB	Handbook
GPS	Global Positioning System
FRR	Flight Readiness Review
FPG-9	9-inch Foam Plate Glider

FMEA	Failure Modes and Effects Analysis
FM	Frequency Modulation
FIRST	For Inspiration and Recognition of Science and Technology
FAA	Federal Aviation Administration
ESD	Electrostatic Discharge
EDGE	Explain, Demonstrate, Guide, and Enable
ECE	Electrical and Computer Engineering
DC	Direct Current
CPU	Central Processing Unit
CP	Center of Pressure
COTS	Commercial Off-The-Shelf
COTF	Commercial Off the Shelf
CG	Center of Gravity
CDR	Critical Design Review
CAD	Computer-aided design
BIC/KIC	Branam and Kremer Innovation Center
APRS	Automatic Packet Reporting System
ADC	Analogue to Digital Converter

1. Summary

Table 1.1: Team Summary

Team Name	Rose Rocketry
Project Name	Project Kirkpatrick
Mailing Address	5500 Wabash Ave, Terre Haute, IN 47803
NAR/TRA Sections	Indiana Rocketry Group Tripoli #132 NAR Section #711
Social Media	Instagram: rose_rocketry
Mentor	Randy Milliken randy@milliken.org NAR#86429 - Level 3
Hours Spent	414

Table 1.2: Vehicle Summary

Official Target Apogee	5000ft
Preliminary Motor Choice	CTI K780BS-15
Recovery System	Dual-Deploy
Rail Size	1010
Vehicle Length	102”

Vehicle Section	Mass (lbs)	Length (in)
Booster (Wet)	7.7	35
Booster (Dry)	5.18	35
Recovery	5.16	29
Payload	7.75	47

1.1. Payload Summary

The payload title is “A View to a Kill” credited to the fourteenth James Bond movie. The payload will deploy a camera upon landing, receive Automatic Packet Reporting System (APRS) commands, and execute the received commands within a maximum time of 30 seconds. The camera must be deployed such that it has a clear image of the terrain and sky, with the horizon in the center of the frame, and be capable of rotating 360°.

In order to accomplish this, upon landing a section of airframe located at the fore of the rocket will deploy external supports to fix the ends of the airframe to the ground while the airframe in between the supports rotates to orient the camera with the horizon. Once the proper orientation is achieved the camera and APRS antenna will be external deployed to receive APRS packets and manipulate the camera.

2. Changes Since the Proposal

2.1. Vehicle Criteria

2.1.1. Extra Hardware

The team has decided to add 1.5 pounds of extra weight to the vehicle, specifically in the payload section to account for extra hardware. This hardware accounts for the GPS and battery, quick release hardware, and extra hardware for payload mounting.

2.2. Payload Criteria

2.2.1. Antenna

The payload will no longer use a custom antenna for RF receiving. Although there were concerns about acquiring COTS components due to supply chain issues, the team has already purchased and tested a ¼ wave monopole antenna and a common electrically short monopole antenna used in amateur radio, called a rubber ducky antenna (See Section 6.4.1).

2.2.2. SDR

Parallel development was proposed for a hardware radio and software-defined radio (SDR) for the processing of APRS commands. However, due to quicker-than anticipated procurement of SDRs and other RF resources, the team will not pursue development of a custom RF processing board.

2.2.3. Rotating Airframe

Due to safety and complexity concerns related to using inflatable righting mechanisms, the leading design for vertical orientation of the payload within the airframe has shifted from tube inflation to a combination of rotating airframe and orientation sensor.

2.3. Project Plan

The project plan now includes dates for all USLI required launches including the Subscale, VDF, and PDF. This allowed more detailed planning for each milestone. We have also determined our weekly meeting times. See Section 8.3 for specific details.

3. Vehicle Criteria

3.1. Vehicle Mission Statement

The objective of the vehicle system is to create a rocket that safely and reliably reaches the target altitude in a variety of launch conditions, deploys recovery systems that allow a safe return to the ground, and allows the payload to be deployed in an effective manner upon landing.

A successful vehicle mission meets all of the following criteria:

1. Launch vehicle lands successfully and allows payload to deploy completely
2. The launch vehicle is launched on a safe, stable, and predictable trajectory
3. The launch vehicle is recovered in a state suitable for immediate reuse
4. All members abide by all safety regulations created by NAR, the FAA, and Rose Rocketry

3.2. System Level Design

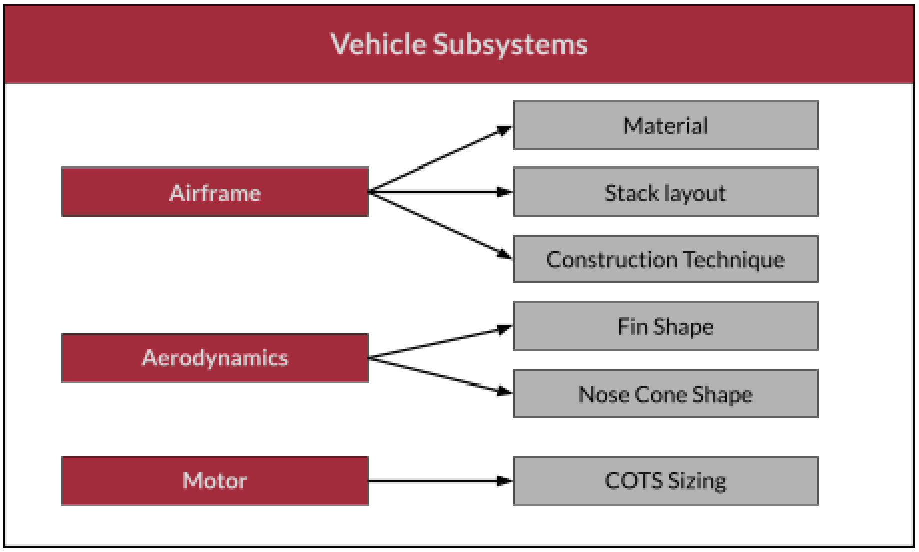


Figure 3.1: Overview of System-Level Breakdown of the Vehicle Subsystems

Table 3.1: Description of Vehicle Subsystems

Vehicle Subsystem	Section	Objective
Airframe	3.3	Provide a structural housing capable of: ● Handling forces of flight ● Protecting the internal systems and components ● Adhering to spatial and mass constraints ● Adhering to safety and reliability requirements
Aerodynamics	3.4	Assure stability and safe ascent of the vehicle.
Motor	3.5	Propel the vehicle to near the target apogee.

In the following sections, we will discuss in detail each subsystem on the launch vehicle. Each subsystem in Table 3.2 is summarized along with several options for the design of the system. Options will be summarized with lists of pros and cons. Then, feasibility studies are conducted for each option evaluating for characteristics such as cost, manufacturability, durability, etc. A written summary of each alternative discusses in depth research of alternatives and the information in the tables.

3.3. Airframe

The design of the airframe of the vehicle is critical to the success of the vehicle. The airframe must tolerate the forces of flight and landing, allow separation and support deployment of recovery devices, contain our payload, and allow the launch vehicle to reach target apogee considering motor constraints. Three aspects of the airframe design will be considered: the material of the airframe, the stack layout of the airframe, including points of separation, and the shape of the airframe. Design alternatives for each aspect of the airframe will be evaluated.

3.3.1. Material

The most fundamental choice in the design of the vehicle is the material that it is constructed from - this will directly impact all other aspects of the design in a wide variety of ways. Generally, the team has limited the design space to only materials which are available off-the-shelf, taking into account the complexity of fabricating an airframe from scratch and the experience level of the team. The high-level “pros” and “cons” of each material alternative are summarized in the table below. Research regarding each design alternative is presented in the subsequent subsections.

The leading choice for airframe material is fiberglass, with the primary considerations being the high robustness and low cost. A detailed description is included in section 3.3.1.1.

Table 3.2: Pros and cons of alternative material airframe

Material Choices	Pros	Cons
Fiberglass	• Good specific strength • Can be easily threaded • Good toughness	• Moderately expensive • May delaminate while machining • Fabrication dust
Cardboard	• Cheapest option • Light material • Easy to bond	• Damaged by water • Hard to machine • Doesn't hold threads • Low strength • Poor longevity
Carbon Fiber	• Highest specific strength • Machines well	• Very expensive • Blocks radio signals • Produces hazardous dust
Phenolic	• Low cost • Machines well • Extremely rigid for its weight	• Brittle in cold weather • Prone to shattering due to shock

In order to study the feasibility of each alternative, the following aspects are considered. Each is listed with a relative importance ratio:

- Cost - 2x
- Specific Strength - 1x
- Manufacturability - 2x
- Safety Hazards - 3x
- Robustness - 1.5x

Each alternative is then given a score from -2 to 2, which corresponds to a 1-5 point scale normalized such that average is zero. For this category of alternatives, -2 corresponds to "severe concerns" while 2 corresponds to "extremely favorable." A "feasibility index" is generated as the weighted sum of all scores. Alternatives with positive and negative scores are considered “feasible” and “infeasible” respectively, while alternatives falling within +/-10% of zero are “possibly feasible.”

Table 3.3: Feasibility study for airframe material selection

Material Choices	Cost	Specific Strength	Ease of Manufacture	Safety Hazards	Robustness	Total (-19 to 19)
Fiberglass	0	2	0	-1	2	2
Cardboard	2	-1	-1	0	-2	-1
Carbon Fiber	-2	2	1	-1	2	0
Phenolic	1	1	2	0	-2	2

Of all the alternatives considered, cardboard and carbon fiber are considered possibly feasible. Cardboard is ranked low largely due to low robustness and manufacturability. Carbon fiber is ranked low largely due to the cost of the material and material safety hazards. Fiberglass and phenolic have the same feasibility score, but due to launch conditions for our test launches, Fiberglass is the top choice.

3.3.1.1. Fiberglass

Fiberglass is a composite material made using glass fibers and epoxy resin. Typically, fiberglass tubes used in rocketry are manufactured via filament winding, while fins and internal components are made from laminated G10/FR4 plate. [8] Downsides of the material are that it may delaminate when cut, it produces dust when abrasively machined that may be a respiratory hazard, and it is not as cheap as cardboard. Fiberglass is strong enough to survive forces of flight, is commonly used in amateur rocketry, readily available, light, and is relatively easy to machine.

3.3.1.2. Cardboard

Cardboard is a manufactured material made of fibers from trees and plants More specifically, cardboard tubes commonly used for airframes are made from spiral-wound kraft paper [39]. Amateur rocketry grade cardboard is lightweight and inexpensive. However, it is heavily susceptible to water damage. Due to low toughness and other material properties, cardboard can be difficult to machine, especially to high tolerances. This increases the complexity and risks associated with making airframe modifications for payload design alternatives, which include

3.3.1.3. Carbon Fiber

Carbon fiber is the colloquial name for a carbon-fiber-reinforced polymer made from very rigid chains of bonded carbon impregnated with resin and left to cure into a solid material [9]. The fibers are extremely stiff, long, and light. A carbon fiber airframe exceeds our performance requirements with a very high strength-to-weight ratio. However, the material is prohibitively expensive for Rose Rocketry's allotted budget and we will not be using it for the competition airframe.

3.3.1.4. Phenolic

Phenolics are a class of materials consisting of phenolic resin impregnating materials such as cloth, paper, or glass-based fabric. Phenolic is cheaper than fiberglass and carbon fiber composites at the cost of reduced strength and increased brittleness. It provides greater strength than cardboard and is not vulnerable to water damage. However, most vehicle launches and testing occur in winter months where, in Indiana and surrounding states, cold temperatures can cause phenolics to fail during flight or landing . This has been confirmed by team experience.

3.3.2. Vehicle Stack Layout

Vehicle Stack Layout is defined as the arrangement of sections and components of the vehicle. This includes points of separation in the airframe and the locations of deployment charges, payload, avionics bay, and recovery hardware. The layout of the vehicle will be evaluated by the following standards:

- Reliability
- Manufacturability
- Payload flexibility
- Minimum required vehicle length
- Recovery robustness

Design alternatives for the layout are summarized with pros and cons in the below chart. Table 3.4 evaluates which designs are feasible. Following the feasibility decisions are detailed descriptions of each alternative presenting research on the designs and discussing pros, cons, and feasibility data.

Dual-separation with central avionic is the leading design alternative, with the primary consideration being recovery deployment reliability. A complete leading design overview is provided in section 3.3.2.1.

Table 3.4: Pros and cons for vehicle stack layout alternative designs

Layout Choices	Pros	Cons
1. Dual separation with central avionics	• Central electronics location means fewer altimeters and short wiring • Efficient use of airframe space • Motor ejection may be used as backup for vehicle separation • Forward payload has positive impact on stability	• Payload restricted to nose cone section • Requires high fineness ratio
2. Single separation with "chute cannon"	• Single point of airframe separation gives better vehicle rigidity • Avbay separates from only one side, allowing for easy relocation of the payload • Deployment charges may be ground-tested in their flight configuration	• Wasted packing volume for parachute due to internal tube • More complex to manufacture
3. Single separation with cable cutter	• Single point of airframe separation gives better vehicle rigidity • Avbay separates from only one side, allowing for easy relocation of the payload • Efficient use of vehicle space	• Increased risk of entanglement with cable cutter activation wires • Parachute unfurling is difficult to effectively test
4. Central avionics with aft payload	• Central electronics location means fewer altimeters and shorter wires • Efficient use of airframe	• Requires high fineness ratio • Motor ejection charge not available as secondary backup

	space - Payload not restricted to nose section	
5. Parachutes from separate locations	- Better flexibility in payload location	- Requires long deployment wires or multiple sets of altimeters - Requires high fineness ratio

In order to study the feasibility of each alternative, the following aspects are considered. Each is listed with a relative importance ratio:

- Manufacturability - 1x
- Recovery Deployment Safety - 2x
- Robustness - 2x
- Payload flexibility - 1x

Each alternative is then given a score from -2 to 2, which corresponds to a 1-5 point scale normalized such that average is zero. For this category of alternatives, -2 corresponds to “severe concerns” while 2 corresponds to “extremely favorable.” A “feasibility index” is generated as the weighted sum of all scores. Alternatives with positive and negative scores are considered “feasible” and “infeasible” respectively, while alternatives falling within +/-10% of zero are “possibly feasible.”

Table 3.5: Feasibility study for Vehicle Stack Layout

Stack Layout Alternative	Manufacturability	Recovery Deployment Safety	Robustness	Payload Flexibility	Total (-12 to 12)
1	2	2	0	0	6
2	-1	-1	1	1	0
3	-1	-2	1	1	-2
4	2	0	0	1	3
5	1	2	0	1	6

The dual separation with central avionics and the parachutes from separate sections layouts scored the highest feasibility rating. This is largely due to the recovery deployment safety - both designs include the ejection charge of the motor as a tertiary backup for drogue parachute deployment. This factor was a big differentiator in these designs. The single separation with cable cutter layout was determined to be infeasible, largely due to the risky recovery deployment system. The chute cannon layout is considered possibly feasible. The choice of design is the dual separation with central avionics layout.

Below elaborations on design alternatives possess diagrams of the stack layout. All diagrams of vehicle stack layouts were created using OpenRocket, a popular and free design and simulation software for model rocketry. OpenRocket calculates significant data useful for vehicle design, such as the center of mass, center of pressure, stability, projected apogee, and other information. OpenRocket uses the Runge-Kutta 4 simulation method using 6 degrees of freedom. The Runge-Kutta 4 method utilizes differential equations similar to Euler's method, except sampling 4 points for a closer approximation [36]. OpenRocket will be discussed further in the Performance Predictions section.

3.3.2.1. Dual separation with central avionics

In conventional hobby dual-deployment high-power rockets, the vehicle is stacked with the drogue parachute located directly above the motor, a central avionics bay located above the drogue parachute, and a main parachute located above the avionics bay. In this configuration, payload and any additional components such as trackers are located above the main parachute. A schematic of this configuration is below, with major internal components, energetic devices, and points of separation labeled.

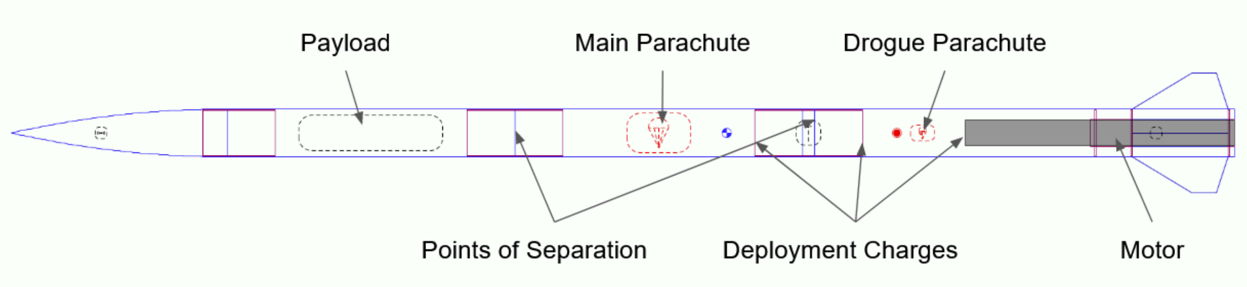


Figure 3.2: OpenRocket diagram of dual separation with central avionics

The primary advantage of this layout is that the drogue parachute is placed directly above the motor. On motors of K class and lower, this means that the motor's internal ejection charge allows for a third means of backup deployment for the drogue parachute, the first two being located within the avbay. In the case of a dual altimeter failure or incorrect flight procedure leading to complete failure of electronic deployment, the drogue parachute will still be deployed. In past recovery failures, our team has found that impact with no parachutes will lead to complete destruction of the vehicle. Emergency deployment of a drogue parachute, while not guaranteeing a safe descent speed, is sufficient to preserve the structure of the airframe. For this reason, we consider this to be a significant factor in the reliability of the vehicle.

3.3.2.2. Single Separation with Chute Cannon

Many high-performance rockets use a "chute cannon" architecture for parachute deployment [7]. In this design, the main parachute is located inside the drogue parachute bay, with a single structural point of separation for both deployments. Inside the tube is a structural bulkhead that restricts the main parachute from deployment until a second set of deployment charges is fired. A schematic of this layout is below.

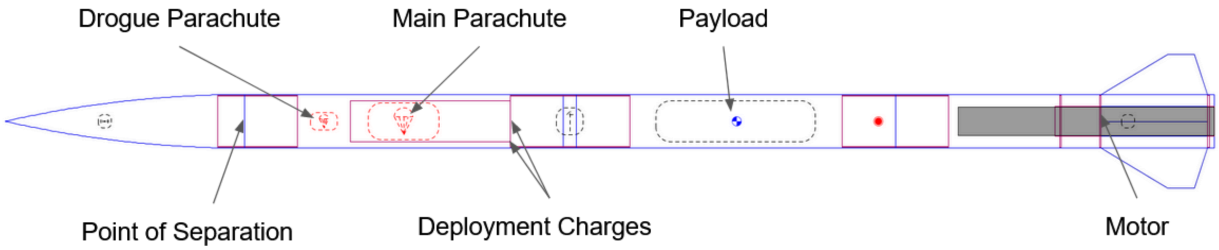


Figure 3.3: OpenRocket diagram of single separation with chute cannon

This layout saves space in the rocket as there is one body tube for the drogue and main parachutes. More importantly, it can improve the structure of the rocket because there is only one point of separation. This also allows for more flexibility in the positioning of the payload. These advantages are important for rockets designed for maximum altitude. However, this is not a significant advantage for this launch vehicle, which does not need to conserve space to reach the target apogee. In addition to this, the stack layout is more difficult to design and manufacture than alternatives due to the nested deployment.

3.3.2.3. Single Separation with Cable Cutter

The single separation with cable cutter design uses one point of separation like the chute cannon layout, but it uses one parachute to act as the drogue and main parachute. [11] A shearable cable is tightened around the bundled parachute so when the parachute deploys it effectively acts as a drogue parachute. Then, the cable is sheared at the desired altitude for main parachute deployment, thereby releasing the full parachute. A schematic of this design is below.

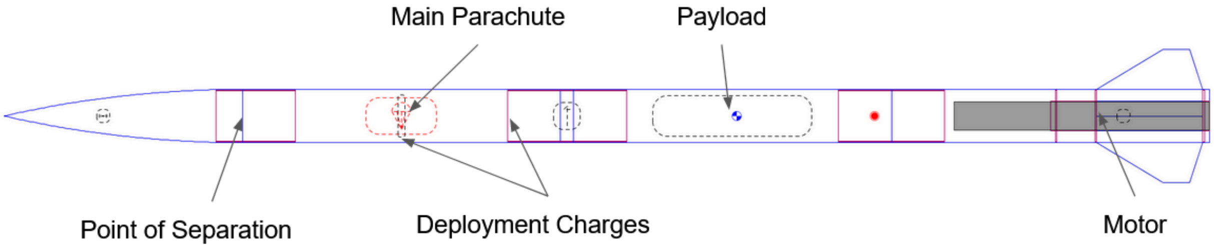


Figure 3.4: OpenRocket diagram of single separation with cable cutter

This design saves space similarly to the chute-cannon layout and leaves our payload location flexible. However, like the chute cannon layout, it is more difficult to design and build when the vehicle does not require this space saving to reach target apogee. Also, there is higher risk for entanglement between the shear mechanism wires and the parachute tether. Since tangling on main parachute deployment has been a cause of flight failure in past team projects, this was deemed an unacceptable added risk.

3.3.2.4. Traditional Layout with Aft Payload

The central-avionics-bay layout from Section 3.3.2.1 may also be modified to locate the avionics bay between the main parachute and drogue parachute sections of the vehicle in the diagram below. In this case, motor ejection is not a factor in parachute location, so main and drogue parachutes may be located in either orientation relative to the avionics bay. A schematic of this layout is below:

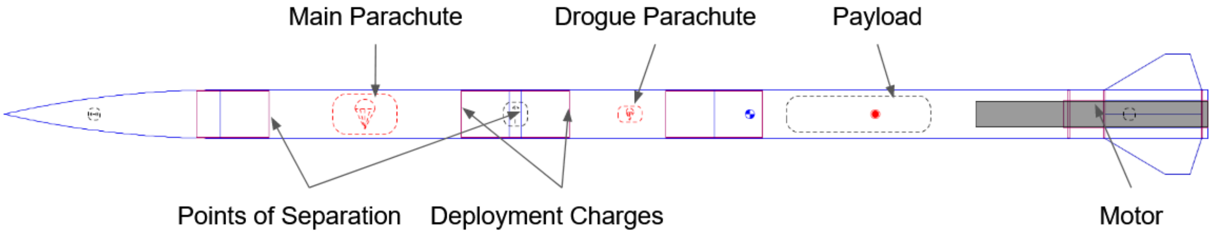


Figure 3.5: OpenRocket diagram of the traditional layout with aft payload

This layout allows for payloads to be located in the aft section of the rocket without the wasted space of a chute cannon or reliability issues of a cable cutter; this has been a critical feature in past projects involving aerodynamic surfaces, since including such payloads further forward would adversely affect stability of the vehicle. This particular payload location would allow the fins to act as stabilizers for the payload system post-landing, which are discussed in section 6.3.1 . However, this layout prevents the motor ejection charge from being used as a third backup, which the team does not consider to be worth the improvement in payload landing stability.

3.3.2.5. Parachutes from separate locations

Another option is for the avionics bay to be split into two halves, with the payload located between the two ends. This could be accomplished by either routing wires through the payload or by keeping two separate sets of avionics, one located at each end. In this configuration, the drogue parachute would be located in the lower half to allow for motor ejection as an emergency backup as in 3.3.2.1. A schematic of one possible configuration is below.

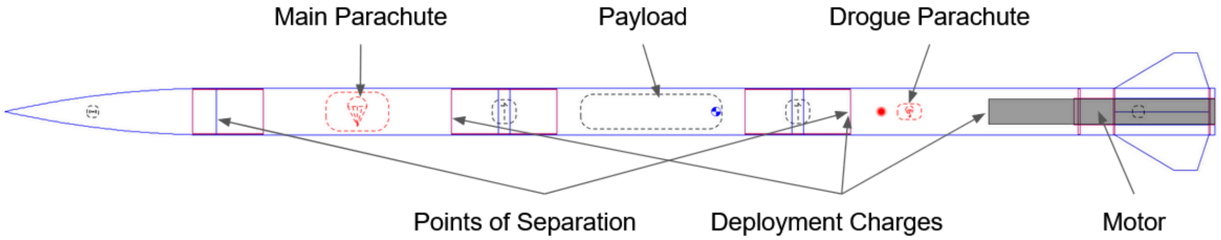


Figure 3.6: OpenRocket diagram of parachutes from separate locations

This option allows for the payload to be located centrally without losing the option of motor deployment in a full power-off failure. However, it lacks the advantages of other low-mounted-payload options. The fins cannot be used to stabilize the payload on the ground, as the booster section is separated to deploy the parachute. It also presents a significant obstacle for the avionics bay layout, since the altimeter wires must be passed through the payload section. If multiple sets of electronics are used, launch procedures are significantly complicated, increasing the risk of a preparation error. In either scenario we decided the central payload location was not worth the added design risks.

3.3.3. Airframe Construction Technique

When deciding an airframe construction technique, the team heavily prioritized the complexity and manufacturability of designs. Additional concerns were strength and usable internal volume. A summary of airframe construction techniques and their high-level “pros” and “cons” are listed in the table below.

The leading design for airframe construction technique is the cylindrical monocoque airframe with the primary consideration of maximizing usable volume and strength when undamage. A more detailed description is included in 3.3.3.1.

Table 3.6: Pros and cons for airframe construction technique alternatives

Design	Pros	Cons
Cylindrical Monocoque Airframe	• Maximizes internal usable volume • Strong when undamaged	• Integrity compromised from slight damage • Requires greater thickness to resist deformation under loads
Cylindrical Semi-Monocoque Airframe	• Strong • Light	• Requires custom supports
Cylindrical Sandwich Aerostructure	• Strong against out of plane loads • High specific strength	• Requires multiple materials • Very complex construction • Much more complex airframe assembly than all other options

Given the airframe construction techniques described above, a feasibility study was conducted to help determine which design best meets the mission requirements and maximizes team resources. The following criteria and weights were considered:

- Cost - 2x
- Manufacturability - 2x
- Payload Volume - 1x
- Robustness - 1.5x

Table 3.7: Feasibility study for airframe material selection

Material Choices	Cost	Ease of Manufacture	Payload Volume	Robustness	Total (-13 to 13)
Cylindrical Monocoque	1	2	2	1	9.5
Cylindrical Semi-Monocoque	0	1	1	2	7
Cylindrical Sandwich Aerostructure	-2	-1	2	2	-1

3.3.3.1. Cylindrical Monocoque Airframe

In this design, the skin of the airframe is used as the structure, making up both the surface and load-bearing portions of the vehicle. This is how the team's vehicle is designed and is conventionally used for vehicle design at this scale. Additionally, the materials required to build a cylindrical monocoque airframe are readily available from multiple manufacturers and at a reasonable cost. This design provides the maximum usable interior space for a low drag area and is strong, at the cost of slightly thicker walls than its semi-monocoque counterpart. To compensate for this, true monocoque airframes have thicker walls than semi-monocoque airframes, making them slightly heavier. Despite these drawbacks, the team decided given the availability of the material, high internal volume, and strength it will be used on the launch vehicle. [16]

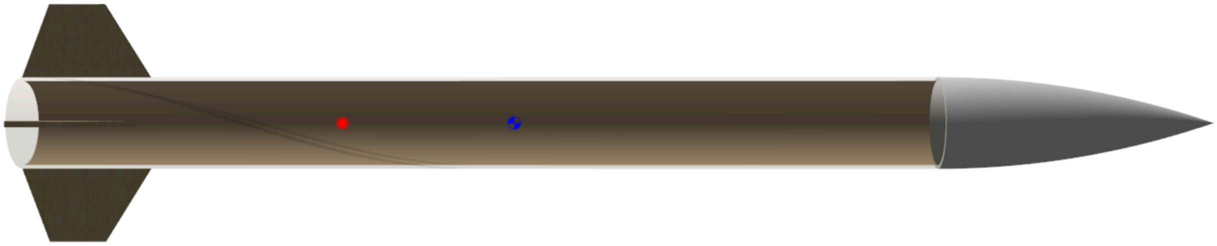


Figure 3.7: Example of a cylindrical monocoque airframe

3.3.3.2. Cylindrical Semi-Monocoque Airframe

A semi-monocoque airframe is similar to a monocoque airframe, except that some additional stiffening members are used which are not part of the aerodynamic body. This design is sufficiently strong while still being lightweight due to the decreased thickness of the airframe walls. However, the supporting members which make this design strong also increase the complexity of the design, manufacture, and assembly of the airframe. Additionally, the supporting members reduce the internal usable volume of the airframe. Due to the reduced usable volume and increased complexity we have decided not to use a semi-monocoque airframe. [16]

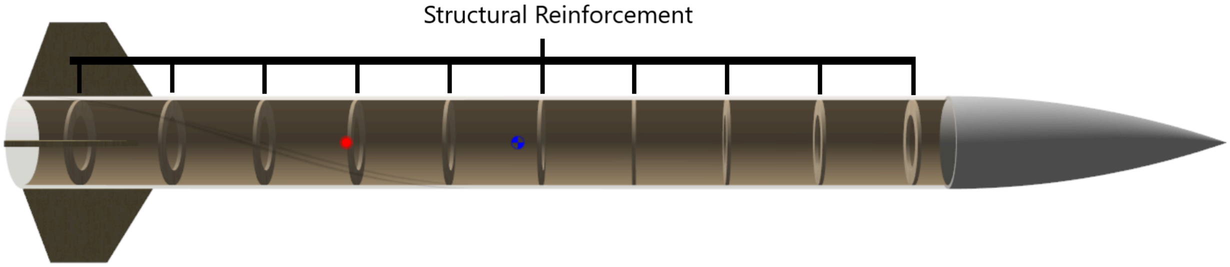


Figure 3.8: Example of a cylindrical semi-monocoque airframe

3.3.3.3. Cylindrical Sandwich Aerostructure

A sandwich structure is a type of macroscale layered composite. Sandwich structures consist of two layers of thin structural material which are adhered to opposite faces of a thicker sheet of material with low density but high specific stiffness, as shown in the figure below. This setup creates high strength and stiffness for low mass through efficient use of structural reinforcement, and depending on the low-density core material selected may be extremely robust against damage. [17] However, both core materials and face sheets are difficult to design, difficult to fabricate, and may be expensive to work with depending on the final design chosen. [17] In order to achieve a proper sandwich aerostructure, complex fabrication methods such as autoclaves, bladder molds, and vacuum bags must be used, which are currently outside the capabilities of our team.

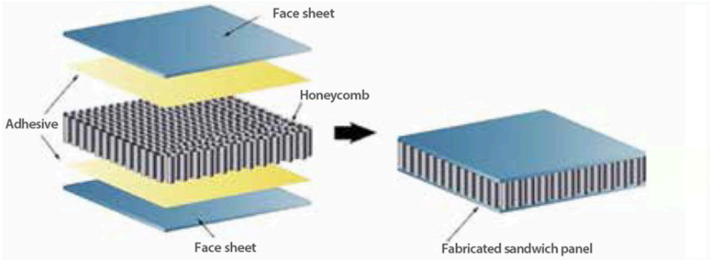


Figure 3.9: Example of a Sandwich Structure [42]

3.4. Aerodynamics

The aerodynamic design of the rocket will ensure the rocket may reach desired apogee with suitable stability and durability. The hardware decisions mainly entail the fin design and nose cone design, as the vehicle stack layout and construction technique has already been decided. There are two sections of design within aerodynamics: the fin design and the nose cone design. Within each section, alternative design choices are summarized with pros and cons. Then, feasibility charts compute how feasible design choices will be. After the charts, detailed descriptions of each design alternative will present research and include discussion of pros, cons, and feasibility.

3.4.1. Fin Design

Fin design most heavily impacts the stability and the speed of the rocket. Fins provide more surface area at the bottom of the launch vehicle in order to move the center of pressure to the aft of the vehicle. Moving the center of pressure further aft from the center of gravity improves the stability. The fins also impact the speed of the vehicle by generating air drag from the leading edge as well as the faces of the fin. Fins will be evaluated using the following criteria:

- Aerodynamic efficiency
- Robustness
- Use of material

The leading fin design is trapezoidal fins, with the primary considerations being the durability and team experience. More detail is included in 3.4.1.1.

Table 3.8: Pros and cons of alternative fin designs

Fin Designs	Pros	Cons
Trapezoidal	• Easy to manufacture • Strong and not prone to damage	• Lower aerodynamic efficiency
Elliptical	• Best aerodynamic efficiency • Strong and not prone to damage	• Need bigger fins for stability • No experience
Rectangular	• Easiest to manufacture	• Low aerodynamic efficiency • Prone to damage on ground contact

Swept	- Improved stability margin	- Prone to damage on ground contact

In order to study the feasibility of each alternative, the following aspects are considered. Each is listed with a relative importance ratio:

- Use of Material - 1x
- Aerodynamic efficiency - 1x
- Robustness - 1.5x

Each alternative is then given a score from -2 to 2, which corresponds to a 1-5 point scale normalized such that average is zero. For this category of alternatives, -2 corresponds to "severe concerns" while 2 corresponds to "extremely favorable." A "feasibility index" is generated as the weighted sum of all scores. Alternatives with positive and negative scores are considered "feasible" and "infeasible" respectively, while alternatives falling within +/-10% of zero are "possibly feasible."

Table 3.9: Feasibility study for Fin Design

Fin Design	Use of Material	Aerodynamic Efficiency	Robustness	Total (-7 to 7)
Trapezoidal	1	1	2	5
Elliptical	-1	1	1	1.5
Rectangular	-1	-2	1	-1.5
Swept	1	2	-2	0

Trapezoidal fins are the most feasible choice and a clear choice for the vehicle, which will be described more in section 3.4.1.1. Rectangular fins were the only option considered infeasible and swept fins are considered possibly feasible. Elliptical fins are also considered feasible, however the feasibility is lower than trapezoidal fins.

3.4.1.1. Trapezoidal

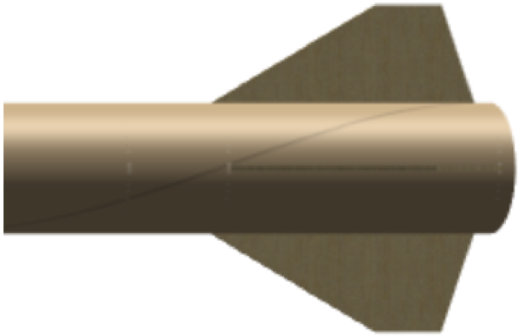


Figure 3.10: Example of trapezoidal fins

Trapezoidal fins possess a smaller tip chord than the root chord in the shape of a trapezoid as pictured in figure 3.10. Through team launch experience, trapezoidal fins have performed reliably on our subscale and full scale launch vehicle from the 2022 NASA SL competition. Trapezoidal fins are very durable because of the trailing edge sweeping towards the fore of the launch vehicle. This mitigates impacts with the ground from being concentrated on the fin and potentially breaking the fin. The main downside to trapezoidal fins is the lower aerodynamic efficiency due to the low surface area compared to other fin options.

3.4.1.2. Elliptical

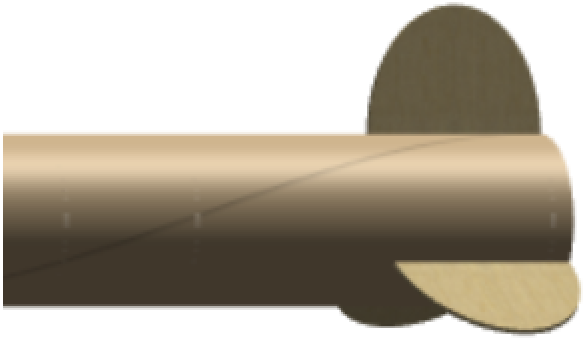


Figure 3.11: Example of elliptical fins

Elliptical fins are theoretically the most aerodynamically efficient fins when calculating air drag using only the leading edge. However, rockets don't fly perfectly straight up, and wind can impact the surface area of the fin experiencing drag [38]. At this scale, the low tip size reduces the ability for the fin to correct the motion of the rocket upward. [12] Elliptical fins would have to be larger to gain the needed stability, which would negate the benefits of the higher efficiency. The team has not utilized elliptical fins in the past, so this design is unfamiliar and untested.

3.4.1.3. Rectangular

Figure 12: Example of rectangular fins

Rectangular fins have a leading edge perpendicular to the airframe, forming a rectangle. The main advantage of rectangle fins is the simplicity of manufacturing the fin. However, The team has access to sufficient fabrication capabilities to construct more complex fin shapes, and simplicity is not a significant advantage. The longer outer tip chord of the fin increases the risk of an impact damaging the fin. Rectangular fins also have low aerodynamic efficiency because the leading edge is perpendicular to the airframe rather than being swept back.

3.4.1.4. Swept

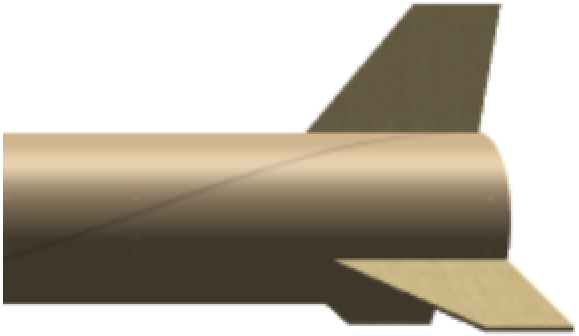


Figure 13: Example of swept fins

Swept fins have a shorter root chord and a substantial sweep on the leading edge, meaning the tip chord extends beyond the aft of the launch vehicle. Swept achieve very good stability for the drag they produce by providing more surface area towards the aft of the vehicle, moving the center of pressure towards the aft. Smaller fins can be used to accomplish the same stability, minimizing drag and maximizing apogee. Though this design has the best stability, it is very prone to damage because the tip chords extending past the airframe are at risk of breaking if the rocket were to land on them - another high possibility, given the aft side of the booster section has the highest weight.

3.4.2. Nose Cone Shape

Nose cones primarily impact the speed of the rocket, although they have some effect on the stability of the rocket due to their weight. The nose cone shape impacts the coefficient of drag for the fore of the vehicle, so a decreased coefficient of drag means higher speed of the vehicle. When the weight of the nose cone is higher, the center of gravity is further upward. This improves the stability of the vehicle, so considering the length of the leading launch vehicle design, heavier nose cones are favorable. Nose cones will be evaluated based on the following criteria:

- Aerodynamic efficiency
- Availability
- Weight

The leading choice for nose cone design is the long ogive shape with primary considerations being the high aerodynamic efficiency and the higher weight. More information is detailed in 3.4.2.1.

Table 3.10: Pros and cons of alternative nose cone shapes

Nose Cone Designs	Pros	Cons
Long ogive	• Easily obtainable • Large space for electronics • Good aerodynamic efficiency	• Heavy
Short ogive	• Easily obtainable • Low weight	• Low internal space
Conical	• Good at supersonic speeds • Simple to model	• Inefficient within this flight regime • Difficult to obtain

		off-the-shelf
Von Karman/other engineered profiles	• Best aerodynamic efficiency	• Hard to obtain

In order to study the feasibility of each alternative, the following aspects are considered. Each is listed with a relative importance ratio:

- Aerodynamic efficiency - 1x
- Availability - 2x
- Weight - 1x

Each alternative is then given a score from -2 to 2, which corresponds to a 1-5 point scale normalized such that average is zero. For this category of alternatives, -2 corresponds to “severe concerns” while 2 corresponds to “extremely favorable.” A “feasibility index” is generated as the weighted sum of all scores. Alternatives with positive and negative scores are considered “feasible” and “infeasible” respectively, while alternatives falling within +/-12.5% of zero are “possibly feasible.”

Table 3.11: Feasibility study for Fin Design

Nose Cone Design	Aerodynamic Efficiency	Availability	Weight	Total (-8 to 8)
Long Ogive	1	2	1	6
Short Ogive	0	1	-1	1
Conical	-1	0	1	0
Engineered Profiles	2	-1	1	1

Of the options considered, long ogive nose cones are the only feasible option. Short ogive nose cones, conical nose cones, and engineered profile nose cones are all possible designs, but the high feasibility of the long ogive design makes it the clear choice for the launch vehicle.

3.4.2.1. Long Ogive

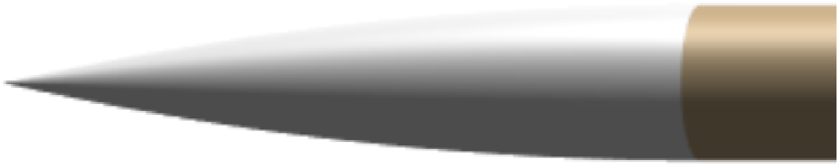


Figure 14: Example of long ogive nose cone

Ogive nose cones are a rotation of the shape created by 2 circular arcs intersecting each other and tangent with the body tube of the air frame. This shape has very good aerodynamic efficiency [13], especially at supersonic speeds. Long ogive nose cones usually have a ratio of length to width of 4:1 or above. This shape of nose cose is very widely available in fiberglass. The downside to this type of nose cone is weight, but for the leading launch vehicle design, higher weight at the fore of the rocket improves stability which is critical due to the length of the vehicle.

3.4.2.2. Short Ogive

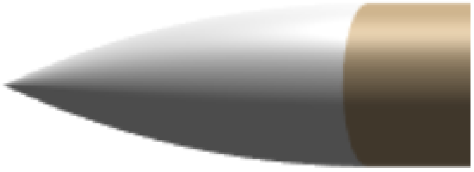


Figure 15: OpenRocket example of short ogive nose cone

Short ogive nose cones are the same shape as long ogive, except the length to diameter ratio is usually 2:1 or 3:1, making them significantly shorter than long ogive nose cones. These nose cones are not as aerodynamically efficient, but they do have significantly lower weight. However, weight to the fore of the rocket increases stability, which means for this vehicle that isn't an advantage. Most importantly, given the architecture selected in Section 3.3.2, this decrease in weight would come at the expense of less volume available for the payload, and so this nose cone design does not align with the goals of our vehicle.

3.4.2.3. Conical

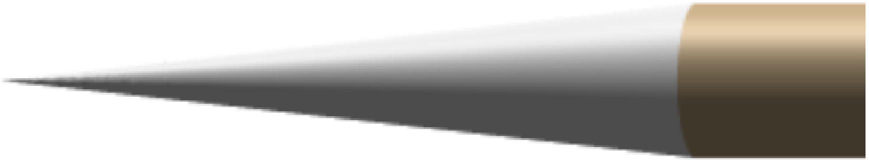


Figure 16: OpenRocket example of conical nose cone

Conical nose cones are very effective at supersonic speeds. For example, the SR-71 Blackbird used many conical shapes to achieve speeds several times the speed of sound [13]. Additionally, they are easy to fabricate due to the simple shape. However, the launch vehicle must remain subsonic, where this shape is much less efficient as the coefficient of drag is much higher [37].

3.4.2.4. Von Karman and other engineered profiles

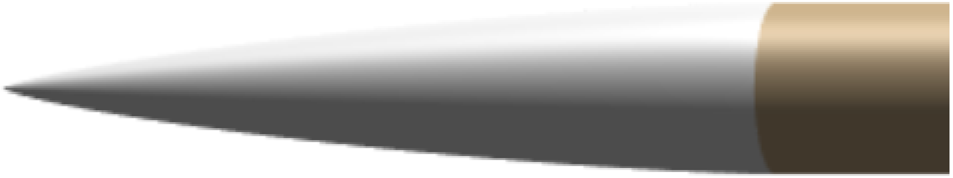


Figure 17: OpenRocket example of Von Karman nose cone

Engineered profiles for nose cones are not defined by standard geometric shapes, but rather by formulas derived to minimize drag. The LD-Haack, or Von Karman design, is a form of the Haack series where the shape parameter is 0 [14]. This design has mathematically the lowest drag of any nose cone option. However, it is very difficult to obtain a nose cone of this shape. Ogive nose cones achieve similar aerodynamic efficiency and are very readily available from fiberglass rocketry component suppliers.

3.5. Motor

The selected launch vehicle motor has the largest impact on the apogee of the vehicle, and expanding motor options is important as the motor can be changed even after the vehicle is fully manufactured, and motors can change in availability from different brands. Several motor options are considered for different predicted payload weights. With the estimated 3lbs of payload weight and 1.5lbs budgeted for other systems such as quick release, 4.5lbs is the current estimate for total payload weight. Motor options were found for 3lbs, 4.5

lbs, and 6lbs in case the payload design becomes lighter or heavier than expected. For each weight, one Aerotech brand motor and one Cesaroni Technology Incorporated motor was considered, in case there are brand-associated issues with motors. All motors utilize 54mm casings in accordance with the leading vehicle design.

Table 3.12: Specifications of alternative motors using our leading vehicle design

Payload Weight (lbs)	Alternate Motors	Total Impulse (N*s)	Burn Time (s)	Velocity Off Rod (ft/s)	Simulated Apogee (ft)
3	K1200WT	2011	1.69	75.6	5128
3	K828FJ	2072	2.83	67.1	5313
4.5	K780BS	2114	2.72	59.1	5007
4.5	K828FJ	2072	2.83	65.4	4937
6	K700W-P	2284	3.3	60.3	5011
6	K820-BS	2384	2.84	62.4	5345

All simulations were run using our leading rocket design using OpenRocket. The launch rod was set to an angle of 5 degrees and a length of 72 inches in order to conservatively judge velocity off the launch rod. The wind was set to 5 mph. The apogee can be lowered by adding ballast, while raising it requires significant engineering work to decrease launch mass. Thus, motors were preferred that were capable of exceeding the target apogee.

3.5.1. Motor Alternate K1200WT

The K1200WT has a more than adequate speed off of the launch rail at 75.4ft/s which is over 20 ft/s more than the required 52 ft/s. In addition, the high speed off the rail means more stability immediately after the vehicle leaves the rail. In other words, the rocket will achieve a very vertical trajectory, which means our achieved apogee will be closer to simulated apogee. The projected apogee is higher than our target, but within the range that ballast could correct for the difference. This is a good alternative for if the fore section of our rocket is more lightweight than expected.

3.5.2. Motor Alternate K828FJ

This motor can work for a wide range of payload weights. At both 3 pounds and 4.5 pounds of payload weight, the launch vehicle is within an acceptable range of the target apogee. The velocity off of the rod is still well over the requirement for both payload weights. Simulated apogee is higher than desirable for a light payload and lower than desirable for a heavy payload, although this can be corrected with ballast or other tweaks to the rocket design. This is a great alternative motor for both a 3 pound and 4.5 pound payload weight.

3.5.3. Motor Alternate K780BS

With the K780BS, we found that the vehicle's velocity off the rod has a 7 feet per second of buffer from the required 52 feet per second velocity off the rod. It also has the advantage of the simulated apogee being the closest to our target apogee. In addition, the team already has the hardware and similar experience to assemble the motor, so no additional parts nor practice is necessary.

3.5.4. Motor Alternate K700W-P

For the 6 pound payload possibility, this motor is an excellent choice. Velocity off the rod is above 60 ft/s which puts it comfortably above the requirement. This motor only fits the target altitude by assuming that the payload mass will be significantly higher than preliminary designs. However, in the case the final design requires increasing payload mass, this motor provides a good alternative.

3.5.5. Motor Alternate K820-BS

The simulated apogee is quite high for this motor. If both the weight of the payload is much higher than expected and additional ballast is added to compensate, this motor will achieve at least our target apogee. It has sufficient velocity off the rod and would function as an alternative at higher payload weight, although this is not expected.

3.6. Leading Design

When selecting from the alternatives presented in sections 3.3-3.5, the primary design considerations were minimizing complexity and maximizing team familiarity/confidence with the chosen architecture. For the airframe material, we chose fiberglass due to relative ease of fabrication, cost, and robustness. The airframe structure is a dual separation with central avionics layout, which allows the ejection charge of the motor to act as a failsafe mechanism for deploying the drogue chute, decreasing the likelihood of a fully uncontrolled descent. We chose a trapezoidal fin shape due to durability, team experience, and adequate aerodynamic performance. A long ogive nose cone shape was selected due to its wide availability, superior aerodynamic efficiency, and additional space available for payload. Finally, we chose the K780 motor, which differentiates itself from other motors with very similar performance because the team has the hardware required to use it on this vehicle and experience flying motors from this manufacturer.

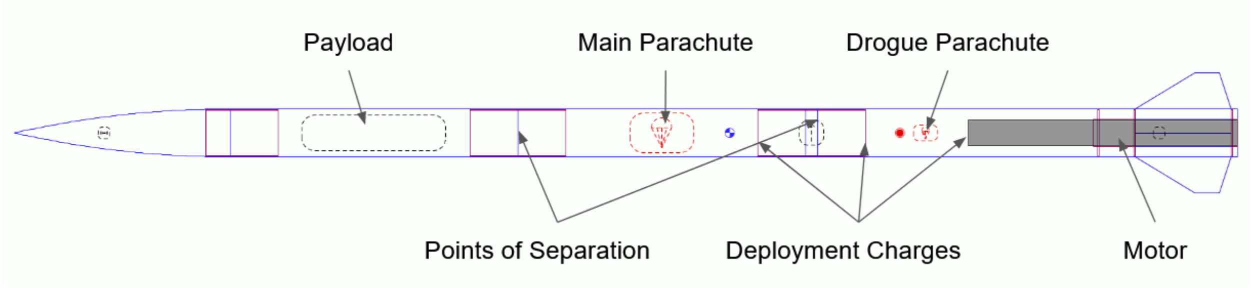


Figure 3.18: The leading vehicle layout

Table 3.13: Summary of Leading Design Choices

Vehicle Characteristic	Choice	Justification
Airframe material	Fiberglass	• Lightweight and durable • Affordable and accessible • Easy to machine
Airframe structure	Dual Separation with Central Avionics	• Backup motor ejection charge to deploy drogue parachute • Easy to manufacture
Airframe Construction	Cylindrical Monocoque Airframe	• Easy to manufacture • Durable • Lots of internal space
Fin Shape	Trapezoidal	• Very strong • Team is experienced with using them • Decent aerodynamic efficiency
Nose Cone Shape	Long Ogive	• Very good aerodynamic efficiency • Readily available
Motor Choice	K780BS	• Very close to target apogee with initial simulations

		- Adequate velocity off of rod - Currently have all motor hardware

4. Recovery Subsystem

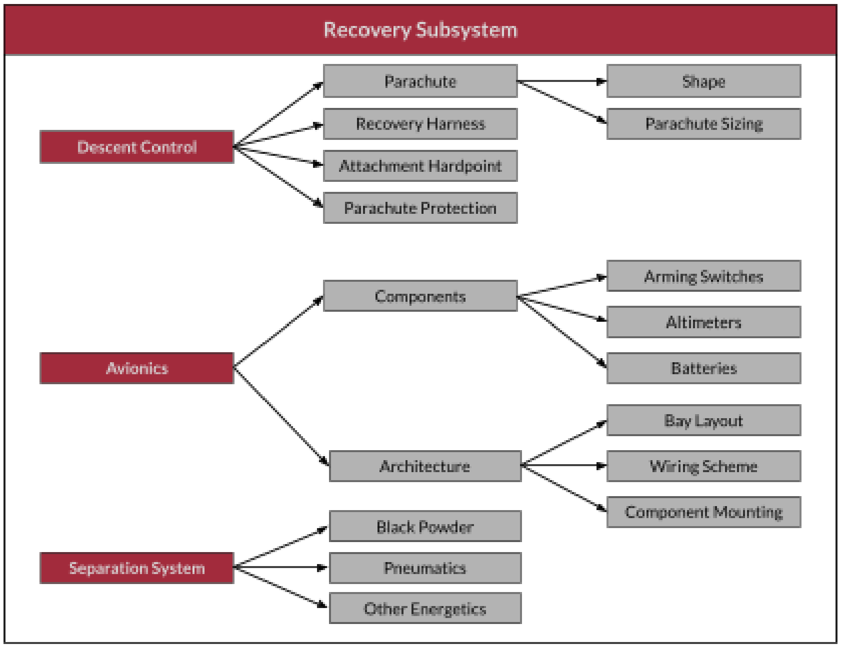


Figure 4.1: System level breakdown of the Recovery system

The recovery subsystem is separated into two categories–the recovery hardware and the avionics bay. Recovery hardware is the actual hardware responsible for controlling the descent of the rocket. This includes our parachutes, recovery harness, attachment point, and parachute protection. The avionics bay is the bay with electronics responsible for initiating separation of the rocket and deploying the recovery hardware. This includes all electrical components such as altimeters and supporting components, and the architecture of the bay in terms of the bay layout and design.

4.1. Descent Control

Table 4.1: Overview of the descent control subsystems

Recovery Component	Section	Objective
Parachute	4.1.1	Slow launch vehicle on descent to minimize damage and recover in reflyable condition
Recovery Harness	4.1.2	Assist in a uniform parachute deployment while connecting additional components

Attachment Hardpoint	4.1.3	Provide a point to securely attach recovery hardware to the vehicle.
Parachute Protection	4.1.4	Prevent damage or destruction to the main and drogue parachute.

4.1.1. Parachute

It is important that the rocket be slowed down before hitting the ground. To that end, a decision was made to have a parachute and drogue on the rocket.

4.1.1.1. Parachute Shape

Several shapes for both the main and drogue chute were considered in the analysis below:

4.1.1.1.1. Main Parachute

Table 4.2: Pros and cons of main parachute shapes

Parachute Design Alternative	Pros	Cons	
Toroidal	• Very stable at low speeds [1] • Very high drag coefficient [1] • Most efficient use of space [1]	• Unstable at high speeds [1] • Most expensive option [1]	✓
Hemispherical	• Stable at medium and low speeds [1] • Medium drag coefficient [1]	• Somewhat unstable at high speeds [1] • Medium cost [1]	
Circle	• Low cost [1]	• Low stability [1]	
X-Form	• Stable at high speed [1]	• Low drag coefficient [1] • Poor performance at low speed [1]	
Streamer	• Lowest cost	• Very fast descent rate [14] • Not suitable for large	

		vehicles [14]	

In order to study the feasibility of each alternative, the following aspects are considered. Each is listed with a relative importance ratio:

- Cost - 1x
- Coefficient of Drag (C_d)- 2x
- Packing Volume - 1x
- Mass - 1x
- Stability - 2x
- Descent Rate - 2x

Each alternative is then given a score from -2 to 2, which corresponds to a 1-5 point scale normalized such that average is zero. For this category of alternatives, -2 corresponds to “severe concerns” while 2 corresponds to “extremely favorable.” A “feasibility index” is generated as the weighted sum of all scores. Alternatives with positive and negative scores are considered “feasible” and “infeasible” respectively, while alternatives falling within +/-10% of zero are “possibly feasible.” Of all considered alternatives for the main parachute, only the X-form was deemed infeasible.

Table 4.3: Feasibility study for main parachute shape

Parachute Shapes	Cost	C_d	Packing Volume	Mass	Stability	Descent rate	Total (-18 to 18)
Toroidal	-2	2	1	1	2	2	12
Hemispherical	-1	1	1	1	1	1	7
Circle	1	0	0	1	1	0	4
X-Form	-1	-1	1	1	1	-2	-3
Streamer	1	-2	2	2	1	-2	-1

4.1.1.1.1.1. Toroidal

A toroidal parachute is a parachute cut from a hollow torus, which is a shape generated by revolving a circle around an axis, similar to the shape of a donut. Toroidal parachutes are decently common as main parachutes in model rocketry, and for good reason. They have the highest coefficient of drag, highest space efficiency, and highest low-speed stability of all of our leading parachute designs. The main drawback to this parachute type is its cost, which is approximately twice as much as a simple hemispherical chute of the same diameter. Due to its excellent performance, our team has elected to use a parachute of this design.

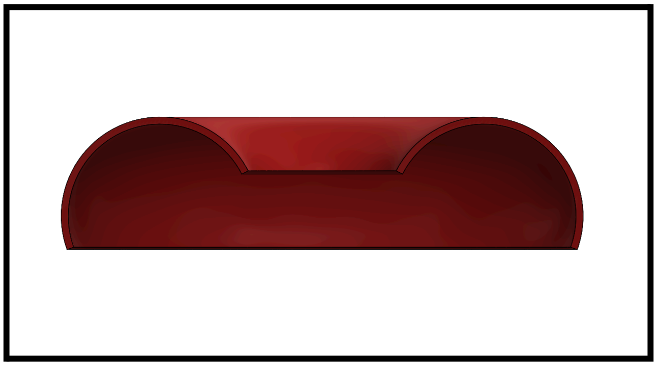


Figure 4.2: Example of the shape of toroidal parachute

4.1.1.1.1.2. Hemispherical

A hemispherical parachute is a parachute cut from half of a hollow sphere. They have been very common in both model and real-scale spaceflight and remain common today. They provide a high amount of drag and are stable at the speeds our vehicle will encounter at main deploy. The main downside to hemispherical chutes for our usage is that they are more expensive than just a flat piece of cloth. While a hemispherical parachute would be a practical choice, the toroidal still has better packing volume, mass, and stability.

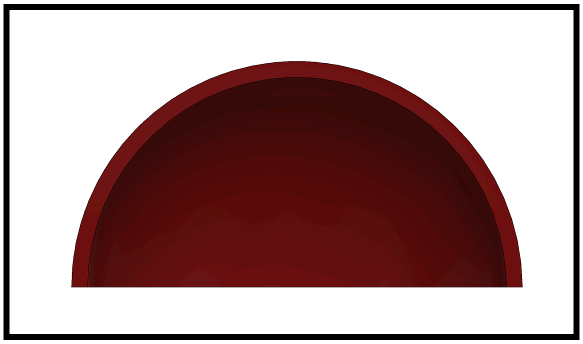


Figure 4.3: Example of the shape of a hemispherical parachute

4.1.1.1.1.3. Circle

A circular chute, also commonly known as a flat-plate chute, is a parachute that is similar to a hemispherical chute, but cut out as a 2D object. They are typically used for low-cost projects. While the cheapest parachute option, they have a low stability and produce less drag than the hemispherical chute. Because of these limitations, we did not choose a circular chute.

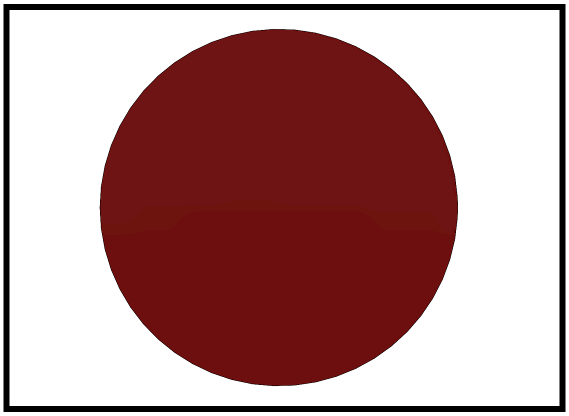


Figure 4.4: Example of the shape of a circular parachute

4.1.1.1.1.4. X-Form

An X-Form parachute, short for cross-form, is a parachute that is shaped like the letter X. They are not the most common parachute, but they are still one of the most popular chutes in rocketry [1]. It is stable at all speeds, however, this type of parachute has the second-lowest drag of all options we considered. Should we have chosen this type of parachute, we would have an excessively heavy and voluminous parachute that would be surpassed by a hemispherical parachute of a smaller size.

Figure 4.5: Example of the shape of a X-form parachute

4.1.1.1.1.5. Streamer

Streamer recovery is a lesser-known form of recovery, as most model kits come with parachutes [14]. It involves using a streamer to stabilize and slow the descent of the vehicle. Streamer recovery is great for small and light rockets, but it suffers from diminishing returns at the fastest rate and the earliest out of all of our considered designs, quickly becoming impractical for vehicles that weigh over an ounce [14]. The planned fin design alone is over 13 times that limit, and as such we have no plans to use streamer recovery.

4.1.1.1.2. Drogue

The drogue parachute design follows the considerations of the main parachute shape, but there is greater emphasis on stability and reliability rather than the exact shape and drag efficiency, as its main purpose is stabilizing the descent and keeping the descent rate just slow enough for the main parachute to deploy safely.

Table 4.4: Pros and cons of drogue parachute shape alternatives

Drogue Design Alternative	Pros	Cons	
Hemispherical	• Stable at medium and low speeds [1] • High drag coefficient [1]	• Somewhat unstable at high speeds [1] • Medium cost [1]	✓
Circular	• Low cost [1]	• Low stability [1]	
X-Form	• Stable at all speeds [1]	• Low drag coefficient [1]	
Streamer	• Very fast descent rate [14] • Helps increase visibility [14] • Very low cost	• High-speed/shock main deployment	
No Drogue	• Not a point of failure • Lowest cost	• Lack of stability • High-speed/shock main deployment	

In order to study the feasibility of each alternative, the following aspects are considered. Each is listed with a relative importance ratio:

- Cost - 1x
- Packing Volume - 1x
- Mass - 1x
- Descent Rate- 2x

Each alternative is then given a score from -2 to 2, which corresponds to a 1-5 point scale normalized such that average is zero. For this category of alternatives, -2 corresponds to “severe concerns” while 2 corresponds to “extremely favorable.” A “feasibility index” is generated as the weighted sum of all scores. Alternatives with positive and negative scores are considered “feasible” and “infeasible” respectively, while alternatives falling within +/-10% of zero are “possibly feasible.”

Table 4.5: Feasibility study for Drogue Parachute shape

Parachute Shape	Cost	Packing Volume	Mass	Descent rate	Total (-10 to 10)
Hemispherical	2	1	1	2	7
Circular	1	1	1	2	6
X-Form	1	1	2	2	7
Streamer	2	2	2	-1	4
No Drogue	2	2	2	-2	2

As depicted in Table 4.5, both the Hemispherical and X-Form parachutes would make the best options, though all options are deemed as feasible, the non-parachute options are significantly below the parachute options.

4.1.1.1.2.1. Hemispherical

As described in 4.1.1.1.1.2, a hemispherical chute is a chute cut from half of a hollow sphere. It is stable at all speeds and the design is readily available. Additionally, hemispherical drogues are sold by a variety of manufacturers, and their drag coefficient is well-known. The team determined that a hemispherical drogue would be the best option, with an X-Form as a backup option.

4.1.1.1.2.2. Circle

As described in section 4.1.1.1.1.3, a circular parachute is a flat plate of cloth or another material shaped like a circle. However, its instability, which often goes up as speed increases [1], makes it a poor choice for a drogue chute.

4.1.1.1.2.3. X-Form

As described in section 4.1.1.1.1.4, an X-Form parachute is shaped roughly like the letter X. It has the lowest drag of all options that use a proper parachute and is stable at high speeds, fitting the role of drogue chute nicely. Additionally, the team already has an X-Form drogue chute on hand, reducing the chance of a failure to acquire a suitable parachute. Should our planned hemispherical drogue not work, this is our backup option.

4.1.1.1.2.4. Streamer

As described in section 4.1.1.1.1.5, streamer recovery is using a streamer to stabilize and slow down a vehicle. While the team quickly dismissed the idea of a streamer for the main chute, we reconsidered it for our drogue device, as it fits the use case much better than it did for the main. However, the main downside of streamers with a vehicle of this size, rapid descent speed, still exists. Such a rate of descent could cause a failure upon main parachute deployment, such as overstressing a part, ripping a cable, or ripping the fuselage. Additionally, should the main parachute fail to deploy, it is possible that a simple streamer would not prevent vehicle destruction in the same way a drogue parachute would. Due to these risks and the multiple flights needed, the team has not chosen to use a streamer for recovery.

4.1.1.1.2.5. No Drogue / Tumble

The last option for a drogue chute is nothing. This is known as tumble recovery, where the vehicle is split into pieces at apogee and tumbles down with no deployment event until the main parachute. While the cheapest and simplest drogue option, the downsides are too great to ignore. Like in streamer recovery, a failure at main parachute deploy from excess forces is more likely and the chances of the vehicle surviving an impact are much worse if the main parachute fails to deploy. An additional risk is that tumble recovery allows for a much larger possibility of entanglement, which could impinge or even prevent main parachute and payload deploy entirely. The team ruled this option as having too much risk for these reasons, and will not use it.

4.1.1.2. Main Parachute Sizing

Our main parachute size is a 60-inch diameter, high coefficient of drag parachute from The Rocketman. This was determined through simulations and a mathematical formula to determine parachute size, and based on the kinetic energy requirements.

4.1.1.3. Kinetic Energy Requirements

The kinetic energy requirements state that no component of the vehicle may exceed 75 ft lbf of kinetic energy on descent, and that bonus points will be awarded to teams that manage to have no section exceed 65 ft lbf of kinetic energy. To ensure that we meet the requirement for the bonus points, we are using 55 ft lbf of kinetic energy as our target energy to base our calculations off of.

4.1.1.3.1. Maximum Descent Velocity

Our maximum descent velocity is based on the kinetic energy of the heaviest component of the launch vehicle, which is 7.75 pounds. Using this information, we can solve for maximum descent velocity using the kinetic energy formula, which results in 21.37ft/s as a maximum descent velocity for the section, and therefore, the maximum descent speed of the launch vehicle.

4.1.1.3.2. Parachute Sizing Equation

An equation about parachute sizing is $D = \sqrt{\frac{8mg}{\pi \rho C_d v^2}}$ [26], where D is the diameter in meters, m is the mass of the rocket in kilograms, g is the acceleration due to gravity in meters per second squared, ρ is the density of air, 1.22 kilograms per cubic meter, C_d is the coefficient of drag of the parachute, and v is the ground impact speed in meters per second. When we convert the figures for the mass of the rocket and maximum descent velocity into the correct units, with our parachute drag coefficient of 2.2, and place all the other constants in, the resulting diameter is 59.8in.

Table 4.6: Pros and cons of different parachutes sizes

Size	Pros	Cons
48in	• Lightest • Smallest • Cheapest	• Exceeds team-derived descent rate maximum
60in	• Closest to calculated size • Reaches descent speed requirements	• More expensive than 48in
72in	• Slowest touchdown velocity	• Longer time to descend • Heaviest option • Costliest

		• Largest

In order to study the feasibility of each alternative, the following aspects are considered. Each is listed with a relative importance ratio:

- Cost - 1x
- Packing Volume - 1x
- Mass - 1x
- Descent Rate - 2x

Each alternative is then given a score from -2 to 2, which corresponds to a 1-5 point scale normalized such that average is zero. For this category of alternatives, -2 corresponds to “severe concerns” while 2 corresponds to “extremely favorable.” A “feasibility index” is generated as the weighted sum of all scores. Alternatives with positive and negative scores are considered “feasible” and “infeasible” respectively, while alternatives falling within +/-10% of zero are “possibly feasible.” All parachute options were deemed feasible with 60 in having the highest score.

Table 4.7: Feasibility study for main parachute size

Parachute Size	Cost	Packing Volume	Mass	Descent rate	Total (-18 to 18)
48in	2	2	2	0	6
60in	1	1	1	2	7
72in	0	-1	1	2	4

4.1.1.3.3. Parachute Selection

This descent rate with this diameter is only achieved under a 2.2 drag coefficient, which is only found on toroidal parachutes. The manufacturer of choice is The Rocketman. Among other sizes, they offer a 48-inch, 60-inch, and 72-inch toroidal parachute, which are the only three options in our size range. The 60-inch parachute is the closest to our required size, and was verified to fit our requirements.

4.1.1.3.4. Size Verification

When putting the above parachute into an OpenRocket simulation of the vehicle, the descent velocity was slightly under the requirement of 21.37 ft/s at 19.95 ft/s. Additionally, for the mass of our rocket, the website of the manufacturer of our parachute gives a similar descent rate for a vehicle within 0.2lbs of ours, verifying our calculations.

4.1.1.3.5. Descent Times

While our parachute selection is based on the kinetic energy requirements for the vehicle on landing, bonus points are awarded if descent time is under 80 seconds. This parachute selection, along with our planned deployment altitude of 600ft, yields a descent time in the 60-second range.

4.1.1.4. Drogue Parachute Sizing

The purpose of a drogue parachute is to stabilize and slow down a vehicle in preparation for deployment of the main parachute.

4.1.1.4.1. Minimum Size

The minimum size of the parachute must be such that it does not exceed the maximum deploy speed of the main parachute. The team determined that this speed is 170ft/s based on previous experience. A parachute that would achieve this speed would be a few inches under 1 ft.

4.1.1.4.2. Maximum Size

The maximum size of a drogue parachute is determined by our desired time to touchdown. Using an OpenRocket simulation of our decided parachute's drag coefficient, our drogue maximum size is 24 in to just barely touch down under 80 seconds.

4.1.1.4.3. Decision

Our decision for the parachute, given these constraints, is a 1ft drogue from The Rocketman, with a drag coefficient of 0.97.

In order to study the feasibility of each alternative, the following aspects are considered. Each is listed with a relative importance ratio:

- Cost - 1x
- Packing Volume - 1x
- Mass - 1x
- Descent Rate- 1x

Each alternative is then given a score from -2 to 2, which corresponds to a 1-5 point scale normalized such that average is zero. For this category of alternatives, -2 corresponds to "severe concerns" while 2 corresponds to "extremely favorable." A "feasibility index" is generated as the weighted sum of all scores. Alternatives with positive and negative scores are considered "feasible" and "infeasible" respectively, while alternatives falling within +/-10% of zero are "possibly feasible."

Table 4.8: Feasibility study for Drogue Parachute size

Parachute Size	Cost	Packing Volume	Mass	Descent rate	Total (-8 to 8)
12in	2	2	2	2	8
24in	1	2	1	2	6

As depicted in Table 4.8, both drogue size options would be feasible, though due to the longer descent and slightly larger mass and form factor, it is less feasible.

4.1.2. Recovery Harness

The recovery harness is in charge of ensuring the vehicles stay tethered while also distributing the force of recovery along its length. We considered several different materials to meet these requirements.

4.9: Pros and cons for recovery harness design alternatives

Recovery Harness Design Alternative	Pros	Cons	
Kevlar	• Very Strong • High thermal resistance • Easy to acquire • Self extinguishing	• Inelastic • Can zipper (rip through) the main body when thrust against it	✓
Nylon	• Elastic • Sufficiently Strong • Easy to acquire	• Poor thermal resistance • Has the potential to snap when thrust against the main body • Weakened by Water	
Spectra	• Strongest Option • Easy to acquire	• Inelastic • Poor thermal resistance • Can zipper (rip through) the main body when thrust against it	

Nylon/Kevlar	- Elastic - Thermally resistant at at risk areas - Very Strong	- Knot adds a critical point of weakness	

4.1.2.1. Kevlar

Kevlar is an exceptionally strong material as it is about 6 times stronger than steel [16]. It is also exceptionally thermal resistant. Kevlar won't melt, and only begins to decompose at around 500 °C [16]. Kevlar is also very easy to acquire as it can be purchased at a multitude of places. Kevlar's primary downside is that it is fairly inelastic so a longer length is required. Kevlar is abrasive enough to zipper a rocket body in nonoptimal conditions, but this is still preferable to snapping which other cabling types will do in similar situations[16]. Due to Kevlar's exceptional strength and durability in the environments a rocket is to be exposed to and its easily negated downsides, it is our primary choice for a recovery harness material.

4.1.2.2. Nylon

Nylon is a competitive alternative but is ultimately too held back by its downsides to be our primary choice. It is significantly more elastic than Kevlar [17]. This gives it the benefit of being more dynamic and excellent shock absorption[18][19]. Nylon is also very easy to work with and like its peers is easy to acquire. On the other hand, nylon has some major downsides. First, nylon is structurally compromised at high temperatures. Heat from separation charges can quickly wear down nylon if it is not protected and sufficient protection can quickly take up valuable space for the rest of the recovery subsystems [18]. Additionally, nylon is water absorbent which reduces its strength by 85-90% when thoroughly exposed [19]. Finally nylon is more likely to completely snap when thrust against a fiberglass main body in non-optimal flight conditions [18]. An event like this would be even worse than zippering and should be avoided if at all possible. Ultimately, while nylon is a viable option for a recovery harness, its environmental weakness holds it back from being a top choice.

4.1.2.3. Spectra

Spectra is an exceptional material that like nylon, fails to escape its downsides.
Spectra is notably the strongest considered option as it is 40% stronger than kevlar [20]. It is also reasonably easy to acquire. Spectra is inelastic which leads to longer length requirements. Spectra also has a weak thermal resistance [22] this leads to the need for

protection against the heat of the blast from charges. Finally, Spectra is durable and abrasive enough to zipper fiberglass rocket bodies but this is still preferable to complete severance of the harness. Ultimately, Spectra is an extremely strong material thats extra strength is not worth the cost of extra weakness.

4.1.2.4. Nylon/Kevlar

Nylon/Kevlar is the method of attaching both a nylon and kevlar cable together, traditionally via a knot, to benefit from the strengths of both materials at the same time. Due to the inclusion of nylon, a nylon/kevlar harness is very elastic [17]. This allows it to withstand greater shocks [19]. A nylon/kevlar harness will be using kevlar in the section of the harness closest to the high temperatures of the separation charges. This allows the harness to take advantage of kevlar's superior thermal resistance [16]. Finally, due to using nylon and especially kevlar, this harness is very strong [16]. The main downside to a nylon/kevlar harness is the intermaterial attachment point. This is typically done via a knot, now an additional point of failure. This factor has a critical impact since nylon/kevlar harness failures almost always occur at the knot [18]. In conclusion, nylon/kevlar harnesses combine the best aspects of both nylon and kevlar but at the cost of an additional notably weak point of failure. Due to this downside, we are not utilizing a nylon/kevlar harness.

4.1.3. Parachute Protection

The intact deployment of parachutes is one of the many things that must go right for a successful mission. As parachutes are being deployed by energetics on our vehicle, they must be protected from excessive heat and force that coil otherwise destroy them, which is what the parachute protector does. The team decided to use a fireproof blanket to serve as parachute protection for both the drogue and main parachutes.

4.10: Pros and cons for recovery harness design alternatives

Parachute Protector Alternative	Pros	Cons
Fireproof Blanket	• Reusable • Already in team inventory • Significant team experience • Harder to lose	• Slightly more expensive than wadding

	- Cheaper for multiple flights	
Wadding	- Lightest option - Cheaper for single flight	- Expendable - Creates litter - More intensive to set up - Complexity scales with area

In order to study the feasibility of each alternative, the following aspects are considered. Each is listed with a relative importance ratio:

- Cost - 0.5x
- Reusability - 2x
- Mass - 1x
- Dirtiness - 1x

Each alternative is then given a score from -2 to 2, which corresponds to a 1-5 point scale normalized such that average is zero. For this category of alternatives, -2 corresponds to “severe concerns” while 2 corresponds to “extremely favorable.” A “feasibility index” is generated as the weighted sum of all scores. Alternatives with positive and negative scores are considered “feasible” and “infeasible” respectively, while alternatives falling within +/-10% of zero are “possibly feasible.”

Table 4.11: Feasibility study for Parachute Protection method

Parachute Shapes	Cost	Mass	Reusability	Dirtiness	Total (-9 to 9)
Fireproof Blanket	2	1	2	2	8
Wadding	0	1	-2	-2	-4

When the size and use case of the launch vehicle was taken into account, only the fireproof blanket was deemed feasible, as it fits the necessary requirement of reusability far better.

4.1.3.1. Fireproof Blanket

Fireproof blankets are blankets that can resist the sudden heat generated from an energetic-initiated separation event. They cover the front end of the parachute when it is packed. Typically, they are attached to the shock cord in front of the parachute, and can be used multiple times. The team already has experience with these blankets on L1 and L2-class vehicles, and has experienced very good reliability from these blankets.

4.1.3.2. Wadding

Wadding is an expendable fire-resistant material, most commonly found on beginner-level model rockets. While it is cheaper for a single flight, it quickly gets expensive when multiple flights, which are required for the test program, are taken into account. It is also more tedious to install and will spread out over the launch field after deployment, especially in larger amounts. Because of the cost, tediousness, and litter potential, this is not a favorable option for the team.

4.1.4. Attachment Hardpoints

Table 4.12: Pros and cons of alternative attachment hardpoints

Attachment Hardpoint Alternative	Pros	Cons	
Eye Bolts in Bulkhead	• More compact than U-Bolt • Relatively Strong	• Can be ripped open • More localized stress on bulkhead	
U-Bolts in Bulkhead	• Most strong • Spreads load on the bulkhead more	• Requires the most space	✓
Epoxy on Airframe	• Most compact • Works well in smaller rockets	• Least strong • Harder to manufacture	

4.1.4.1. Eye Bolts in Bulkhead

Eye bolts are a single bolt with a loop on the head of the bolt. This loop can be manufactured as a bent metal shaft or forged [46]. Eye bolts are readily available and popularly used in model rocketry. However, bent shaft eye bolts can be ripped open by extreme force. Also, eye bolts only have one bolt going into the bulkhead, which means all the forces from the parachute are concentrated on the one bolt. This more concentrated stress could cause damage to the vehicle or recovery failure, which is why we are not using this option.

4.1.4.2. U-Bolts in Bulkhead

U-bolts are bent metal bars with two bolts on one side. These are the sturdiest options for our vehicle [46]. This is because rather than relying on a loop of metal that can come unbent, they are a simple loop with both ends secured to the bulkhead. This eliminates one mode of failure, and in the other mode of failure, it spreads the stress from one bolt to effectively two bolts in the bulkhead. For this reason, the U-bolt is the top choice for our vehicle's hardpoint attachment.

4.1.4.3. Epoxy to Motor Tube

Only to be used for the subscale. This option requires

1. Epoxying a half inch section of a 1-inch wide recovery harness along the inner diameter of a centering ring
2. Passing the recovery harness through a notch made on the centering ring
3. Inserting the centering ring through the airframe so that it fits snug with the inner motor tube
4. Epoxying the other half of the 1-inch wide recovery harness around the motor mount from the aft side of the launch vehicle so there is a secure attachment to the motor tube

Figure 4.6 shows the recovery harness (in black) along the inner wall of the airframe which is run through the notch on the outer edge of the centering ring. The recovery harness is then wrapped around the motor mount once and epoxied for a secure fitting.

The team is using this epoxy method on the subscale vehicle due to space constraints which prevent the use of U-Bolts, because of a wider motor tube proportional to the airframe.

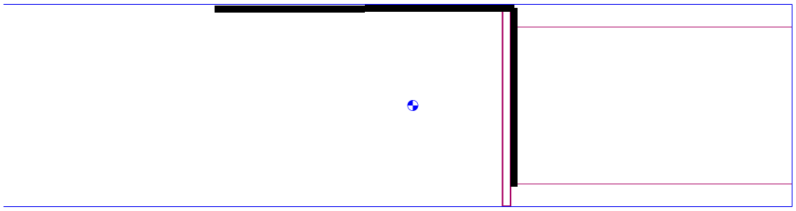


Figure 4.6: Recovery harness to motor mount assembly

The full-scale epoxy work does not require the process used for the subscale since there is quick-link hardware attached to the U-Bolt which is epoxied to the centering ring.

4.2. Avionics

Table 4.13: Overview of avionic subsystems

Recovery Component	Section	Objective
Avionics Bay Layout	4.2.1	Within space constraints, arrange and secure recovery electronics and maximize reliability
Altimeter	4.2.2	Track the altitude of the vehicle so the parachutes can be deployed at target altitudes
Switch	4.2.3	Allow the avionics bay to be turned on or off while vehicle is assembled

4.2.1. Avionics Bay Layout

Table 4.12: Pros and cons of alternative avionics bay layout designs

Alternate Designs	Pros	Cons	
Triangle	• Moderately large effective surface area • Structurally strong • Most accessible surface area	• Low vertical clearance for tall electronics • Center area is difficult to service • Moderately complex • Heaviest design	
One Tray	• Simplest to assemble • All surfaces are accessible	• Lowest total mounting surface area	✓
Two Trays	• Balance of pros from One and Three tray designs	• Balance of cons from One and Three tray designs	
Three Trays	• Largest effective surface area of considered design	• Difficult to service without ability to remove center tray • Greatly added complexity with removable center	

		tray ● Lowest clearance for tall electronics	
Donut Bay	● Saves total rocket length	● Length is not a major constraint to rocket design ● Hard to manufacture ● Increases required rocket diameter	

Table 4.13: Feasibility study for avionics bay layout

Avionics Bay Layout	Mass	Surface Area	Length (Better Smaller)	Serviceability	Total (-9 to 9)
Triangle	-1	2	1	-1	1
One Tray	2	2	-1	2	5
Two Tray	1	1	0	-1	3
Three Tray	-2	2	1	-1	-1
Donut Bay	1	0	-1	-1	-1

4.2.1.1. Triangle

A triangle design for the avionics bay consists of three equal-length trays arranged in an equilateral triangle. The total width for this design is ~2.6 times the diameter of the rocket. The maximum clearance between tray and outer shell is 0.25 times the diameter of the rocket. For the subscale with a diameter of 3 inches, this gives us a width of 7.79 inches and maximum clearance of 0.75 inches. This is a large enough area to put all of our electronics in. The low clearance, however, makes it difficult to service electronics while the sled is still inside the airframe. It is also one of the heaviest options.

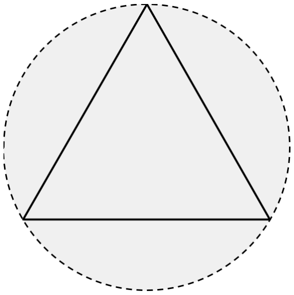


Figure 4.7: Example of a triangle avionics bay layout (as a cross-section of the rocket)

4.2.1.2. One Tray

A one tray design consists of one tray spanning the diameter of the rocket. The total width for this design is equal to the diameter of the rocket. The maximum clearance is half the diameter of the rocket. For the subscale with a diameter of 3 inches, this gives us a width of 3 inches and maximum clearance of 1.5 inches. Although this design provides the least space, we are not currently limited on space for electronics. The high clearance leaves plenty of room for large components and easy service access.

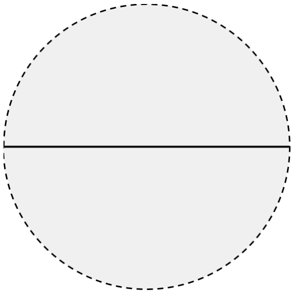


Figure 4.8: Example of a a single tray avionic bay layout

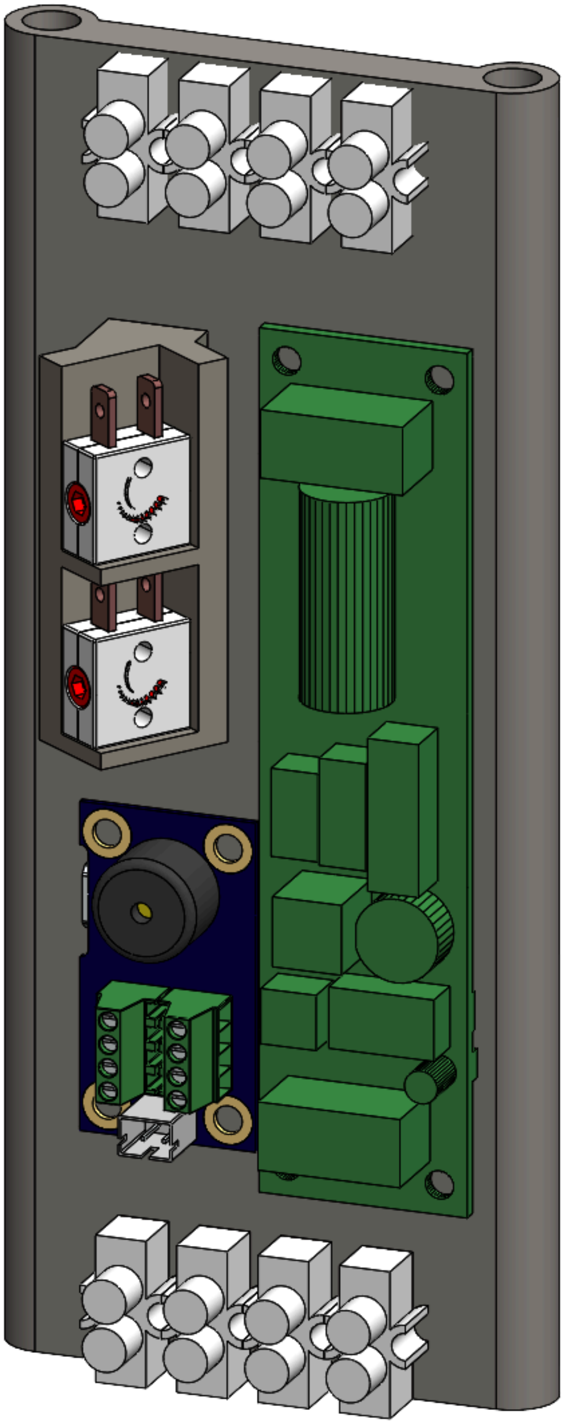


Figure 4.9: A 3D Model of the one-tray avionics sled.

4.2.1.3. Two Trays

A two tray design consists of two equal sized trays spaced equally apart. The total width for this design is ~1.89 times the diameter of the rocket. The maximum clearance between tray and outer shell is 0.33 times the diameter of the rocket. For the subscale with a diameter of 3 inches, this gives us a width of 5.66 inches and maximum clearance of 1 inch. This is a moderate amount of area, however, the space between the two trays is just small enough to be uncomfortable while servicing. Additionally, this clearance issue cannot be mitigated by removing the sled from the airframe, at least one tray needs to be removed for easy access.

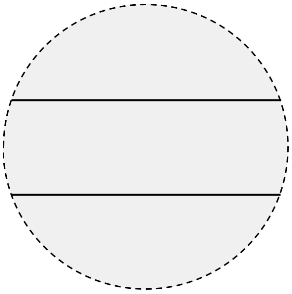


Figure 4.9: Example of a two-tray avionic bay layout

4.2.1.4. Three Trays

A three tray design consists of three equal sized trays spaced equally apart. The total width for this design is ~2.73 times the diameter of the rocket. The maximum clearance between tray and outer shell is 0.25 times the diameter of the rocket. For the subscale with a diameter of 3 inches, this gives us a width of 8.20 inches and maximum clearance of 0.75 inches. This option gives more area than the two tray design, but is much worse in terms of clearance. The space between the outer plates and center plate is only 0.75 inches, barely large enough to get a finger inside. Taking apart the sled would be necessary to service electronics on the center tray.

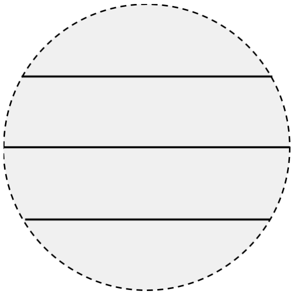


Figure 4.10: Example of a three-tray avionic bay layout

4.2.1.5. Donut Bay

A donut bay consists of a section of the rocket where the electronics are mounted in the same section as the motor (or other component of the rocket that has a large enough clearance between it and the shell). The total width for this design is 3.14 times the diameter of the rocket and the maximum clearance is dependent on the diameter of the component in the section. For the subscale with a diameter of 3 inches and a 54mm motor, this gives us a width of 9.42 inches and a maximum clearance of 0.75 inches. This gives the most area, but has the highest complexity of all designs. There is added difficulty in attempting to mount straight, rigid electronics to a round airframe.

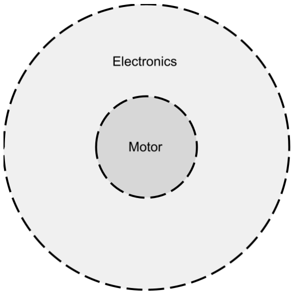


Figure 4.11: Example of a donut bay avionics bay layout

4.2.2. Altimeter

The main considerations for altimeters are COTS, reliability, and dissimilar redundancy.

Table 4.14: Pros and cons of alternative altimeter selection designs

Alternate Designs	Pros	Cons	
Missileworks RRC3 Sport	• Omni Directional • Powerful flight recording	• Inexperience with programing procedure • Do not own the Missileworks LCD Terminal Module • Large	✓
Altus Metrum EasyMini	• Very Small	• Difficult to work with	✓

Eggtimer Quark	Extremely Low Cost Very Small	Requires assembly Low Customizability	

4.2.2.1. Missileworks RRC3

The Missileworks RRC3 Sport is a powerful altimeter. It comes with advanced flight recording of around 7 hours worth of storage [19]. It is also noteworthy that it is omni-directional which will lead to an easier and more organized avionics assembly [19] Compared to other options it is significantly larger at around 100mm L x 20mm W [19]. The team has less experience with this altimeter's programming process. Finally, we have been unable to acquire the LCD terminal module due to supply chain issues. This will mean that programming without a PC will be more difficult. Despite these issues, with accessory modules we still believe that the Missileworks RRC3 Sport is a leading choice.

4.2.2.2. Altus Metrum EasyMini

The Altus Metrum EasyMini is a great altimeter whose strengths and downsides come from its small size. Its dimensions are 38 mm x 20 mm W, it is extremely small and space efficient while not sacrificing on functionality [20]. Past club experience with this product has unfortunately shown that this can sometimes make working with it difficult. Despite this, it is still our other leading choice.

4.2.2.3. Eggtimer Quark

The Eggtimer Quark is a sufficient altimeter that struggles to escape its price range. It costs just $25 [21] which easily places it as the cheapest alternative choice. It is also very small at 1.85" L by 0.75" W [21]. Its biggest downside is that it is a kit that requires assembly. It also comes with limited customizability in regards to main deployment altitudes [22]. We believe its cost is not enough to offset the downsides, especially the assembly factor, so we are not planning on utilizing the Eggtimer Quark.

4.2.3. Switch

Table 4.15: Pros and cons of alternative switches

Alternate Designs	Pros	Cons	

Twist and Tape	• Low chance of permanent damage • Minimal cost • Easily replaceable	• Risk of disconnection in flight • Unintuitive to operate	
Slide switch	• Inexpensive • Easy to operate	• Prone to switching due to shock load	
PCB screw switch	• Moderately easy to operate • Good shock resistance	• Can shake loose in flight • History of failure in past flights	
Tabbed screw switch	• Moderately easy to operate • Very good shock resistance	• Requires specialized tools to actuate	✓

4.2.3.1. Twist and tape

Twist and tape is an extremely basic method of switch design. Its main appeal is that its simplicity reduces its cost and makes it difficult to damage and easy to replace [23] This comes with the moderate risk of disconnection in flight and its unintuitive activation method can lead to longer periods on the pad [23]. Ultimately, twist and tape has too large of a room for error and is feasible enough for our design.

4.2.3.2. Slide switch

Slide switches are a simple switch alternative. They are extremely inexpensive while being quick and easy to operate [24]. Their primary downside is that most available slide switches are not built for the forces of flight. This can lead them to switching themselves due to shock[25]. This risk makes this design not feasible enough for our design.

4.2.3.3. PCB screw switch

PCB screw switches are more resistant at the slight cost of complexity. PCB screw switch's main appeal is that in our experience, it is much more shock resistant. PCB screw switches have a tendency to shake loose in flight and in some cases come loose simply walking a rocket out to the pad [26] We also have a history of this type of screw mechanically failing in past launches. These downsides make this alternative not feasible for our design.

4.2.3.4. Tabbed screw switch

Tabbed screw switches are overall the best option for a switch. They are moderately easy to operate when compared to the other options and our experiences show them to have great shock resistance. Their main downside is that they require specialized tools to operate them, but this is easily negated. Tabbed screw switches are the best due to their minimal and easily negated downsides.

4.3. Separation System

The separation system is concerned with how the section of the rocket separates to deploy parachutes. Common techniques were considered.

Table 4.16: Pros and cons of alternative separation systems

Alternate Designs	Pros	Cons	
Black Powder	• Prior art • Team experience	• Consumable • Sensitive to preparation technique • Hazardous	✓
Pneumatics	• Reusable	• Heavy • More complex	
Non-Black Powder explosives	• Easier to obtain than black powder • Safer	• Unreliable results in rocketry • Greater sensitivity than black powder	

4.3.1. Black Powder

Black Powder charges are the most common method of section separation in hobby rocketry. Charges consist of a premeasured amount of black powder that is then ignited by an e-match when section separation is desired. Black powder charges have been used for rocketry for many years and are therefore well understood. They are also quite light. Due to being explosives, black powder charges can only be used once before needing to be refilled. Black powder also offers prepping hazards and considerations. These include installing charges shortly before launch, packing charges by hand, and storing and handling charges safely.

4.3.2. Pneumatics

Pneumatic separation consists of using compressed gas to provide the motive force for separating sections of the rocket. Cylinders containing compressed gas can be installed onto the rocket ahead of time, unlike explosive charges. The metal cylinders, however, are heavier and more complex than explosive charges. Higher complexity increases the number of points of failure. Pneumatics are not feasible for this design.

4.3.3. Other Energetics

Other energetics are very similar to the black powder equivalent. Compared to black powder, synthetic explosives are easier to obtain. However, these explosives are much less commonly used than black powder, and the odds of mispacking a charge or failure are much greater than with black powder.

4.4. Proof of Redundancy

Our recovery system has dissimilar redundancy in the form of two completely different altimeters wired to two completely separate electrical circuits (4.2.2) connected to separate black powder charges (4.3.1). In the event one altimeter, battery, or wire fails, the flight will return nominally. An additional motor ejection charge deploys the drogue parachute (4.1) in the event of a total avionics failure. The vehicle uses components made from materials well above the factor of safety for the forces expected in the rocket flight including the airframe (3.3.1), recovery harness (4.1.2), and bolt attachments (4.1.4).

5. Performance Predictions

5.1. Summary of Predicted Flight Parameters

Table 5.1: Predicted Flight Parameters

Official Target Competition Launch Altitude	5,000 ft
Landing Kinetic Energies	Payload: 28.75 ft lbf Recovery: 28.64 ft lbf Booster: 43.02 ft lbf
Expected Descent Time	63.9s
Expected Maximum Drift	1934ft

5.1.1. Simulation of Vehicle Flight Profile

5.1.1.1. Simulation Methodology

Flight profile simulations for this mission were performed in the vehicle's default configuration, with a payload mass of 4.5 pounds and a Cesaroni Technology, Inc. K780BS motor. The thrust curve of that motor is included below:

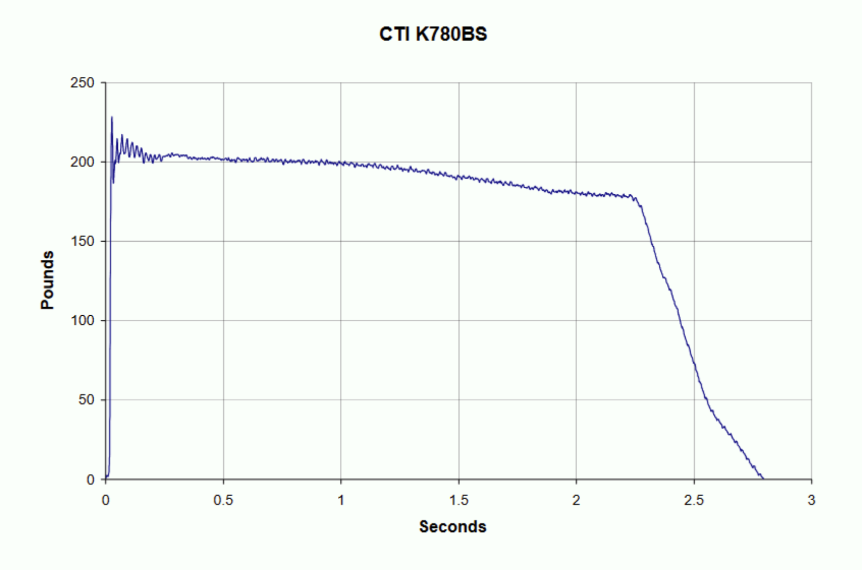


Figure 5.1: Thrust curve for a CTI K780BS

OpenRocket and RASAero were used to simulate the rocket's flight profile. For each piece of software, a primary simulation was conducted at the median rail angle of 7.5 degrees and median allowable wind speed of 10 mph, which was recorded in full. Additionally, 8 further simulations were conducted by varying the launch angle of the rocket by up to 2.5 degrees and wind speed by up to 10 mph to ensure that the vehicle's performance would remain within mission constraints for all possible flight conditions.

5.1.1.2. Simulation using OpenRocket

Primary simulations for this project were performed in OpenRocket. OpenRocket is an open-source rocketry simulation program developed in 2009 by Sampo Niskanen as a graduate thesis project and maintained by a team of volunteers. [9] OpenRocket is the *de facto* standard in hobby rocketry and has proven accurate in thousands of flights throughout the hobby.

The primary simulation for OpenRocket yielded the Figure 5.2, presented as a function of time and as a side profile respectively.

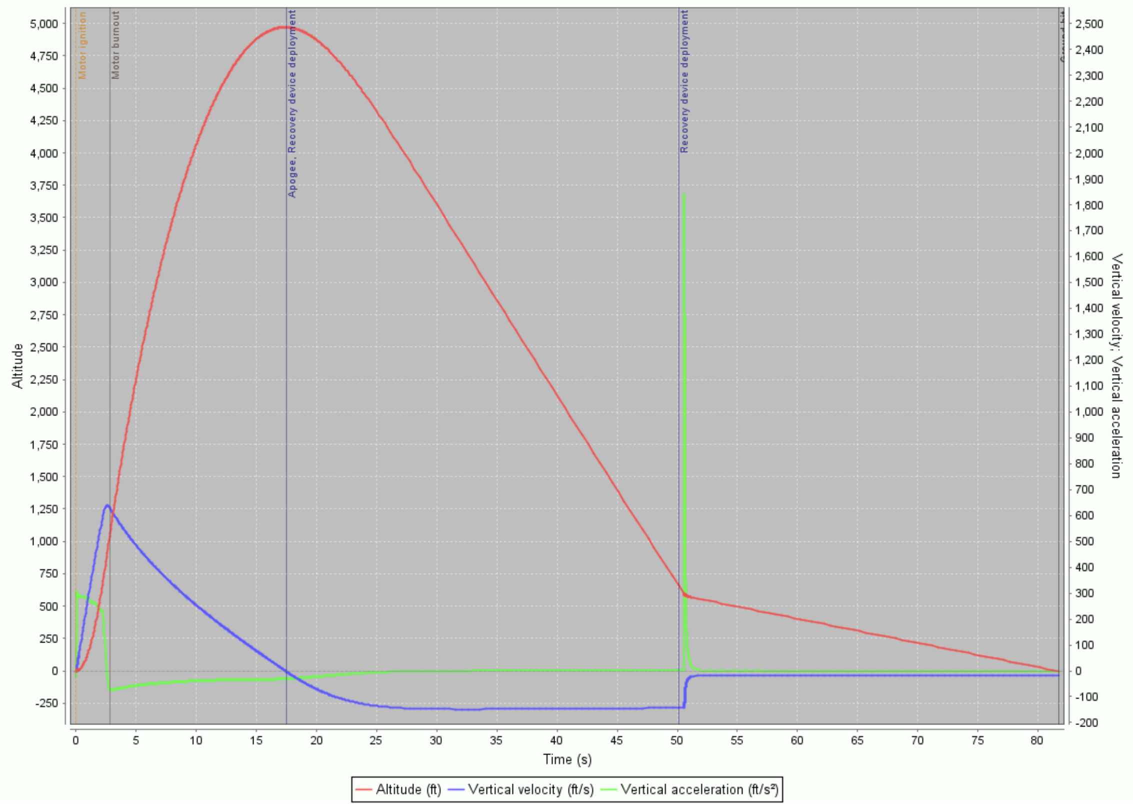


Figure 5.2: Simulation of flight using of OpenRocket

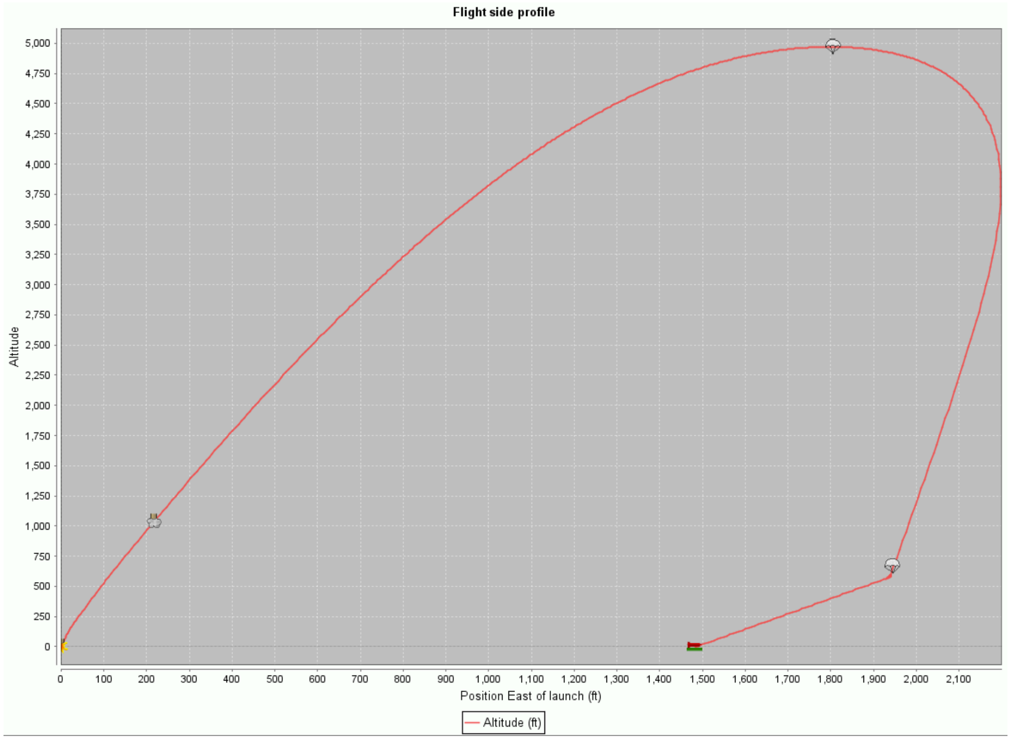


Figure 5.3: Flight side profile with OpenRocket

In this simulation, the vehicle reached a maximum altitude of 4970 ft, which is within OpenRocket's typical margin of error of our target 5000 ft. Additionally, the flight profile graph did not reveal any concerning results; the only note of interest was that due to the relatively high rate of descent under drogue, the vehicle landed upwind of its launch site, as it traveled upwind significantly during upward flight.

Additionally, a series of 8 additional simulations were run such that every combination of wind speeds of 0, 10, and 20 mph and launch angles of 5, 7.5, and 10 degrees were considered. The maximum values of each major flight parameter for each of those simulations are summarized in the table below.

Table 5.2: Flight results of the simulated vehicle at various wind speeds and launch angles using OpenRocket

	Wind Speed		
Launch Angle	0 mph	10 mph	20 mph
5 degrees	Altitude: 5169 ft Velocity: 656 ft/s	Altitude: 5064 ft Velocity: 655 ft/s	Altitude: 4931 ft Velocity: 653 ft/s

	Acceleration: 308 ft/s^2	Acceleration: 309 ft/s^2	Acceleration: 308 ft/s^2
7.5 degrees	Altitude: 5108 ft Velocity: 656 ft/s Acceleration: 309 ft/s^2	Altitude: 4970 ft Velocity: 655 ft/s Acceleration: 309 ft/s^2	Altitude: 4815 ft Velocity: 653 ft/s Acceleration: 309 ft/s^2
10 degrees	Altitude:5024 ft Velocity: 657 ft/s Acceleration: 309 ft/s^2	Altitude: 4857 ft Velocity: 656 ft/s Acceleration: 309 ft/s^2	Altitude: 4681 ft Velocity: 654 ft/s Acceleration: 309 ft/s^2

All altitude results from this simulation were comfortably within the limits set by the NASA Handbook of 4000 to 6000 feet, and the worst result, with an altitude of 4681 feet, yields a scoring deficit of only 8%. This is within the acceptable range for our mission.

5.1.1.3. Simulation using RASAero

Secondary simulations for this project were performed in RASAero. RASAero was developed by Charles Rogers in 2008 to simulate amateur rockets at supersonic speeds. While lacking some of the polish of more consumer-oriented programs, it provides a high degree of customizability and has proven extremely accurate on a number of high-performance flights, with an average error of 3% in predicted altitude across flights ranging from 4000 to 120,000 ft.

RASAero simulations were conducted with the same motor and conditions as the OpenRocket simulations for both the primary and secondary simulation. The results for the primary simulation are displayed in the graph below:

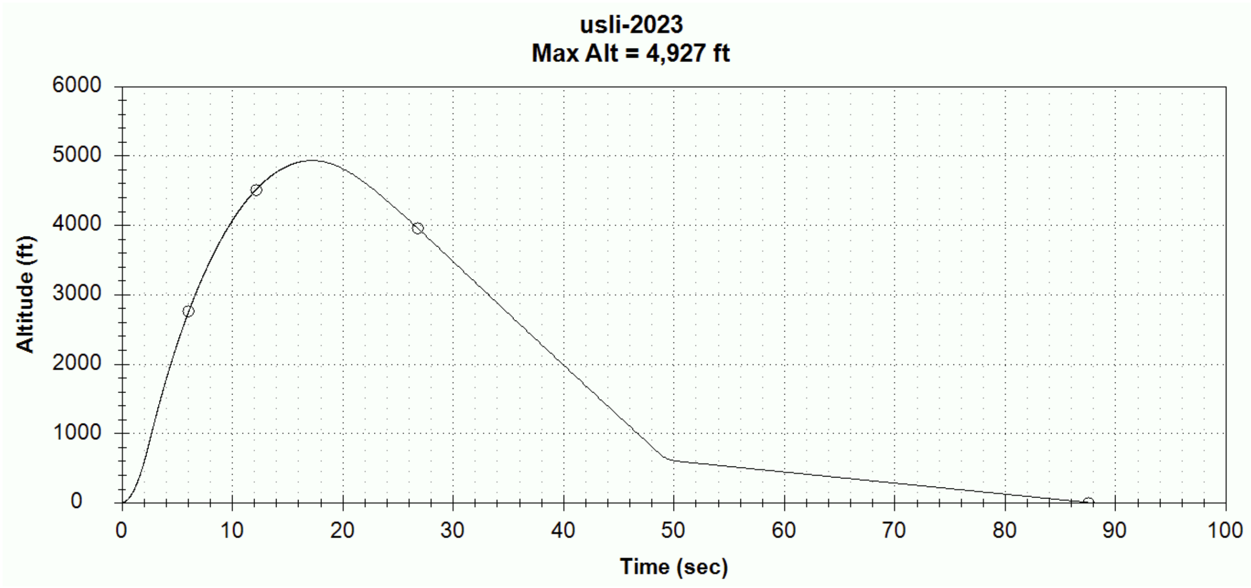


Figure 5.4: Flight profile using RASAero

This result closely agrees with those yielded by OpenRocket, with a discrepancy of only 33 feet in apogee altitude. RASAero does not offer a side-profile graph to compare to the corresponding OpenRocket result, but there were no anomalies in either the graph nor in the numerical data to suggest that any issues would be encountered.

As with OpenRocket, 8 additional simulations were conducted to ensure that the rocket's performance would stay within allowable bounds for all field conditions. The results are presented in the table below:

Table 5.3: Altitudes of the simulated vehicle at various wind speeds and launch angles using OpenRocket

	Wind Speed		
Launch Angle	0 mph	10 mph	20 mph
5 degrees	Altitude: 5117 ft Velocity: 656 ft/s Acceleration: 309 ft/s^2	Altitude: 5064 ft Velocity: 655 ft/s Acceleration: 309 ft/s^2	Altitude: 4820 ft Velocity: 661 ft/s Acceleration: 309 ft/s^2
7.5 degrees	Altitude: 5032 ft Velocity: 656 ft/s Acceleration: 309 ft/s^2	Altitude: 4927 ft Velocity: 659 ft/s Acceleration: 309 ft/s^2	Altitude: 4690 ft Velocity: 663 ft/s Acceleration: 309 ft/s^2

10 degrees	Altitude: 4916 ft Velocity: 657 ft/s Acceleration: 309 ft/s^2	Altitude: 4857 ft Velocity: 656 ft/s Acceleration: 309 ft/s^2	Altitude: 4544 ft Velocity: 665 ft/s Acceleration: 309 ft/s^2

Overall, estimates of altitude are consistently lower than those of OpenRocket, though all are within a reasonable margin of the corresponding OpenRocket results. However, even in the worst case, the score deficit from the lowest altitude of any simulated results in a loss of only 11.4%. This is considered an acceptable worst case with regards to altitude scoring by the team.

5.1.2. Determination of Vehicle Stability

5.1.2.1. Simulation Methodology

As with projected altitude, vehicle stability was determined via both RASAero and OpenRocket. The NASA Handbook requires a margin of stability of at least 2 body diameters between the vehicle's center of mass and center of pressure. Because our vehicle has a length-to-diameter ratio of greater than 20, at 25.5, we additionally impose a stability margin requirement of 10% of the airframe length, or 10.2 inches. [10]

Based on preliminary mass audits of components and estimates of payload mass, the vehicle's center of mass was found via OpenRocket to be located at an aftmost position of 61.7 inches from the tip of the nose cone with all expected payload masses and motor selections; as this calculation is considered to be trivial, this figure was used for both simulation techniques.

Aerodynamic stability ceases to be meaningful at very low airspeeds due to the lack of airflow over the rocket's fins [10]. For this reason, only speeds above 20 m/s were considered for this calculation; as this is less than the 52 ft/s minimum mandated by the NASA Handbook for speed on rail exit, stability below this speed will not significantly affect the vehicle's trajectory.

5.1.2.2. Simulation Results Using OpenRocket

As OpenRocket does not support generating aerodynamic data for arbitrary flight conditions, center of pressure location was instead plotted for the range of velocities encountered during a simulated flight. The results are presented below:

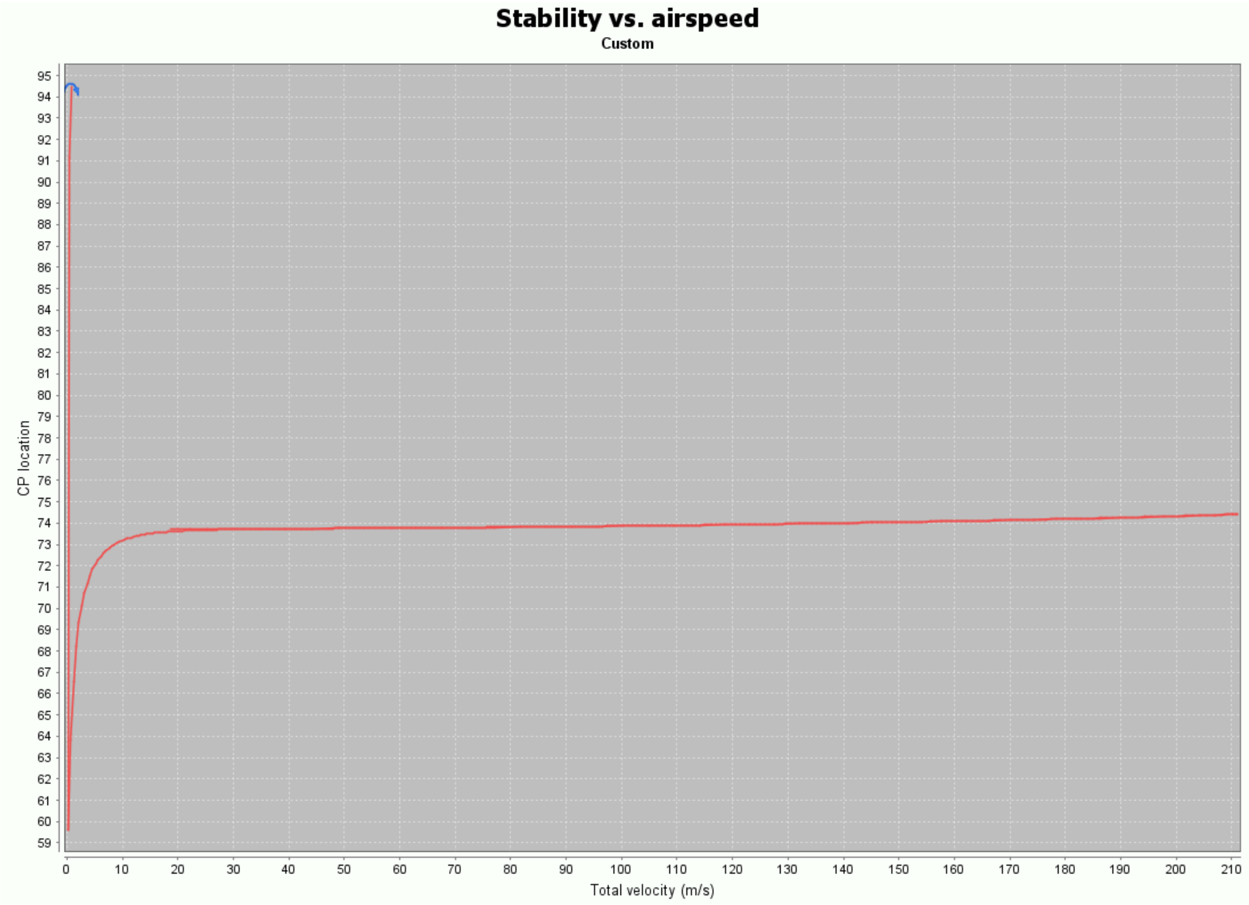


Figure 5.5: OpenRocket Simulation of the CP location based on velocity of the vehicle

Above 20 m/s, the forwardmost position of the center of pressure of the vehicle is 73.5 inches from the nose cone tip. This yields a stability margin of 11.8 inches, equivalent to 2.95 body diameters or 11.6% of the airframe length. This is sufficient to fulfill both the 2-diameter and 10%-of-length requirements for this mission.

5.1.2.3. Simulation Results Using RASAero

To confirm the OpenRocket results, the same design was simulated in RASAero across a wider range from rest to Mach 3, or approximately 1020 m/s, with angles of attack of 0, 2, and 4 degrees. The results are presented below:

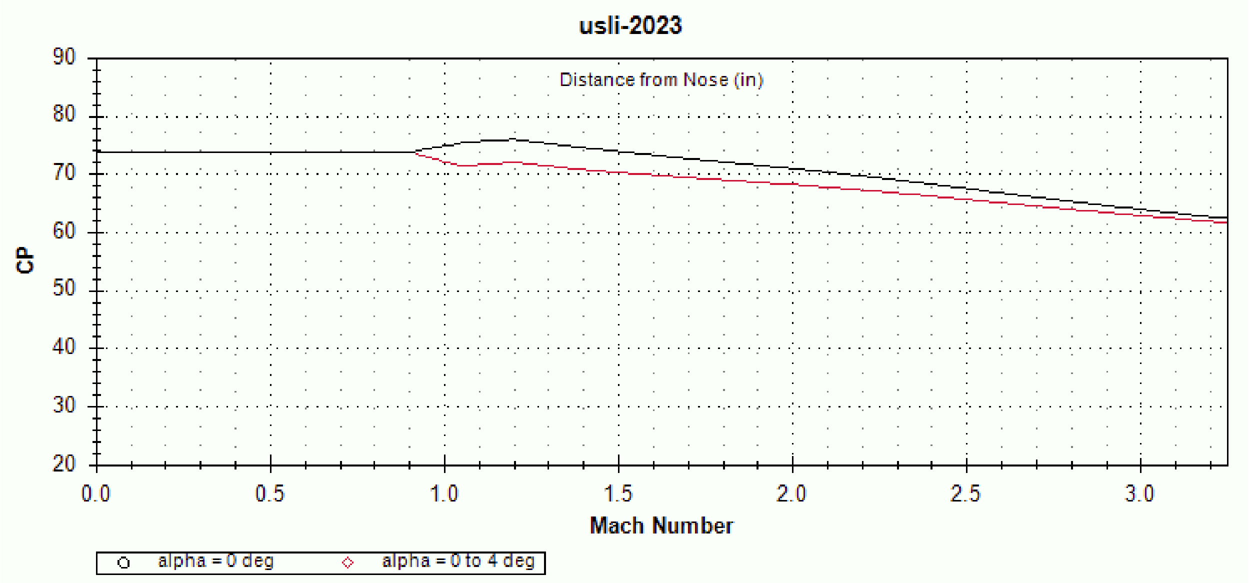


Figure 5.6: RASAero simulation of Figure 5.1

Below Mach 0.9, RASAero predicts a static center of pressure of 74 inches from the nose tip. This yields a static stability margin of 12.3 inches, equivalent to 3.08 body diameters or 11.4% of the airframe length. This is once again sufficient for the mission requirements of 2 body diameters and 10% of the airframe length. Additionally, the stability margin remains above the acceptable minimum of 10.4 inches until just over Mach 1 at 4 degrees of angle of attack or in excess of Mach 1.5 at no angle of attack. Since the vehicle is predicted not to exceed Mach 0.7, this is a strong indication that it will be stable throughout the flight.

5.1.3. Vehicle Robustness

Three main potential points of failure were identified with regards to the airframe's robustness in flight: securement of the motor to the airframe, stiffness of the couplers under aerodynamically-induced torque, and resistance to "flutter", or resonant vibration, of the fins. Each of these concerns are examined in detail in the following paragraphs.

5.1.3.1. Securement of Motor to Airframe

The motor is epoxied to three centering rings which are in turn epoxied to the airframe. The centering rings are made of 1/8th inch fiberglass sheet. The epoxy we use has an adhesive bond strength of 3400 psi [44]. The cross sectional area between the 54mm motor and the centering rings is 0.87 in^2, allowing one ring to support 2900 lbf. The maximum force that the motor exerts on the rocket is 228 lbf. This gives a factor of safety of 13 for one ring. The rings have a cross sectional area of 0.21 in^2 and shear strength of 38000 psi [43], allowing them to support 8000 lbf.

5.1.3.2. Robustness of Couplers

If the airframe of the rocket crumples or fails, it is likely to be at one of the coupling joints. The portion of the rocket experiencing the greatest aerodynamic forces is the fins. The maximum lift coefficient of a flat-plate fin is approximately 0.7 [41]; at the vehicle's maximum speed of 655 ft/s, this corresponds to a maximum lateral force of 77.4 lbf. The cross sectional area of the coupler is 1.2 in^2 and the shear strength is 38000 psi [43], giving us a factor of safety of over 600.

5.1.3.3. Stiffness of Fins

One concern when flying high power rockets is fin flutter. Fin flutter happens when a positive feedback loop forms in which the increasing relative angle of attack of the fin causes an increase in lift and a moment which changes the angle of attack leading to intense oscillations. While this phenomenon is usually trivial in subsonic rockets, it is still an important consideration to ensure the rocket does not lose its fins in flight and spin out of control. In order to calculate the maximum speed for a set fin shape, we use equations derived from an article in [4]. These equations consider fin geometry, material, and rocket performance metrics. All of the equations are used by a Matlab script which takes inputs of the fin parameters, material, and rocket performance and computes the max allowable velocity before fin flutter would cause damage to the fins. Using this script, the maximum speed of this fin design is calculated at 2051 ft/s, a factor of safety of approximately 3 above the maximum expected speed of the vehicle.

5.1.4. Determination of Kinetic Energy

The kinetic energy of each of the body segments when hitting the ground was calculated twice. Once through simulations using OpenRocket, and once through manual calculations based on manufacturer supplied parachute descent rate for rocket mass and wind speed.

5.1.4.1. OpenRocket Kinetic Energy Calculations

$$V=18.9\text{ ft/s},\ m_{tot}=18.8\text{lb}$$

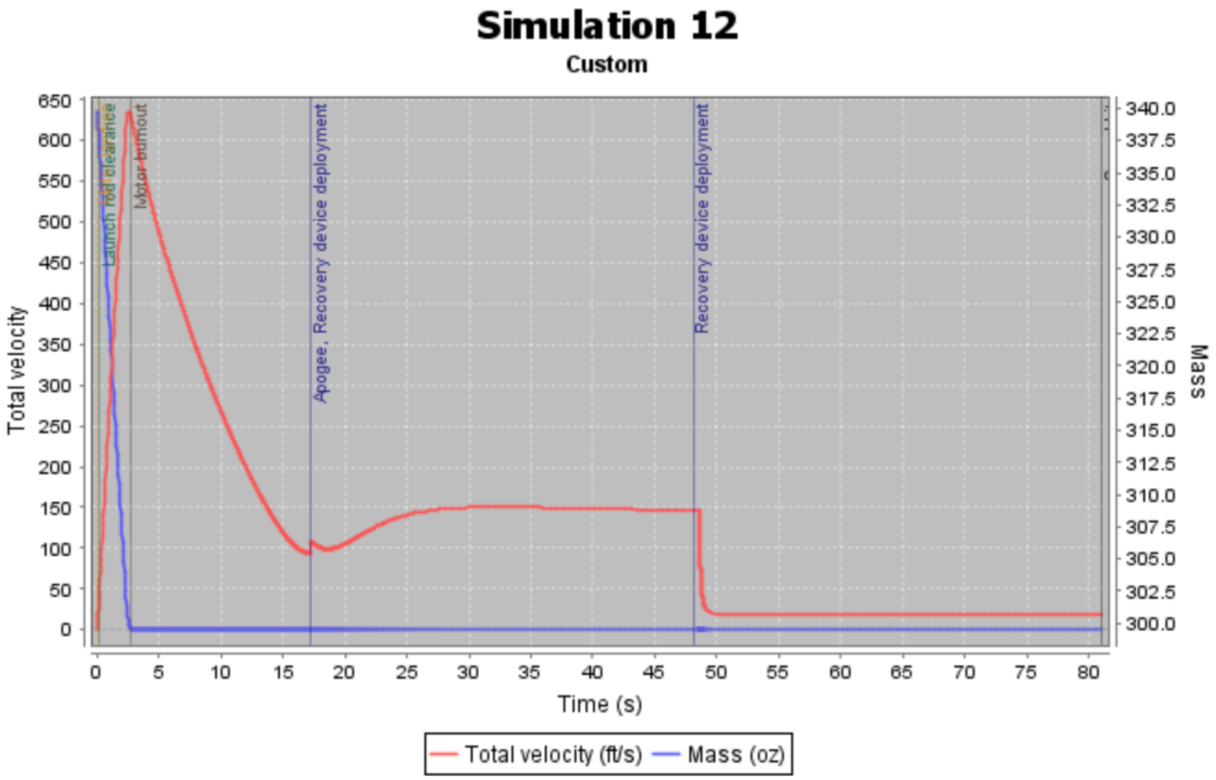


Figure 5.7: OpenRocket Simulation of the velocity and mass of the vehicle

The above figure shows the velocity (red) and mass in oz (blue) through the flight of the vehicle in the middle case of 10 mph winds and a 7.5 degree launch angle as a function of flight time.

- Booster: 28.75 ft lbf
- Recovery: 28.64 ft lbf
- Payload: 43.02 ft lbf

5.1.4.2. Manual Kinetic Energy Calculations

V_y=20 ft/s, V_{wind}=14.7 ft/s

$$KE = \frac{1}{2}m * \sqrt{(V_y)^2 + (V_{wind})^2}$$

- Booster: 64.2 ft-lbf
- Recovery: 64.0 ft-lbf
- Payload: 96.1 ft-lbf

5.1.5. Determination of Descent Time

The descent time of the rocket from apogee was calculated twice. Once through simulations using OpenRocket, and once through manual calculations based on manufacturer supplied parachute descent rate for rocket mass.

5.1.5.1. OpenRocket Descent Time Calculations

$$T_{total} - T_{Apogee}\ 81.1s - 17.2s = 63.9s$$

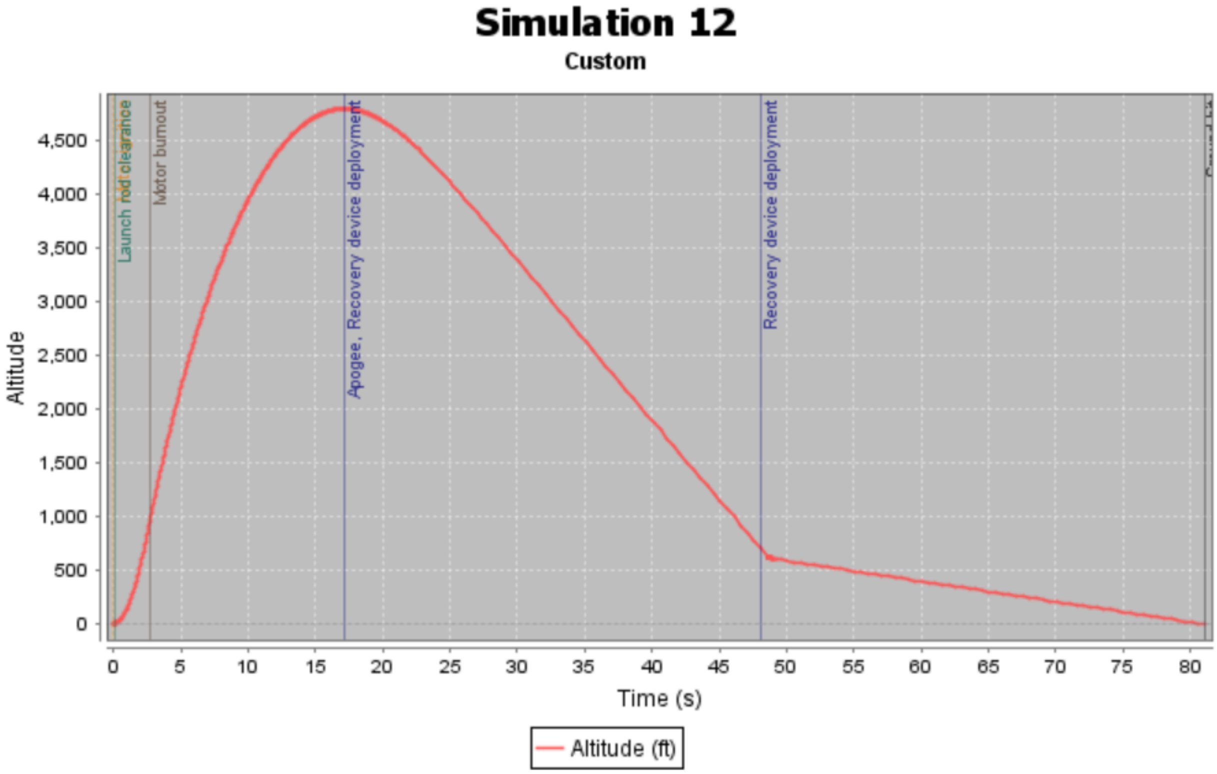


Figure 5.8: OpenRocket Simulation of the altitude of the vehicle

The above figure depicts altitude (red line) as a function of time of the flight. This particular simulation was done in the middle case, 10 mph of wind and a 7.5 degree launch angle.

5.1.5.2. Manual Descent Time Calculations

V_{drogue}= 139 ft/s, V_{main}=20 ft/s [45], y_{apogee}=5000 ft, y_{chute}=700 ft

$$t = \frac{y_{apogee} - y_{chute}}{V_{drogue}} + \frac{y_{chute}}{V_{main}} = 66\ s$$

5.1.6. Determination of Drift Distance

The drift distance of the rocket was calculated twice. Once through simulations using OpenRocket, and once through manual calculations based on previously calculated descent times and worst-case scenario wind speeds.

5.1.6.1. OpenRocket Drift Distance Calculations

Drift at 20mph winds = 660ft

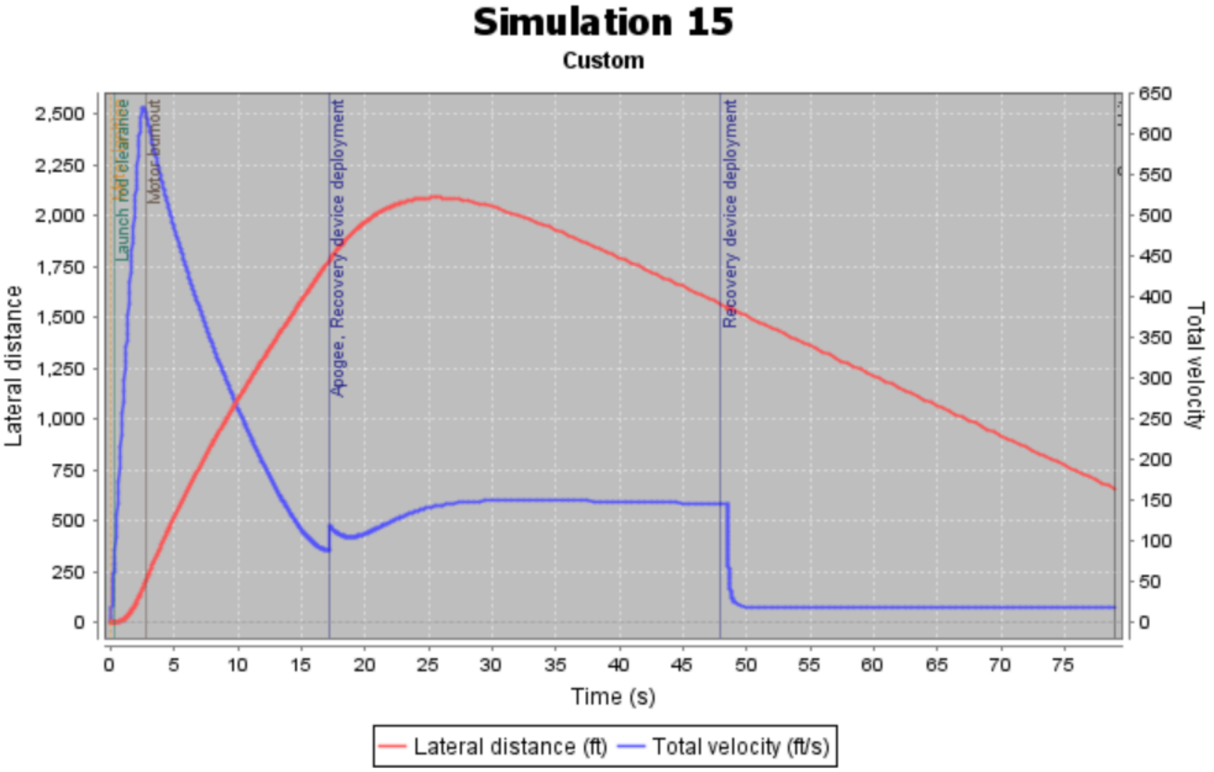


Figure 5.9: OpenRocket Simulation of the lateral drift

The figure above showcases the lateral distance of the launch vehicle from launch to landing (red line) and the total velocity of the vehicle (blue line) as a function of flight time.

5.1.6.2. Manual Drift Distance Calculations

V_{wind}= 20 mph = 29.3 ft/s, t= 66s

$$Drift = Vwind * t = 1934\ feet$$

Wind Speed

5 mph	10 mph	15 mph	20 mph
607ft	1214ft	1820ft	2430ft

5.1.7. Precision of Results

In order to guarantee precision of the results of our simulation, we used a python script that varied the drag coefficient, the launch angle, and the thrust of the motor to reach different apogees, simulating the flight using the finite difference method with 2D kinematics and ignoring the contribution of crosswinds. Performing 1000 trials, we obtained the figures below.

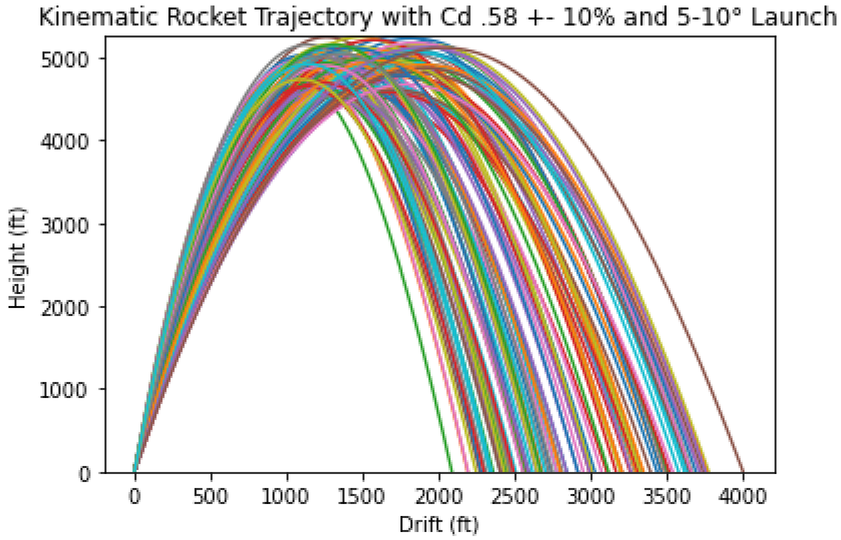


Figure 5.10: Simulated launches over varied launch parameters

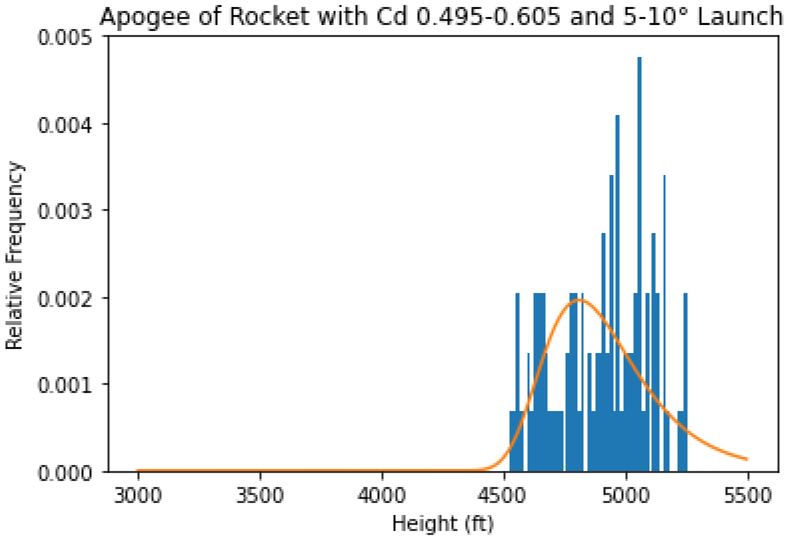


Figure 5.11: Frequency of a given apogee.

This data shows our apogee has a 95% confidence interval of 4500-5500 ft with our average at 4800 ft. This range will keep us within competition requirements with a certainty of 95%. This simulation reports marginally higher apogees than OpenRocket simulations, but this probably due to the fact that this simulation does not account for wind. Regardless, this confirms our calculations of apogee accounting for multiple variations (most not within our control) that could occur during flight. This validates that our simulations are accurate

6. Payload Criteria

6.1. Payload Mission Statement

The payload challenge is to autonomously control a camera to take pictures of the surrounding area by using a rotating airframe, antenna and camera deployment, and software filters to apply time stamps to the pictures. A successful design will be able to:

- Receive packets and take photos regardless of the landing orientation
- Capture images where the horizon is less than 5 degrees off the horizontal axis
- Have a command-packet loss rate of less than 25 percent
- Apply the required image filters when capturing the images
- Stabilize and position the payload via the rotational airframe
- Rotate 360 degrees along the x-axis via the camera gimbal.

6.2. System Level Design

The payload has been separated into two major components: an electronics subsystem, which includes handling RF commands, and a mechanical subsystem, which consists of all moving components. Within both subsystems are individual design components listed in Tables 6.1 and 6.2 and shown in Figure 6.1 below. The component-level design of each of these subsystems is discussed in Sections 6.3 and 6.4, and the leading design choices are summarized in Section 6.5.

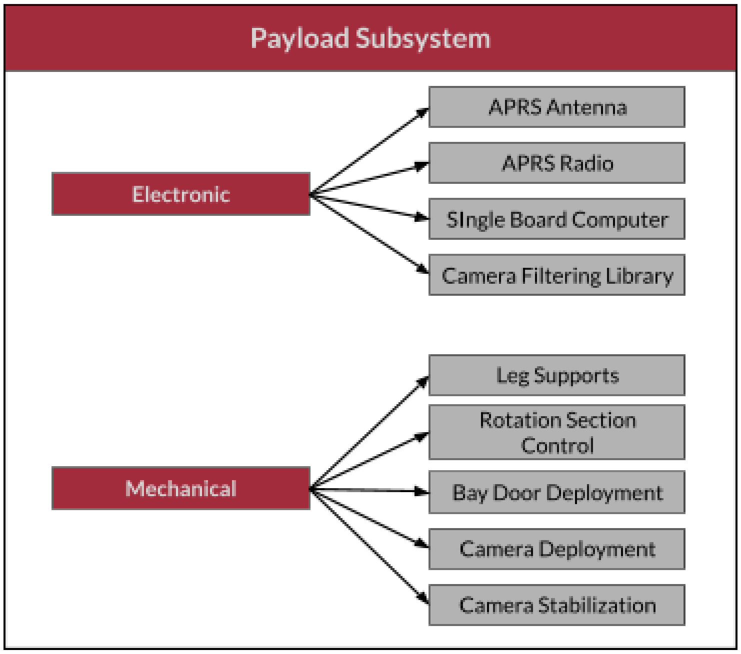


Figure 6.1: System-level breakdown of the payload subsystem

Table 6.1 Payload Mechanical Components

Payload Subsystem	Section	Objective
Leg Supports	6.3.1	Prevent the airframe from rotating as the camera moves
Rotating Section Control	6.3.2	Rotate a section of the airframe in order to vertically-orient the deployment mechanism
Bay door Deployment	6.3.3	Open up after facing upward for the camera and antenna to came out
Camera Deployment	6.3.4	Lift the camera above the airframe and passively aim the camera at the horizon. Rotate the camera 360 degrees
Camera Stabilization	6.3.5	Ensure that the camera is reasonably level with the horizon.

Table 6.2: Payload Electronics Components

Payload Subsystem	Section	Objective
APRS Antenna	6.4.1	Receive RF signals on the 145MHz band and transfer them to the APRS Radio with minimal interference. Be able to receive signals regardless of the relative location of the NASA transmitter (i.e. omnidirectional)
APRS Radio	6.4.2	Demodulate incoming FM signal into digital audio
APRS Decoder	6.4.3	Decode and parse APRS packets from the digital audio signal
Camera Filtering Library	6.4.4	Take pictures of the surroundings and apply timestamp, grayscale conversion, and edge detection filter overlay according to APRS commands
Orientation Subsystem	6.4.5	Calculate orientation data and re-orient the payload bay as needed.

6.3. Mechanical Payload Design Alternatives

For each mechanical component outlined above in Section 6.2, a set of design alternatives are provided below. A complete payload system level overview and leading design is provided in Section 6.5.

6.3.1. Leg Supports

After the airframe lands and untethers from the parachute, the spiral legs will deploy to provide necessary friction in order to prevent the airframe from rotating with the payload section. We considered several designs to meet this requirement.

Table 6.3: Pros and cons for the alternative leg support designs

Alternate Designs	Pros	Cons	
Spiral legs	• Compact volume for stowage	• Not long enough to keep the body from rotating.	
Simple rotating legs	• Rigid • Easy to actuate	• Takes up more space	✓
Doubly Articulated Legs	• Similar volume constraints as above • Perpendicular to the ground	• More complicated • More mass • Multiple failure modes	

In order to study the feasibility of each alternative, the following aspects are considered: length of section deployed outside the airframe, space efficiency while stowed, deployment simplicity, and robustness. Each alternative is then given a score from 1 to 5. For this category of alternatives, 1 corresponds to "severe concerns" while 5 corresponds to "extremely favorable."

Leg Design choosed	Length of section deployed outside the airframe	Space efficiency while stowed	Deployment simplicity	Robustness	Total (out of 20)
Spiral Legs	1	5	2	3	11
Simple rotating Legs	4	2	4	4	14
Doubly Articulated legs	5	4	2	2	13

This feasibility study shows that the simple rotating legs are the most favorable due in part to their well-rounded meeting of our constraints. The other two options are not far behind, but don't fulfill all the requirements to our satisfaction.

6.3.1.1. Spiral legs

The legs will be stored inside the airframe before deploying in a spiral configuration, connected to a 180 degree servo at the center of the airframe. As we decided before, the diameter of the airframe will be 4 inches, the legs will be about ¾ of the diameter, which would make them 3 inches long. The length of the section of the legs that will be sticking out of the airframe would be 1.5 inches.

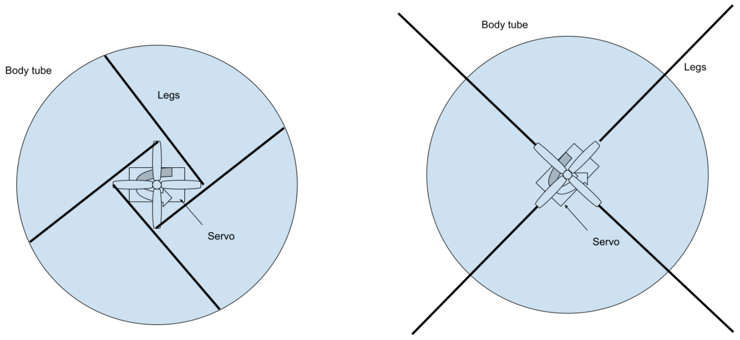


Figure 6.2: The stowed and deployed states of the spiral leg alternatives

This design is more mechanically complicated than the others since we'd have to find a method to lock the legs. In addition, the short fixed length deployed outside the rocket may not be enough to prevent the airframe from rolling.

6.3.1.2. Simple Rotating Legs

The simple rotating legs will deploy using burn wire and torsion springs mounted around the rotation point. The legs will be stored flush with the outside of the airframe to reduce drag while in flight. Burn wire is used so that no wires need to leave the rotating portion of the payload and deployment actuation is simplified.

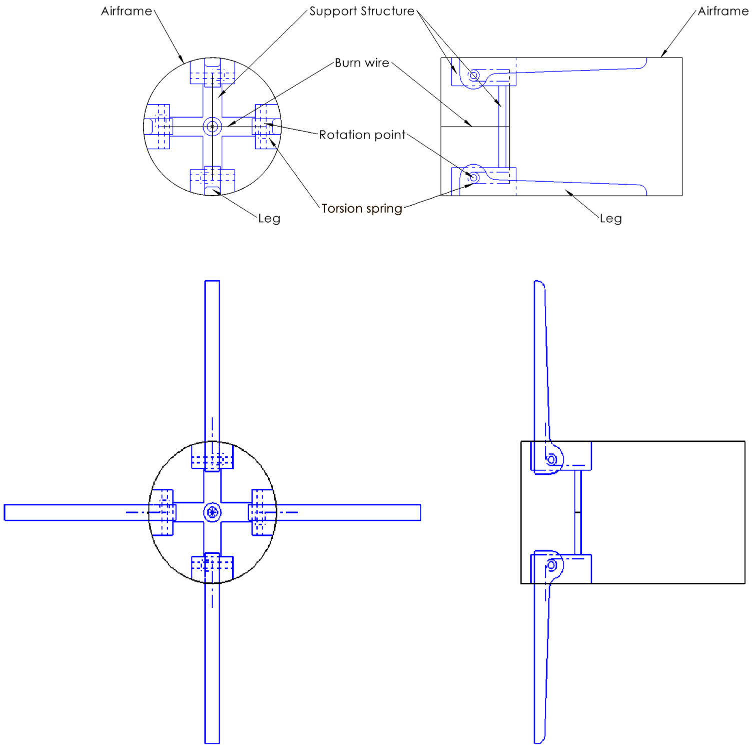


Figure 6.3: Stowed and deployed states of the simple rotating leg alternative

This method is the easiest to articulate and has the potential to be very strong. The biggest downside is it will require a large hole cut in the airframe.

6.3.1.3. Double-Articulated Legs

The double-articulated legs would use a servo connected to a pulley to wind up a rope which holds the legs flush with the airframe. After the payload lands, the servo would unwind and torsion springs between the inner and outer legs. This would deploy the legs so the payload is held in a constant orientation so the camera can rotate to the correct orientation.

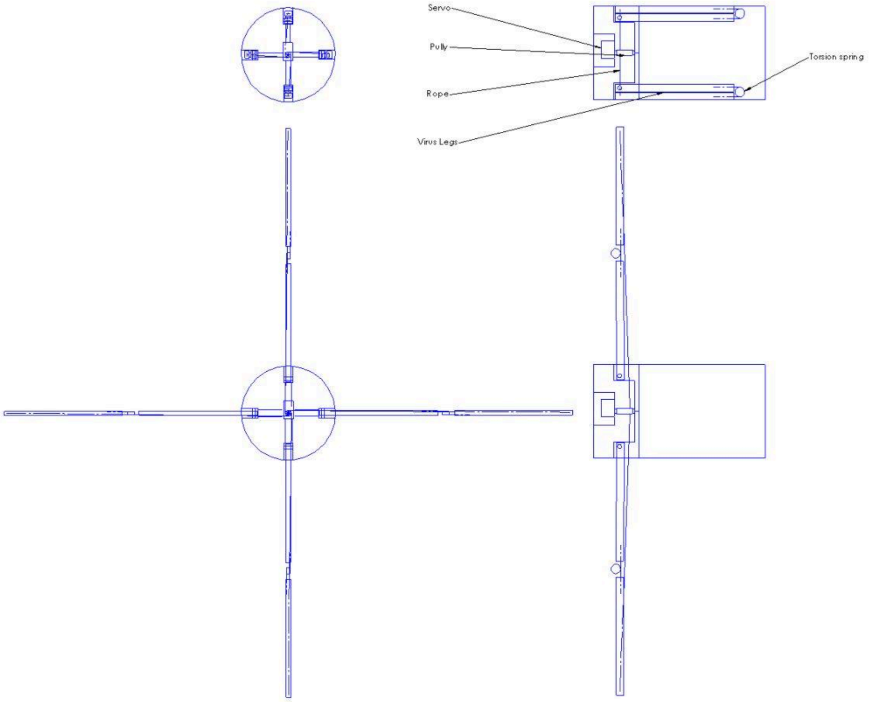


Figure 6.4: The stowed and deployed states of double articulated legs

One downside of this design is that the connection between the upper and lower legs is not very rigid because it is only held by the torsion spring. This does, however, allows for a more compact design for a given leg length. Figure 6.4, shown above, demonstrates the stowed and deployed states of the legs after the actuator has unwound the pulley.

6.3.2. Rotating Airframe

After the airframe section that contains the payload lands, it is unlikely that the airframe will land such that the bay door is facing upright. Therefore, a reorientation system is needed to rotate the section of the airframe to a desirable orientation. A section of the first body tube is cut out and has two bearings at each end: one passive and one active. The active control consists of an orientation sensor, the rotation airframe section, and a motor. The reorientation system will also keep the camera from tilting and therefore keep the horizon level in the picture.

Table 6.4: Pros and cons of the rotating airframe bearing

Alternate Designs	Pros	Cons	
3D printing bearing	• Customizable • Cheaper • Easy to replace	• Additional friction • Weaker • Less reliable • Requires assembly	✓
COTS Ball Bearing	• Reliable • Does not require prototyping time	• Integration issues • Not available in needed sizes	

Table 6.5: Pros and Cons of of the rotating airframe actuator

Alternate Designs	Pros	Cons	
360 degree Servo	• More control • Easy interface • Cannot rotate freely by external force	• Limited Torque • Limited angle range	✓
DC Motor with gear	• More torque • Higher speed • Continuous	• More power needed to drive • Difficult to control precise movement	

The feasibility of all components are presented within its section.

6.3.2.1. 3D printed bearing

A 3D printed bearing would provide more design flexibility than a COTS bearing. To test its functionality, a preliminary design was 3D modeled and assessed. Figure 6.5 below shows the bearing design.

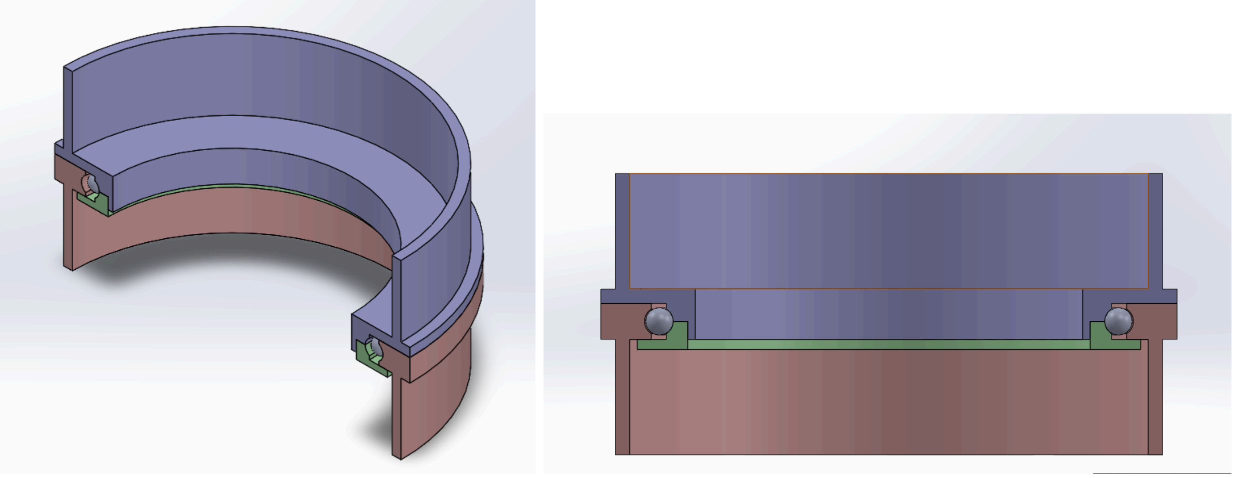


Figure 6.5: CAD of a 3D printed custom bearing

Figure 6.6: Prototype of 3D printed custom bearing

The outer diameter of the bearing is the same as the inner diameter of the airframe and the ball bearings are 3.5mm BB balls. During launch and parachute deployment, there will be significant thrust force acting on the bearing.

This bearing has the flexibility to be designed to easily integrate with the airframe. It will, however, need thorough testing to ensure it can handle the forces of launch and recovery.

6.3.2.2. COTS Ball Bearing

Bearings that companies manufacture are more reliable. However, few fit the airframe dimensions directly, so a custom plate is needed. A gap between the plates is required for two plates to rotate without too much friction, so when the rocket accelerates or lands, any shear force will force one side of the two plates to press against the other. It will create significant friction during rotation or, in the worst-case scenario, with extreme shear force when launching; it might rip the bearing out of the plate and result in the failure of the whole rocket. Figure 6.7 below shows a motor connected to a custom plate with the bearing mounted on it. The other half of the bearing is mounted to the second plate with a small gap between the plates to minimize friction.

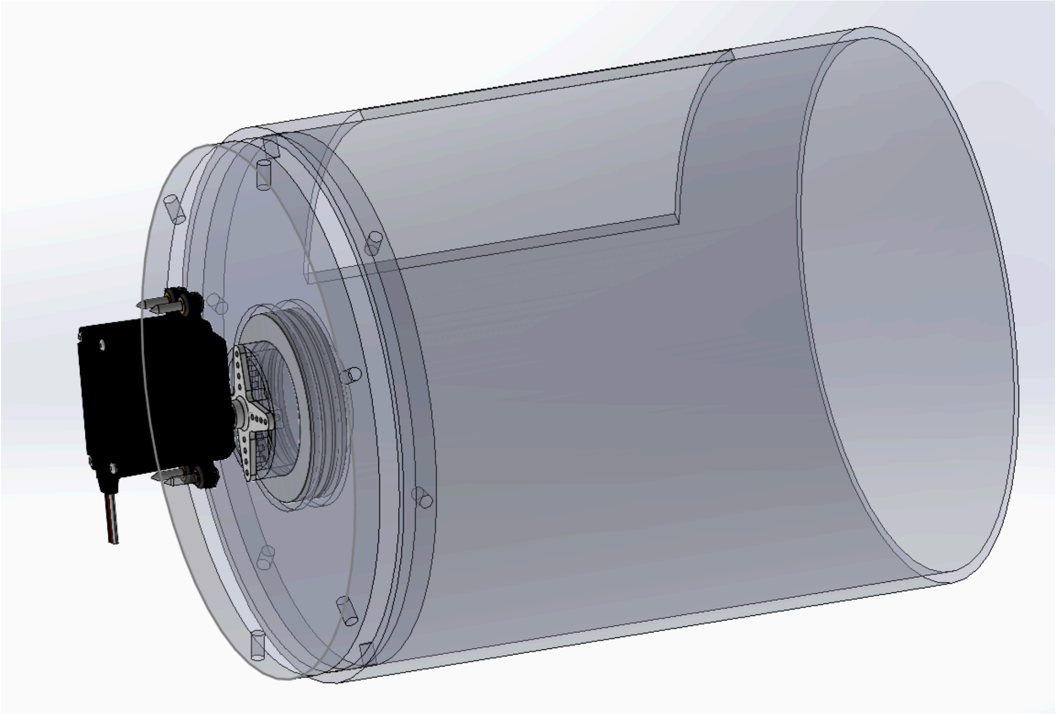


Figure 6.7: CAD of the COTS incorporated into the airframe

6.3.2.3. Servo Motor

The servo motor is designed for precise angular movement and therefore is more suitable for when angular movement needs to be accurate. For the implementation of a rotating section of the airframe and to keep the camera from tilting, precise angular movement is required. The minimum angle step for a servo motor is 1.8 degrees, therefore the minimum angle for the camera tilt is also 1.8 degrees. This error is tolerable for the system needs. Due to the team's experience with servo motors and the lack of need for additional hardware, this solution would be feasible to implement.

The servo motor will be mounted at the center of the rotation axis. The servo motors we are considering range in torque specs up to about 9.4 kgf*cm. This indicates it could spin a 9.4 kilogram mass with a 1 cm lever arm. Since our mass is roughly 3.5 kg or less, with a lever arm of 2.5cm (assuming all mass is concentrated on the outside), these servos will be sufficient.

6.3.2.4. DC Motor

Rather than being mounted about the axis of rotation, the DC motor would be attached to a small spur gear meshed with a large internal gear (See Figure 6.8). The torque required to move the section of airframe (assuming a 7.75 lbs payload section assuming worst-case scenario of all the mass concentrated on the outside with a minimum needed angular acceleration of 5 degrees/sec^2) is approximately 129 g-cm or .0094 lbf-ft which is well within the stall torque of motors between 5 and 12V. The drag on the ground was also taken into consideration when calculating the necessary torque.

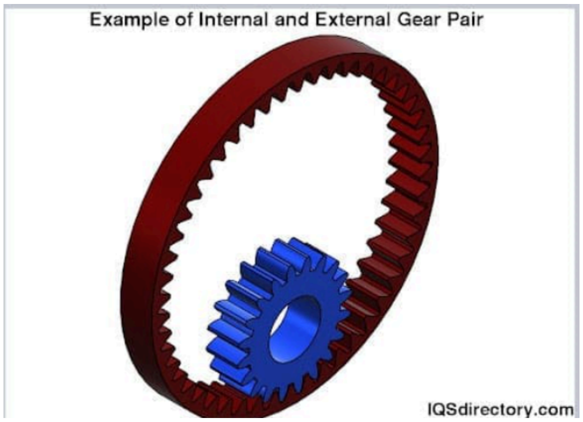


Figure 6.8: Example of an internal external gear pair (Source: IQSdirectory.com)

6.3.3. Bay Door Deployment

The bay door we are designing requires a rotating actuator to open it when landed. The following is a discussion of these options. Feasibilities are presented within each component discussion.

Table 6.6: Pros and cons for the hinge alternatives for the bay door deployment

Alternate Designs	Pros	Cons	

Spring-loaded Commercial Off The Shelf (COTS) Hinges	- Less development time - Known strength	- Less flexibility - More expensive	✓
3D-printed Linkage	- More precise	- Complex - Design Time - Harder to mount	

6.3.3.1. COTS Hinges

The COTS hinges available are mostly for home use, giving us many different purchase options. Despite this, there are few that meet our design specifications. Ideally, a COTS hinge would be at equilibrium at or near 180 degrees since the bay door should be at equilibrium while open to not obstruct the view of the camera or its deployment. As a result, we found simple spring-loaded hinges and experimented with orienting and combining such that these specifications were met. Figure 6.9 shows the hinge(s) combined to complete our objective. This mechanism will be activated by the use of a servo motor releasing locking pins holding the spring-loaded hinges and door in place .

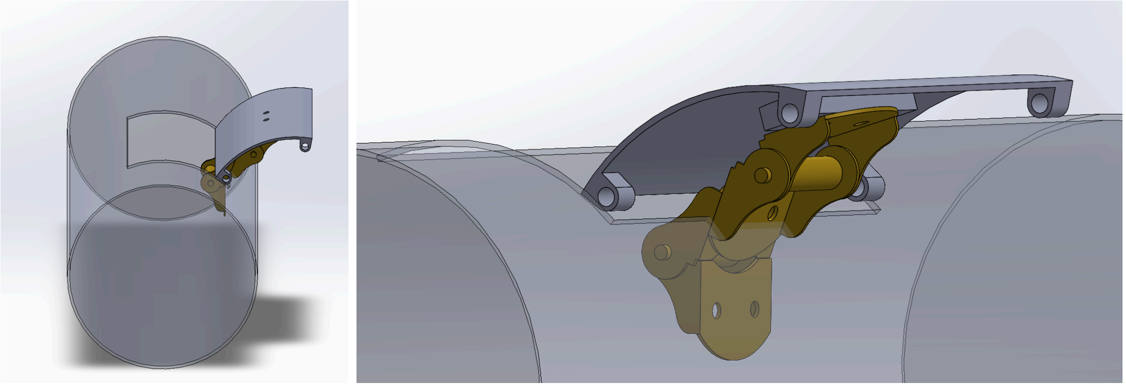


Figure 6.9: CAD of COTS hinge implementation

This design has yet to be prototyped, but with the CAD model demonstrating functionality and the low design time needed for this system, COTS hinges are the current best approach.

6.3.3.2. 3D-printed Linkage

A 3D printed linkages such as a 90 degree four-bar linkage or the linkage in Figure 6.10 are included in this section. Overall, these linkages are difficult to actuate and have a large design time. Since the linkages would be of a specific geometry, most would have to be 3D printed which brings up concerns for strength. This solution would, on the other hand, meet all our design specifications due to its increased flexibility over other hinges.

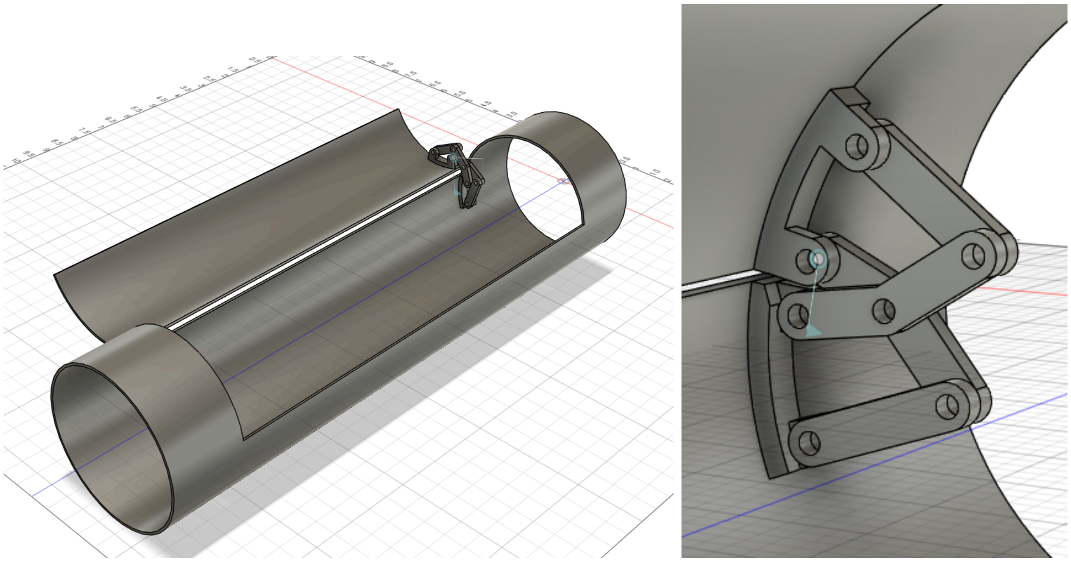


Figure 6.10: Example of 3D printed linkage design

6.3.4. Camera Deployment

Table 6.7: Pros and cons for camera deployment alternatives

Alternate Designs	Pros	Cons	
Four-Bar lift	• Simple actuation • Small • Flexibility in top attachment	• Less rigid • Less space to mount camera and antenna	
Simple Rotation Lift	• Simple • Can change orientation of camera in one axis if rocket lands on a clod	• Large bay doors	
Scissor lift	• Stiff • Easy to stow • Camera stays in final orientation	• Heavy • Requires expensive actuator	✓

6.3.4.1. 4-Bar Lift

The four-bar lift is a lifting linkage. Compared to other four-bar linkages, its main advantage is keeping opposite linkages parallel throughout lifting. In HB 4.2.1.1, the handbook states that the “z axis is perpendicular to the ground plane.” Operating under the assumption that the rocket will be on the ground plane, the bottom linkage will be located on the bottom of the rocket oriented perpendicular to the ground so that the top linkage matches the HB requirement. Figure 6.11 below shows the deployment.

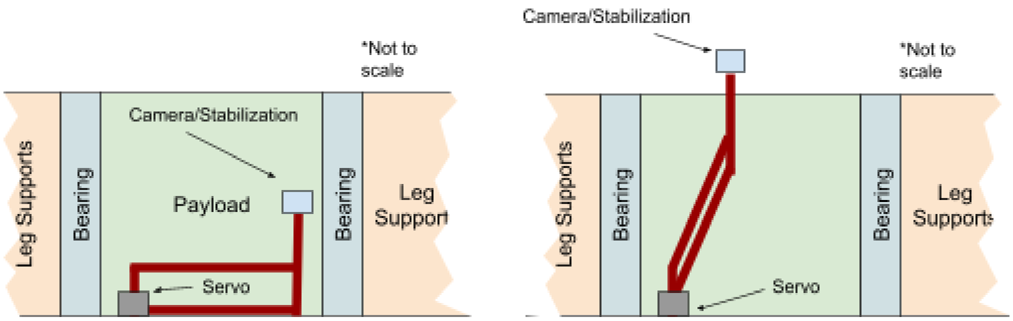


Figure 6.11 - The two configurations (stowed and deployed) of the four-bar lift design

The main concern with this design was whether a 9g servo would have enough torque to lift the linkages and the Camera/Stabilization. In order to test this as well as the manufacturability, a CAD model and 3D printed prototype were developed. Figure 6.12 below shows the final outcome of prototyping.

Figure 6.12: CAD (left) and prototyped (right) versions of the four-bar lift

Using a 9g servo, a servo tester, and some weight on the top linkage, the 3D printed prototype was tested to ensure lifting capability. The 9g servo did have enough torque to lift the mechanism, but other concerns such as ensuring the pins (M3 screws in this case) did not loosen, and the stability of the mechanism were called into question. These concerns will be addressed with further prototyping and iteration.

When compared to the other alternatives, the four-bar lift offers several benefits. For example, the design employs simple actuation with the single COTS 9g servo. The length of each linkage determines the space it takes up as well as the amount it lifts above the airframe, so it can be adapted as parameters such as the size of the bay door and the space within the payload bay change. One issue is in order to keep the bar extended, the servo must be running. This can be combated with a rubber band or spring attached to the linkages such that the equilibrium position is the extended configuration. In addition, this design offers less flexibility in how the camera and camera stabilization can be mounted as it must be attached to the single top bar.

6.3.4.2. Simple Rotation Lift

The simple rotation lift uses a servo motor to lift a single bar. The camera and stabilization would be attached to the top of the bar. Figure 6.13 shows the stowed and deployed configurations.

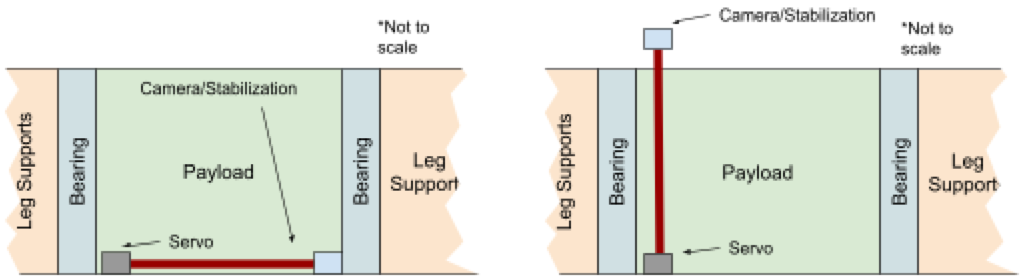


Figure 6.13: Stowed and deployed states of the simple rotation lift alternative

We determined this design was feasible based on calculations. If we were to use a 9g TowerPro servo (stall torque of 1.56 kg*cm), then we could lift a mass of 88 g to 7in which is the ballpark of our current estimates of height and weight requirements.

The simple rotation lift has benefits in simplicity as well as corrective stabilization. For example, if the rocket were to land on a mound of dirt and the rocket body is not parallel with the ground plane, a sensor onboard the rocket could orient and stabilize the camera with the same servo used to lift it up. This would result in explicit roll control.

One downside, however, is the large size needed for the bay door. If the lift is mounted at the bottom of the rocket and needs to lift 3in above the airframe, the bay door would need to be at least 5.7in long (calculated using the chord length formula). Figure 6.14 demonstrates this. This problem could be mitigated by mounting the servo higher in the airframe so that the lever arm is smaller.

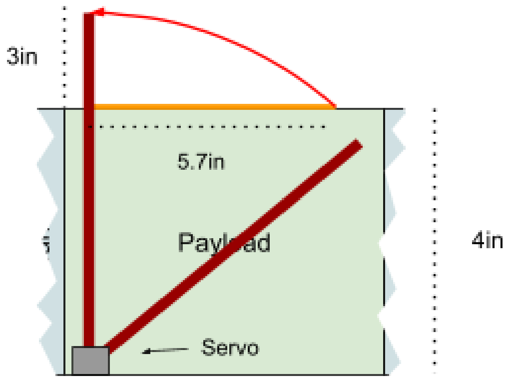


Figure 6.14: An example length visualization of the size bay door needed for the simple rotation lift

The last downside is the stability. The servo would have to remain active to ensure the camera and stabilization are balanced. One way to account for this is, similarly to the four-bar lift, is a spring mounted such that it is equilibrium at the deployed state.

6.3.4.3. Scissor Lift

The scissor lift uses a series of linkages to convert linear horizontal displacement into a proportionately larger vertical displacement. The camera and gimbal will also be held parallel to the airframe while in the frame and while it is deploying. The scissor lift will be actuated with a two-inch stroke linear actuator. The scissor lift will be made from laser cut linkage members, wooden dowels, and 3D printed parts to hold the bottom in place and to connect to the gimbal at the top of the scissor lift. Figure 6.15 shows the stowed and deployed positions of the scissor lift.

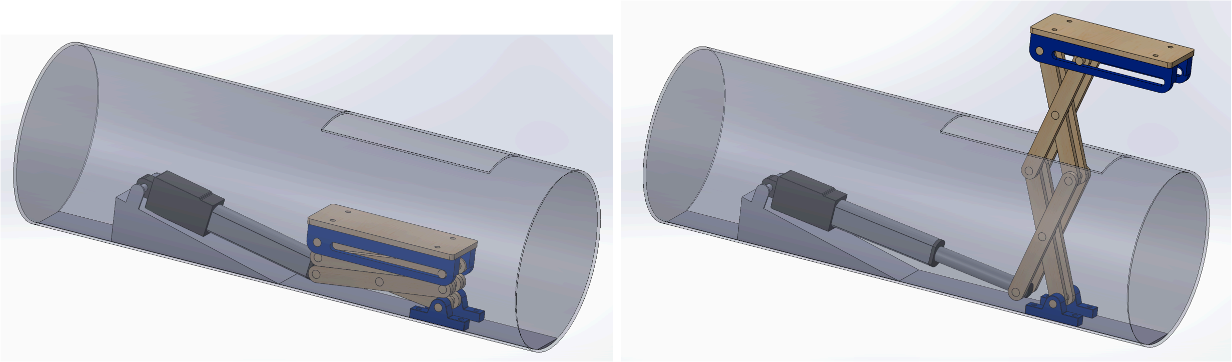


Figure 6.15: Stowed and deployed state of the scissor lift alternative

The scissor lift design has the benefit of high stability both while stowed and after it is deployed. It can also be made from simple materials like 1/8in plywood and 3D Printed filament. It is also known to be effective linkage design as shown in many industries such as construction lifts. One downside about a scissor lift is it is heavier compared to the alternatives. The prototype lift itself is 29g, not including the 55g linear actuator.

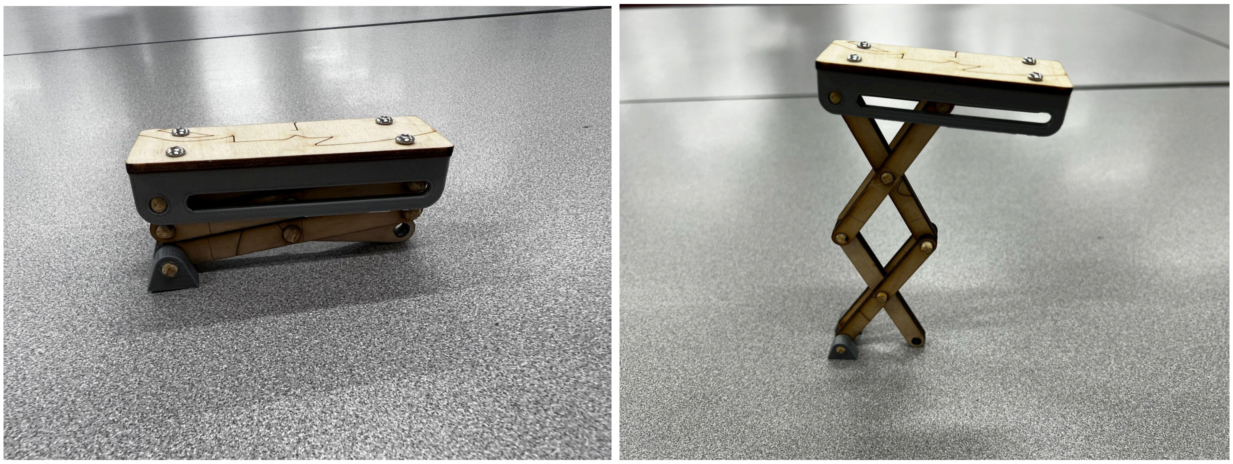


Figure 6.16: Prototype scissor lift

6.3.5. Camera Stabilization

The camera stabilization component will handle any necessary amendments to the camera pitch and roll.

Table 6.8: Pros and cons of camera stabilization alternatives

Alternate Designs	Pros	Cons	
Passive Gimbal	• Small • Compact • Simple	• No active stabilization • Prone to jamming or sticking • May not provide sufficient stabilization	✓
Active Gimbal	• Improved stabilization	• Need additional motors • Large in weight and volume • More failure points • Complex to design	
None	• Simple • No Cost	• No stabilization	

6.3.6. Passive Gimbal

The passive gimbal uses connected hinges and the weight of the components to stabilize the attached camera. The passive gimbal utilizes integrated hinges and is 3D printed from PLA plastic as one object to allow for compact design. The passive gimbal will also contain supports that connect it to the Camera Rotating System. Its small size and limited weight allow for easier lifting from the Camera Deployment System. Figure 6.17 shows how this alternative controls both roll and pitch.

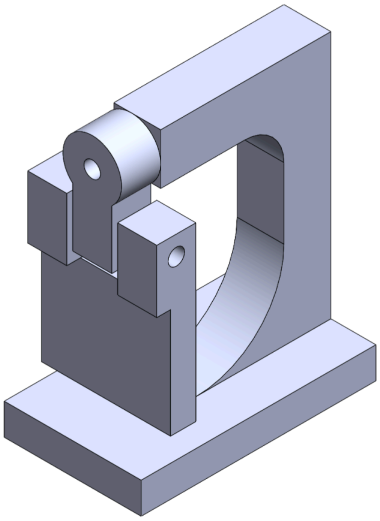


Figure 6.17: CAD example of a passive gimbal

The camera will be mounted on the flat section of the gimbal. Additionally, the connecting hinge has holes at the axes of rotation.

One identified failure mode is the possibility of the rocket landing at a steep enough angle for the gimbal to be unable to correct the vertical change as it contacts parts of the support. The wires of the camera must also have enough length, and the gimbal must be weighted enough, to prevent the tension of the wires from altering the stabilization of the camera. Since these challenges have reasonable solutions, this design is feasible.

6.3.6.1. Active Gimbal

With precise pitch and roll control, the camera has a horizontal view of the horizon regardless of the environment and degree of the rocket relative to the surface. However, this would require two additional motors to allow for rotation along the x and y axis relative to the camera. This leads to additional weight and requires a system capable of supporting the rotation of both gimbals while also keeping connected wires untangled. It would also require an inertial measurement unit on the moving part of the gimbal which would further increase complexity. This proves difficult to design and has more points of failure due to the addition of extra motors which might fail individually, thus, we did not pursue this design further.

6.3.6.2. None

The last option we considered was having no gimbal at all. Without stabilization, there is the possibility that the camera is not oriented according to HB 4.2.1.1. Its error in orientation depends which Camera Deployment method we end up using. This solution is clearly the easiest to implement, however it relies on the Camera and Deployment Systems for stabilization instead. To reduce complexity of the Camera and Deployment Systems, we declined to pursue this design further.

6.3.7. Camera Rotating System

The camera rotation system is only concerned with rotating the camera about the z axis (yaw). We considered a number of different actuators presented below.

Table 6.9: Pros and cons for each camera rotating system

Alternate Designs	Pros	Cons
180 Degree Servo and gear system	• Easy access • Wide range of rangle	• Large • Specialty gears required
DC Motor	• Continuous rotation	• Large • More design time required • Requires separate positioning sensor.
Direct Drive 360-degree Servo	• Small • Simple	• Specialty servo required

In order to study the feasibility of each alternative, the following aspects are considered: Space efficiency while stowed, gear simplicity, angle accuracy, robustness, and cost. Each alternative is then given a score from 1 to 5. For this category of alternatives, 1 corresponds to “severe concerns” while 5 corresponds to “extremely favorable.”

Table 6.10: Feasibility Study for actuator in Camera Rotating System

Motor type choosed	Space Efficiency	Gear simplicity	Angle accuracy	Robustness	Cost (higher cheaper)	Total (out of 25)
180 Degree Servo and	2	3	5	3	5	18

gear system						
Direct Drive 360 Degree Servo	4	5	5	4	3	21
DC Motor	3	5	2	4	2	16

The direct drive alternative has the highest feasibility at 21. It has the highest possible scores for gear simplicity and angle accuracy, but is slightly more expensive. Despite this, the team has decided to move forward with it as our leading design.

6.3.8. 180 Degree Servo and gear system

One option for camera rotation is a 180 Degree Servo connected to a small transmission to allow for 360 degrees of rotation. The upduction could be completed using either a system of HTD3 pulleys, or a set of gears. The advantages of this system is it increases the options for servos we can use as 180 degree servos are more common in the hobby industry. One drawback of this method is it will be harder to manufacture and package compared to a direct drive system. This is because making small gears or pulleys accurately is difficult, and the tolerances for all the components to fit together will be hard to get to a usable and flight-safe state.

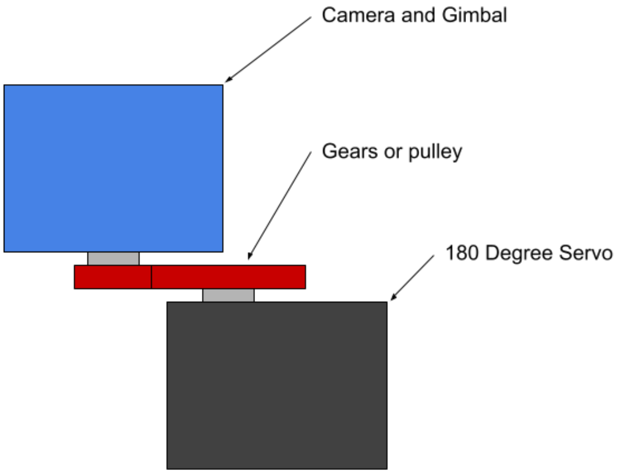


Figure 6.18: Example of camera rotating system layout with 180 degree servo

6.3.9. Direct Drive 360 Degree Servo

A 360 degree servo is the second and most optimal option for camera rotation. The only drawback to this servo is that it requires a specialty servo. The 360 servo is ideal because it is a small and simple design since it allows for direct drive from the servo to the gimbal and camera subsystem. The rotation system can be packaged into the lifting mechanism allowing for a more compact and therefore lighter design. Using direct drive would also improve stability.

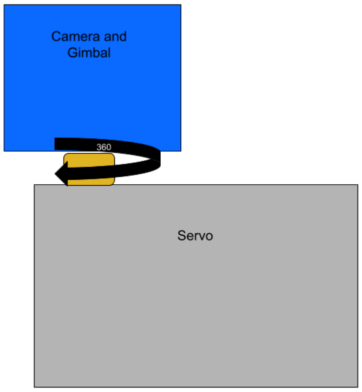


Figure 6.19: Example of layout using a 360 degree servo

6.3.10. DC Motor

A DC Motor would allow for continuous rotation along the z axis. This would allow the camera to have a range of motion greater than 360 degrees. However when integrated with the Camera Stabilization system, there is no need for rotation greater than 360 degrees. Further rotation would also require more advanced cable management, since the length of the wires connected to the Camera Stabilization System and camera would wrap around the servo during rotation and prevent movement when the wires become taut. In addition, a DC motor is more expensive than the 180 and 360 Degree Servo alternatives. It also requires a separate positioning sensor, adding to weight and space constraints. There is no additional benefit from the DC motor that the 180 and 360 Degree Servo with gear systems do not already provide.

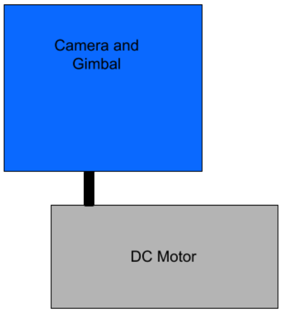


Figure 6.20: Example layout using a DC motor

6.3.11. Electronics Sled

The electronics sled's (containing all electronics for the payload mission) main consideration was the shape, similarly to Section 4.2.1. The payload only considered one-tray and two-tray solutions from 4.2.1 since the others would not allow enough space for the mechanical systems in the payload sections.

Table 6.11: Pros and cons for electronic sled designs

Alternate Designs	Pros	Cons	
One Tray	• Simplest to assemble • All surfaces are accessible	• Lowest total mounting surface area	
Two Tray	• Large effective surface area of considered design	• Difficult to service without ability to remove center tray • Greatly added complexity with removable center tray	

		• Lowest clearance for tall electronics	
Custom Sled	• Provide Structure for components that need special spacing • More mounting surface area	• Add complexity to the assembly	✓

All solutions are equally feasible in construction, but only the custom sled allows room for all the mechanical systems required for this year's payload competition.

The customized sled consists of one center tray, one bottom tray, and extra structure for bay door deployment. The center tray will provide space for all electronics and battery. The bottom tray is for linear servo and camera lifting structure.

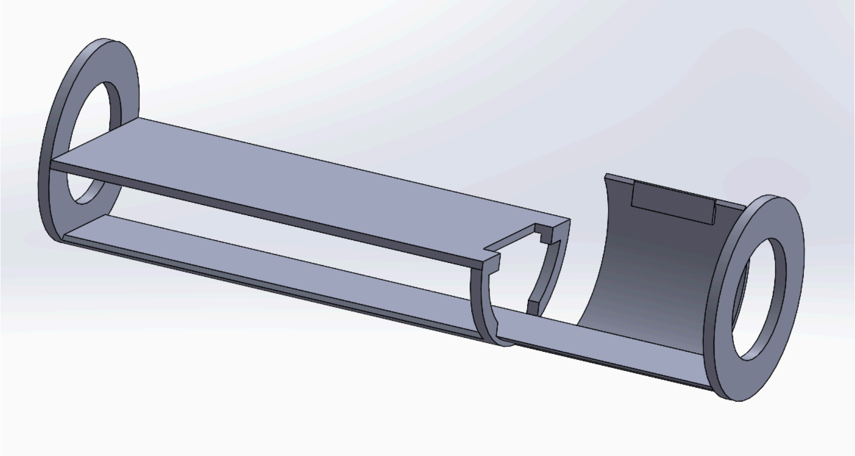


Figure 6.21: Leading design for payload bay

6.3.12. Quick Release

Table 6.13: Pros and cons of the quick release mechanism alternatives

Alternate Designs	Pros	Cons	
Servo actuated hook	• Reliable • Minimum prepare time	• Unstable orientation	
Burn wires	• Small and light • No moving part	• Slower deploy • Surrounding	

	- Fewer parts - Interface with current electronics	components may catch fire - No prior data / experience	
Pincer mechanism	-	- Too complicated to design and prototype - Not enough experience from students - Dangerous, considering the use of blades - Unreliable when cutting rope	
Cord quick release	- Less development time - Stronger material	- Unreliable orientation	✓

6.3.12.1. Servo Actuated Hook

The servo actuated hook will be mounted at the bottom of the payload airframe. It will connect the airframe with the main parachute. Upon landing, after the payload detects that it has reached the ground, the servo will release the pin and untether the system from the rest of the rocket airframe.

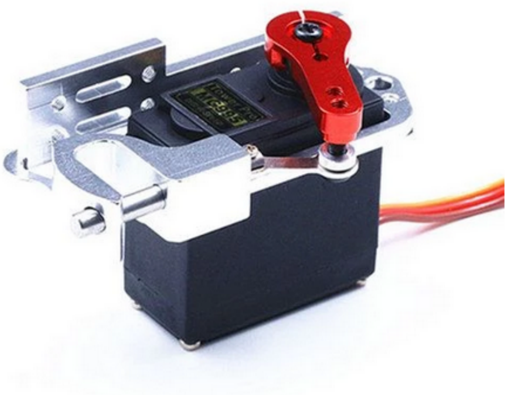


Figure 6.22: COTS Remote Control Servo Release Hook

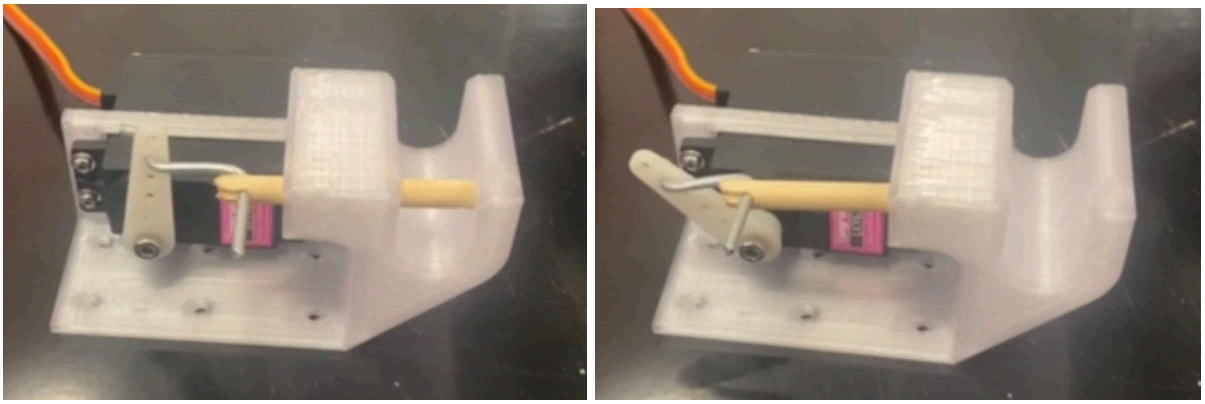


Figure 6.23: 3D printed release hook at its stowed and released state

6.3.12.2. Burn Wires

The Burn Wire release mechanism utilizes a compression spring system in order to apply a force and a stroke to the nichrome burn wire. When a constant current is applied to the nichrome wire, it will thermally cut through a Vectran cable allowing it to release the parachute. The free length of the nichrome wire is configured into a V shape with the apex in the V being the primary area for cutting through the cable.

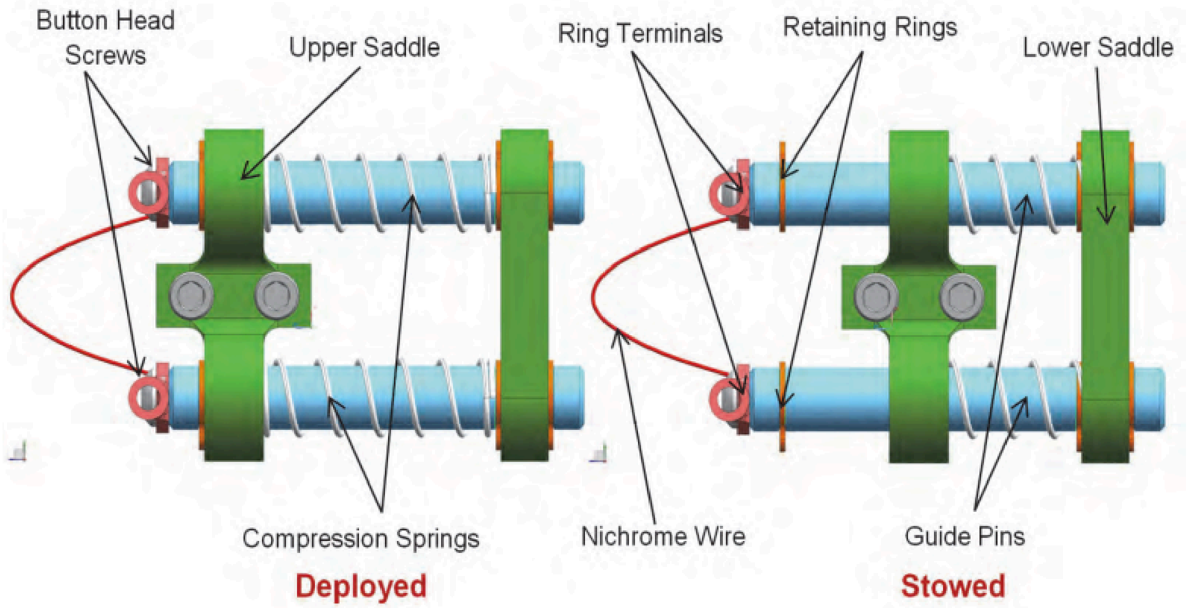


Figure 6.25 Nichrome burn wire release mechanisms in the deployed and stowed configurations (A. Thurn, S. Huynh, and S. Koss).

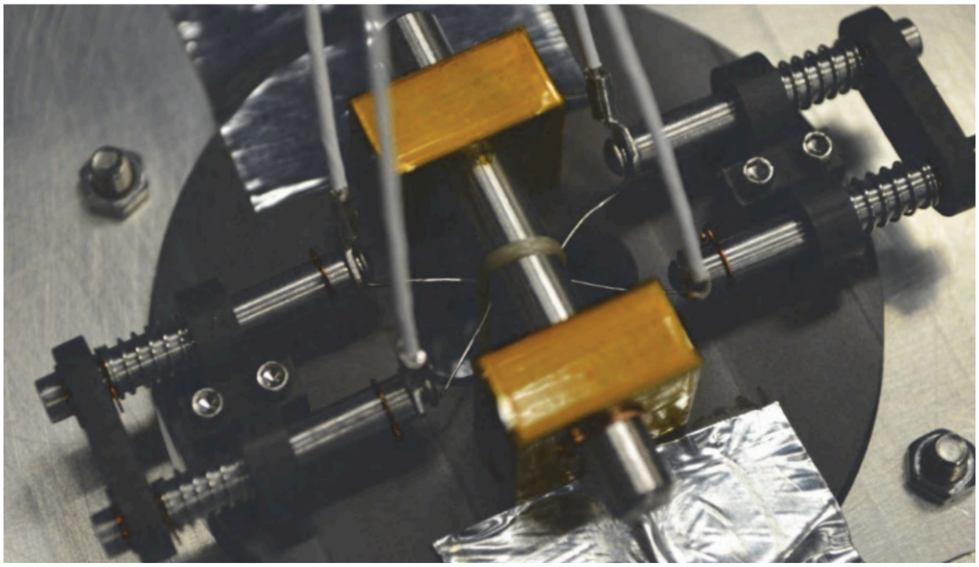


Figure 6.26 Release mechanisms on Vectran tie down cable (A. Thurn, S. Huynh, and S. Koss)

As shown in Figure 6.26, the Vectran cable will tie on the pin bar over the bulkhead.

6.3.12.3. Pincer Mechanism

One way to detach the payload from the rest of the launch vehicle is to cut the nylon rope that connects the two together. The pincer actuator first stabilizes to keep the rope taught, and then using high speed servos, the razor blades are linearly actuated to cut the nylon rope. Because the team will be using razor blades to make this mechanism possible, and is a dangerous process for testing purposes, this will not be a feasible design.

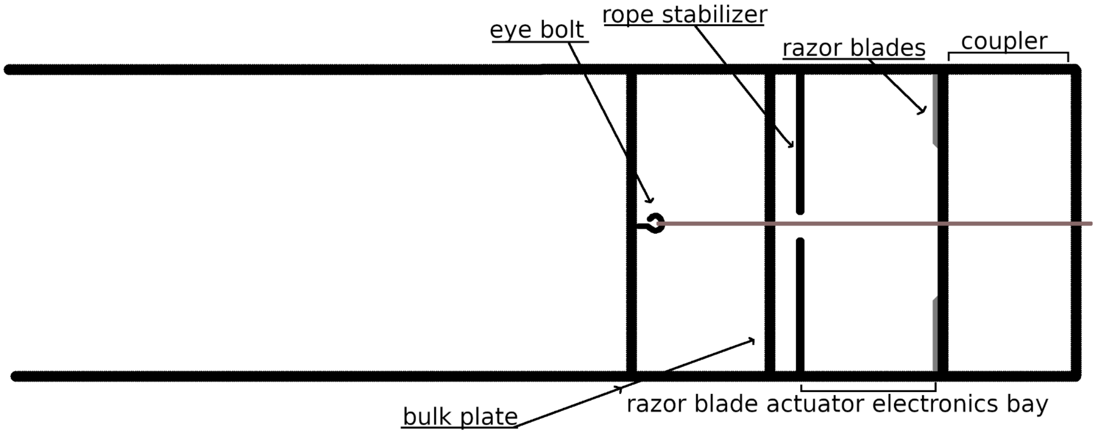


Figure 6.27 Pincer mechanism to cut through the nylon rope

6.3.12.4. Cord Quick Release

A servo will be mounted on the other side of the bulkhead to pull the cord, and the parachute will connect through the top hook. The hook can be released by pulling the cord. Compared with servo actuated hook and burn wires, quick release requires less development time and it is easy to connect to the eye bolt on the bulkhead. However without the drag force on the parachute the quick release might require extra length of the cord to be pulled in order to release the top hook connecting the parachute.
The quick release is more expensive than actuated hook but has more structural integrity.

Figure 6.27 COTS KONG Quick Release

6.4. Electronics Payload System Design Alternatives

6.4.1. APRS Antenna System

Table 6.14: Pros and cons of different APRS antenna system alternatives

Alternate Designs	Pros	Cons
Quarter-wave monopole antenna deployed from rocket	● Very good signal to noise ratio ● Matches the vertical polarization provided by NASA ● Well-studied design	● Physically large ● Requires a deployment mechanism such that it is perpendicular to the ground ● Must be stored outside the rocket due to a length longer than the payload bay ● Potential failure modes

		from external mounting ● Produces more in flight drag ●
Deployed electrically short monopole “rubber ducky” antenna	● Physically small ● Matches the vertical polarization of the transmission ● Can be stored inside the payload bay ● Well-studied design	● Less efficient than a quarter wave antenna ● Requires a deployment mechanism such that it is perpendicular to the ground
Non-deployed quarter-wave “whip” monopole antenna	● Well-studied design ● No moving parts ● Stronger signal to noise than electrically short	● Physically large ● Possible gap in receiving coverage depending on landing orientation ● Does not match the polarization of the transmission ● Will cause some drag in flight ● Weaker signal to noise ratio than deployed quarter-wave antenna ● Potential failure modes from external mounting
Internal electrically short monopole “rubber ducky” antenna	● Physically small ● No moving parts ● No modification of airframe tube ● Can be stored in payload section ● Well-studied design	● Weak signal to noise ratio ● Increased likelihood of dropped packets ● Possible gap in coverage depending on the landing orientation of the payload ● Does not match the polarization of the transmission

6.4.1.1. Deployed quarter-wave “whip” monopole antenna

Quarter-wave monopole antennas commonly referred to as “whip” antennas are desirable because of their RF characteristics, price, and existing wide-scale use in the amateur RF field. Whip antennas are ¼ the length of the wave they are intended to receive, or 20.35 inches long for 145MHz. In monopole RF antennas, a ¼ wavelength size is considered ideal in terms of omnidirectional, due to the properties of electromagnetic waves, and yields a high signal-to-noise ratio (SNR). A 5/8th wave is also common for similar reasons. A high SNR is desirable to reliably decode the transmitted APRS messages.

Additionally, the whip antenna is vertically polarized, which matches the polarization transmitted by NASA’s ground station and increases the received SNR. However, due to the horizontal orientation in which the rocket lands, the antenna must be deployed in a vertical orientation, the same orientation as the camera, to avoid decreased performance. Adding complexity, with a length of 20.35 inches, is longer than the allocated space for rotating part of the payload airframe section, which is 16 inches. This requires the antenna to be secured to the outside of the airframe and then deployed upon landing and an added electro-mechanical system to actuate the antenna. A prototype of this design is provided in figure 6.28. This qualitative prototype showed that the design is feasible, but revealed possible torque and separation issues from the antenna’s stowed position. From the prototype, additional concerns were raised about the antenna becoming stuck on debris in the launch field as the payload section rotated to orient the antenna and camera.

Overall, this design was heavily considered due to its high SNR and optimal RF characteristics but was not chosen due to the added complexity of attaching and actuating an antenna outside of the rocket. Additionally, the team found, through the testing described in section 6.4.1.2, that the mechanical complexity generated by this design was not worth the benefit.

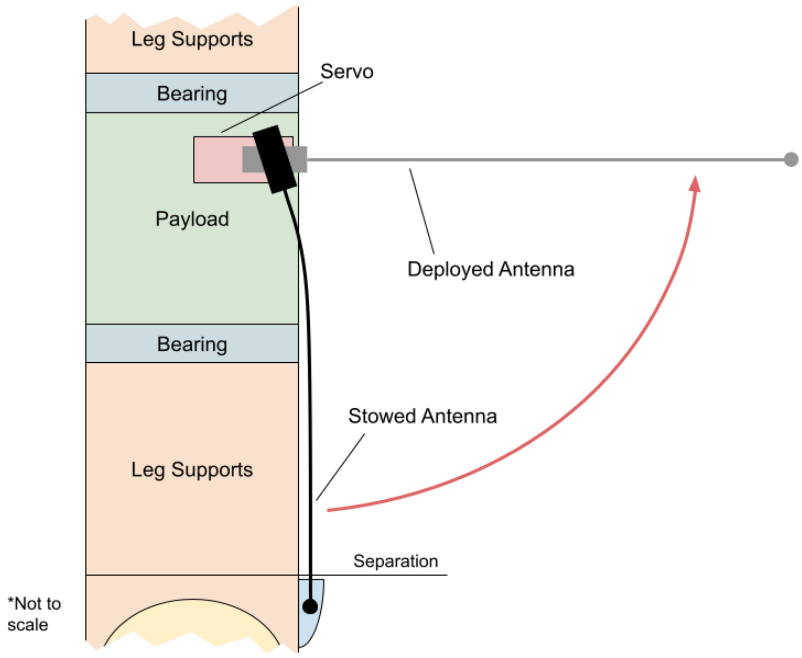


Figure 6.28: Deployment of whip antenna

6.4.1.2. Deployed electrically short monopole "rubber ducky" antenna

In antenna design, an electrically short antenna is an antenna that is smaller than ¼ of the wavelength which it is meant to receive. Common and readily available electrically short antennae are those used on handheld radios, called "rubber ducky" antennas. These antennas are small in size, less than 8 inches, which allows for them to fit inside the payload airframe section. These antennas are also commonly understood by the amateur RF community and are cheap to purchase.

In contrast with the quarter-wave whip antenna presented in Section 6.4.1.1, a rubber ducky antenna is desirable to us in physical size at the performance costs of a lower SNR. However, as with the whip antenna, the antenna still must be deployed in a vertical orientation for optimal received SNR and optimal decoding of APRS packets.

Due to the small form factor of the rubber ducky antenna, this design allows us to completely stow the antenna inside the payload airframe. This eliminates potential failure modes produced by the antenna being fixed outside the rocket completely.

The team was concerned about the reduced SNR performance and the resulting impact on decoding APRS packets. Before proceeding with the design, the team conducted a quantitative test where a HackRF One SDR transmitted APRS packets at an estimated 20 to 30 milliwatts and an RTL-SDR was stationed roughly 200 feet away with a 145MHz rubber ducky antenna. The team was able to receive and decode almost all of the transmitted APRS packets. Through the fine-tuning of SDR receiver settings, the absence of street lamps and other obstacles on the launch field, and more transmit power, the team is confident in proceeding with this design. The full test results are below in table 6.13.

Table 6.15: Packet loss for different antenna configurations

Tested Configuration	Measured Packet Loss (lower is better)
Deployed quarter-wave “whip” monopole antenna	5%
Deployed electrically short monopole “rubber ducky” antenna	6%
Non-deployed quarter-wave “whip” monopole antenna	33%
Internal electrically short monopole “rubber ducky” antenna	100%

Ultimately, this design is the leading design due to its compromises between mechanical complexity and RF performance. Initial quantitative tests show that the compromised RF performance will likely be sufficient for decoding APRS on the launch field. Additionally, this design eliminates potential failure modes from fixing an antenna to the outside of the airframe.

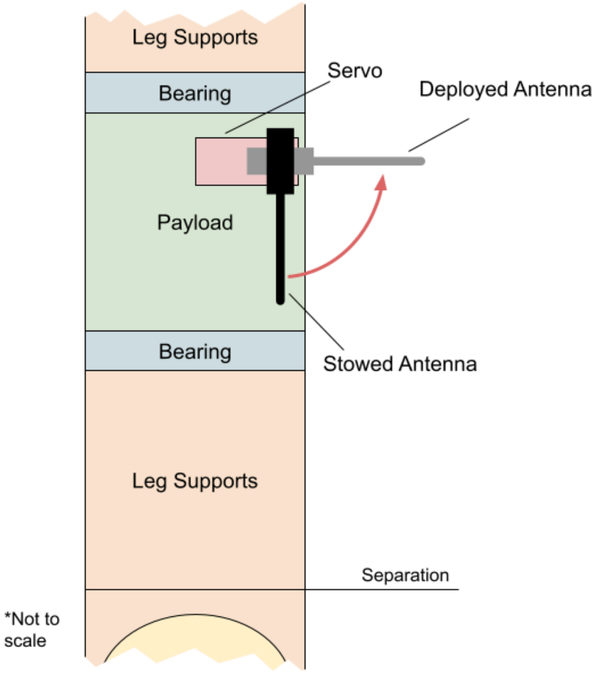


Figure 6.29: Deployment of rubber ducky antenna

6.4.1.3. Non-deployed quarter-wave “whip” monopole antenna

Similar to the “Deployed quarter-wave ‘whip’ monopole antenna” described in section 6.1.4.1, this design was pursued for its mechanical simplicity and ideal RF characteristics, mainly a high SNR which would allow for the highest success rate in receiving APRS packets. The design, shown in figure 6.30, is similar to the design presented in 6.1.4.1 except for the absence of a mechanical mechanism to rotate the antenna upon payload landing.

Due to landing in a horizontal orientation and not including a method to deploy the antenna, the team was concerned about reduced RF performance. During the same qualitative RF test, outlined in section 6.4.1.2, the team tested receiving APRS packets on the RTL SDR using the ¼ wave whip antenna in a horizontal and vertical orientation. Results showed that the whip antenna in horizontal orientation performed much worse than the rubber ducky antenna in vertical orientation.

The team decided not to use this design due to its poor RF characteristics which made receiving APRS packets, even at short ranges, worse than the smaller rubber ducky antenna in a vertical orientation. This design also brings forth increased failure modes and vehicle constraints due to the antenna's size and attachment to the outside of the airframe.

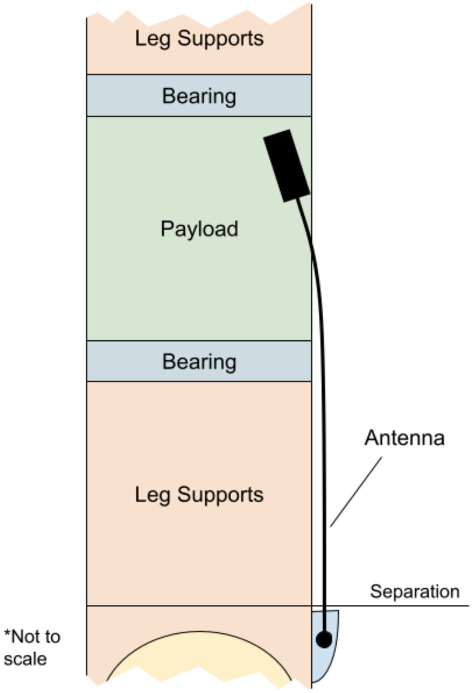


Figure 6.30: Example fixed whip antenna layout

6.4.1.4. Internal electrically short monopole "rubber ducky" antenna

The team considered utilizing an electrically short rubber ducky antenna secured in a fixed position inside the payload airframe. The benefits of this design included the removal of all electromechanical systems related to the antenna that was deployed, which removes potential failure modes. However, the team did not choose this design because of the risk that the antenna points towards the transmitting antenna, causing RF performance to drop below acceptable levels as shown in the testing in section 6.4.1.2.

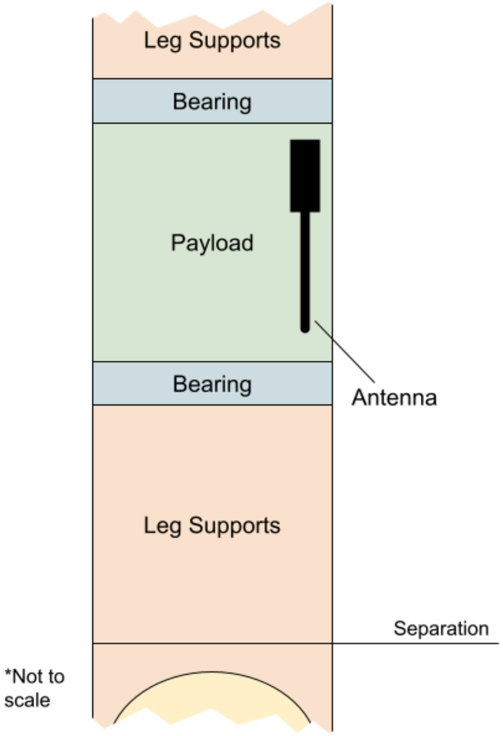


Figure 6.31: Fixed whip antenna layout

6.4.2. APRS Radio System

Table 6.16: Pros and cons of alternative SDR APRS radio systems

Alternate Designs	Pros	Cons	
RTL-SDR	• Commonly used • Very easy to find drivers, example code, and support • Easy to source, cheap and widely available	• SDR's can have a high CPU load compared to dedicated hardware	✓
Funcube Pro Plus SDR	• Possibly higher quality / lower SNR	• Less commonly used • More difficult to find and install drivers and get support • Expensive to replace • SDR's can have a high CPU load compared to	

		dedicated hardware	
Dedicated FM radio module and audio ADC	• Specially designed RF modules could have better quality then an SDR • Low CPU load	• Difficult to source • Large amount of effort to design a working system • Less flexible then an SDR	

6.4.2.1. RTL-SDR

The RTL-SDR is a software-defined radio based on the RTL2832U chip. It is very inexpensive and commonly used. The community-supported Software Development Kit (SDK) is easy to use and has first-class Linux support. The SDK is in the Raspberry Pi OS repositories; therefore, the installation will be quick and easy. In addition, due to its prevalence, examples, and tutorials for how to use the RTL-SDR to decode APRS are widely available. Due to the RTL-SDR's costs, support, availability, and current team stock, we have chosen this device as our leading design for the APRS Radio System.

6.4.2.2. Funcube Pro Plus SDR

The Funcube Pro Plus is a powerful and compact Software Defined Radio (SDR). While the Funcube Pro Plus performance is potentially better than an RTL-SDR, it is less commonly used and does not have first-class Linux support or extensive tutorials and examples. Despite extensive testing, we could not get the Funcube to work successfully with a Raspberry Pi. In addition, the Funcube is more expensive than the RTL-SDR and is not currently in stock, so it is not feasible for us to purchase a backup.

Due to the difficulties regarding the operation, lack of documentation, and the inability to purchase a backup, we decided against using the Funcube Pro Plus SDR.

6.4.2.3. Dedicated FM radio module and audio ADC

One final option that we considered was a dedicated hardware frequency modulation (FM) radio. We could not find a COTS module that met our needs; thus, we would have had to design our RF system. When compared to software-defined radio, hardware-defined radio presents substantially more challenges when testing various parameters, such as different frequencies, bandwidths, gains, and deemphasis.

Due to the lack of flexibility, increased effort, and risk posed by designing an entirely custom radio system, we decided to use a software-defined radio instead.

6.4.3. APRS Decoder System

Table 6.17: Pros and cons of alternative APRS decoder systems

Alternate Designs	Pros	Cons
Direwolf	• Very good performance when signals have interference • Generally Robust	• High CPU load
multimon-ng	• Very simple piece of software, easy to interface with and extend	• Worse performance than Direwolf in testing
Hardware terminal node controller (TNC)	• No CPU load	• Poor performance reported by others • Not flexible or extendable • Difficult to interface with SDR

6.4.3.1. Direwolf

Direwolf[50] is a software modem and terminal node controller (TNC) that can decode APRS audio signals from a radio or SDR. It employs a variety of algorithms in order to decode packets incredibly reliably, even in cases with a low signal to noise ratio (SNR), lack of pre-emphasis, or a single bit flip. The most important aspect of our decoder was its performance and packet loss, so we tested it using the "TNC Test CD" [51]. This CD contains hundreds of sample packets and is a good example of real-world packets and contains many examples of difficult-to-decode packets with low SNR. It is commonly used to evaluate TNC hardware and software. We decided to use this to evaluate our options. First, we converted the source wav files into raw audio data compatible with the decoder. Then we piped this data into each program that we were testing. Finally, we counted the number of packets that were successfully decoded. This gave us a good quantitative measure of the packet loss we could expect in real-world conditions. In testing, direwolf was able to decode nearly 100% of the packets on tracks 1 and 2, and performed significantly faster than realtime even on a comparatively slow Raspberry Pi Zero W. In other words, it's able to process the audio data at a rate faster than it would be generated.

6.4.3.2. multimon-ng

Multimon-ng[52] is a very simple software modem that can decode a variety of audio modulations, including AFSK1200 which APRS uses. Because it communicates through STDIN and STDOUT, common communication interfaces within Linux, it is very easy to route data between software applications and integrate into our payload software stack. When testing with tracks 1 and 2 of the TNC Test CD, it was able to process the data very quickly, running many times faster than realtime on a Raspberry Pi Zero W. However, it was not able to decode the majority of the packets, so it was discontinued from further testing.

6.4.3.3. Hardware Terminal Node Controller (TNC)

A terminal node controller is a piece of hardware that connects to an FM radio, decodes incoming APRS packets, and then sends them to a computer over a serial connection. We chose not to use a hardware TNC due to the following reasons. First, as TNCs are primarily designed to connect to a hardware radio, interfacing them with an SDR (our current leading APRS radio system design) would require adding an audio DAC to our payload. Also, in testing performed by John Langer[53], the creator of Direwolf, both hardware TNCs that he tested decoded over 30% fewer packets than Direwolf. Finally, using a TNC would require us to purchase and test extra hardware, and the TNC will take up a significant amount of the limited payload space. Using a software TNC has few drawbacks as the implementation written for Direwolf is not processor resource intensive.

6.4.4. Camera Filtering Library

Table 6.18: Pros and cons of alternative camera filtering libraries

Alternate Designs	Pros	Cons
OpenCV	• Experience among members • Portability of code • Compatibility with the rest of the project • Simplicity and convenience of image processing	• Large and complex documentation required for use.
MATLAB	• Simplicity and convenience of image	• Not commonly used on embedded devices or

	processing ● Used in courses at the university	for image processing ● Difficult to setup and configure ● Requires a verified Linux distribution
Physical Filter	● Lack of need for software dependencies and simplicity of design ● Decreased workload for the Electronics Payload Team	● Increased workload for the Mechanical Payload Team ● Lack of physical grayscale filter
libcamera-still command	● Very simple to use ● Pre-installed and setup on Raspberry Pi ● Built-in grayscale filter ● Built-in image rotation ● Built-in special effects filters	● Limited image processing compared to OpenCV ● Not testable outside of Raspberry Pi

6.4.4.1. OpenCV

Open Computer Vision (OpenCV) is a cross-platform library used for image and video processing with support for use in python and is the industry standard for embedded computer vision. The main advantage for OpenCV is its wide support for hardware, well-documented API, and efficient processes, all of which reduce the software development time. Additionally, OpenCV's python support makes it easy to integrate into the rest of the payload software and make use of existing team member's experience in python. The team has tested basic grayscale and line-detecting filter programs on a raspberry pi and determined that extra computational resources do not impact the processor's performance.

6.4.4.2. MATLAB

Matrix Laboratory, commonly known as MATLAB, is a piece of software that many of our team members have experience with from required coursework for all majors. MATLAB does support code execution on a raspberry pi through external libraries, called toolboxes. The team conducted a feasibility study in which we attempted to execute a grayscale filter on a raspberry pi. However, after several hours of work, we were unable to run MATLAB programs on the raspberry pi. This is in stark contrast to OpenCV, which took less than an hour for new team members to download, install, and execute.

6.4.4.3. Physical Filter

The team considered using a mechanical system to place and remove physical light filters in front of the camera lens. The advantage of this method is increased simplicity of the electrical payload subsystem at the cost of adding an additional mechanical system to actuate the physical filters. Additionally, the team could not find a source for physical grayscale in a reasonable timeframe.

6.4.4.4. libcamera-still commands

Python comes built-in with the “libcamera-still” command. This command takes a few parameters to describe . This can easily be run from python, and it supports image rotation with the “--rotation” parameter. It also has many built-in post processing filters that can be used for the grayscale and “special effects filter”. We have successfully used libcamera-still to take JPEG images using our wide-angle camera. Unfortunately, libcamera-still cannot be easily tested outside of a raspberry pi, so we haven’t been able to do extensive testing with it. In addition, it doesn’t have as many options for image processing as OpenCV, so it is not currently our leading design.

6.4.5. Orientation Subsystem

Table 6.19: Pros and cons of alternative camera filtering libraries

Alternate Designs	Pros	Cons
Integrated with existing Payload SBC	• Experience among members • Portability of code • Compatibility with the rest of the project • Simplicity and convenience of image processing	• Requires a single computational point-of-failure. • Compute resources are diverted from other subsystems
Separate Orientation Control Microprocessor	• Allows for more complex computation for orientation	• Requires additional space • Adds another failure

		mode - Additional power consumption

6.4.5.1. Integrated with existing Payload SBC

This design uses the same computer that controls the actuators in the mechanical system and processes the data given from the radio subsystem. Because all the data and computations for the payload are processed on one computer, the computer is a single point of failure. There are, however, several ways to mitigate most of the failure modes associated with a single computer including but not limited to system daemons, processor choice, and software modularity. The main benefit to an integrated computer is the electrical hardware design can be simpler compared to the alternatives outlined in 6.4.5.2 and 6.4.5.3. We have selected this solution to be in the leading design due to its simplicity and ease of integration with the existing leading payload designs.

6.4.5.2. Separate Orientation Control Microprocessor

Redundant microprocessors are common in the aerospace industry and would alleviate most of the cons found in the single microprocessor plan. However, because of the recent silicon shortage, finding additional processors has become a major challenge and would require more complexity when multiple varieties of SBCs with varying levels of compute power will suffice. Therefore, we did not choose this design because of the additional cost, risk, and complexity.

6.5. Leading Design

The leading design of the payload synthesizes the work of the mechanical and electronics and are presented as a complete and interfaced system.

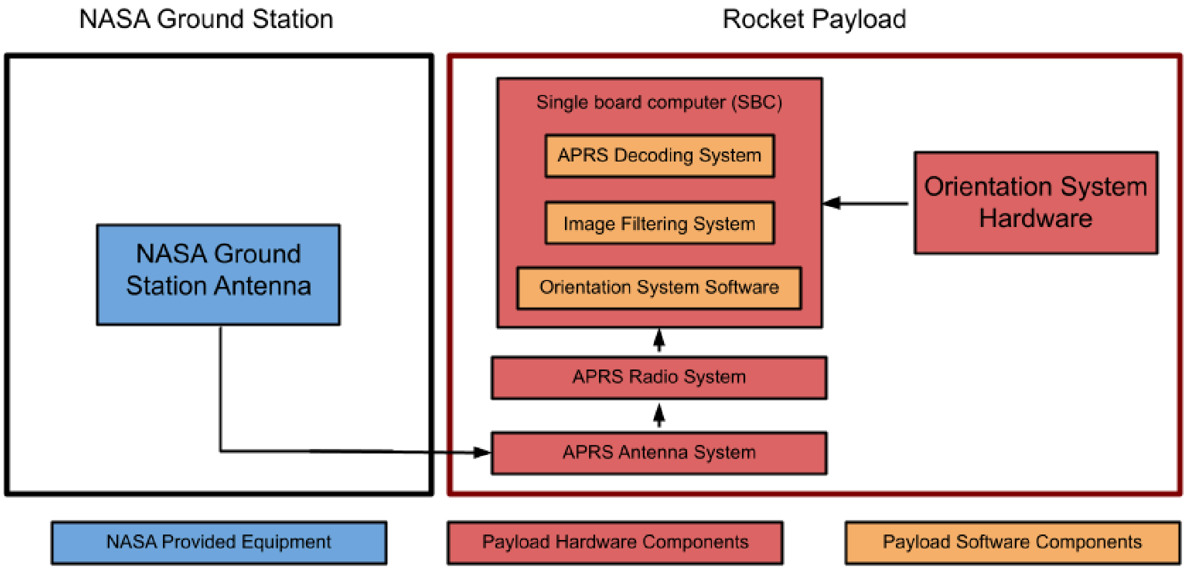
6.5.1. Electronic Subsystem

Table 6.20 compiles all of the components from the Electronics Payload and their leading design choice and the justification we used to make the final decision.

Table 6.20: Leading designs for electronic subsystems

Component	Choice	Justification
APRS Antenna System	Deployed "Rubber Ducky" antenna	• Relatively easy to deploy • Sufficient performance in testing • Balance of mechanical complexity and RF performance
APRS Radio System	RTL-SDR	• Easy to use • Widely available • Prior team experience • Extensive documentation and community support
APRS Decoder System	Direwolf	• Best performance in our testing • Official Raspberry Pi Support • Easy to integrate into payload software stack • Easy to isolate program execution and reduce risk of payload software failure
Camera Filtering Library	OpenCV	• Cross-platform support • Wide range of filters • Prior team experience • Extensive documentation and community support •
Orientation Subsystem	Integrated Payload Computer	• Provides the information needed for the camera system to be deployed in the correct orientation.

Our leading design is centered around supporting the camera deployment and antenna subsystem. Using data from the orientation subsystem, the single board computer will actuate the payload bay to orient the payload. The antenna subsystem is a direct requirement for receiving the APRS commands from NASA. We then use the radio system to take data from the antenna and convert it into a digitally sampled dataset. We then use the APRS Decoder system which takes the sample set and processes it into the commands sent by NASA. We then send these commands to the single board computer, of which there are several options, but our preferred would be a Raspberry Pi Zero 2 W. The computer then actuates the camera subsystem according to those commands and takes the pictures using the camera filtering library.



According to the received APRS commands, the program will be called with parameters to indicate whether the grayscale and or the distortion filter. Then, an image will be taken and the time it is taken will be recorded. Depending on the received commands, the grayscale filter and or the edge detection filter or no filter will be applied to the image. Lastly, the time the image is taken will be stamped on the upper left corner of the processed image, and the image will be saved to a location that will be returned as a Flowchart for process for handling image processing:

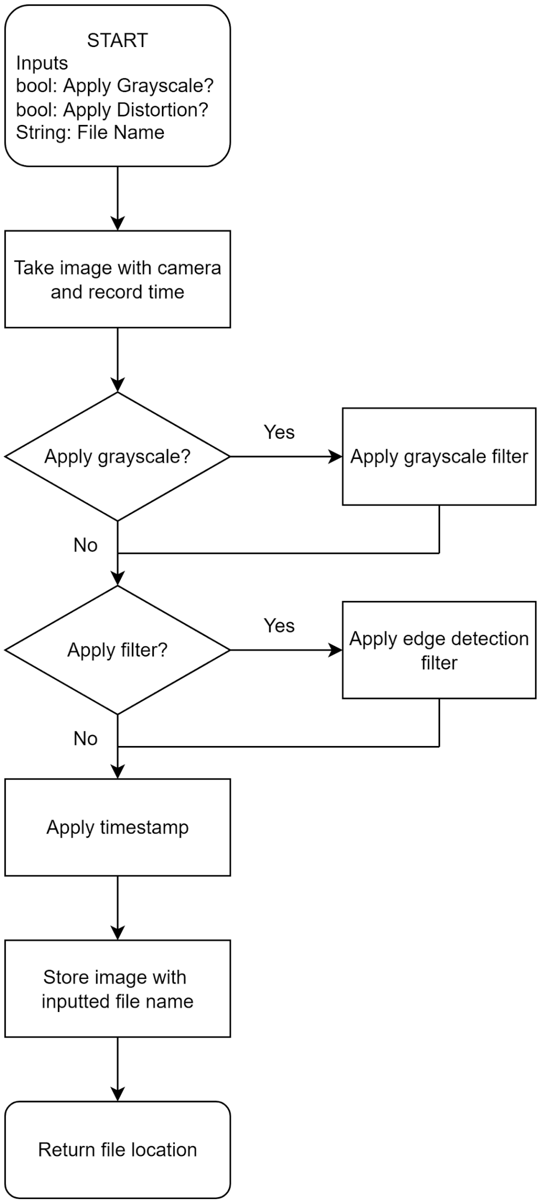


Figure 6.29: Flowchart of Image Processing

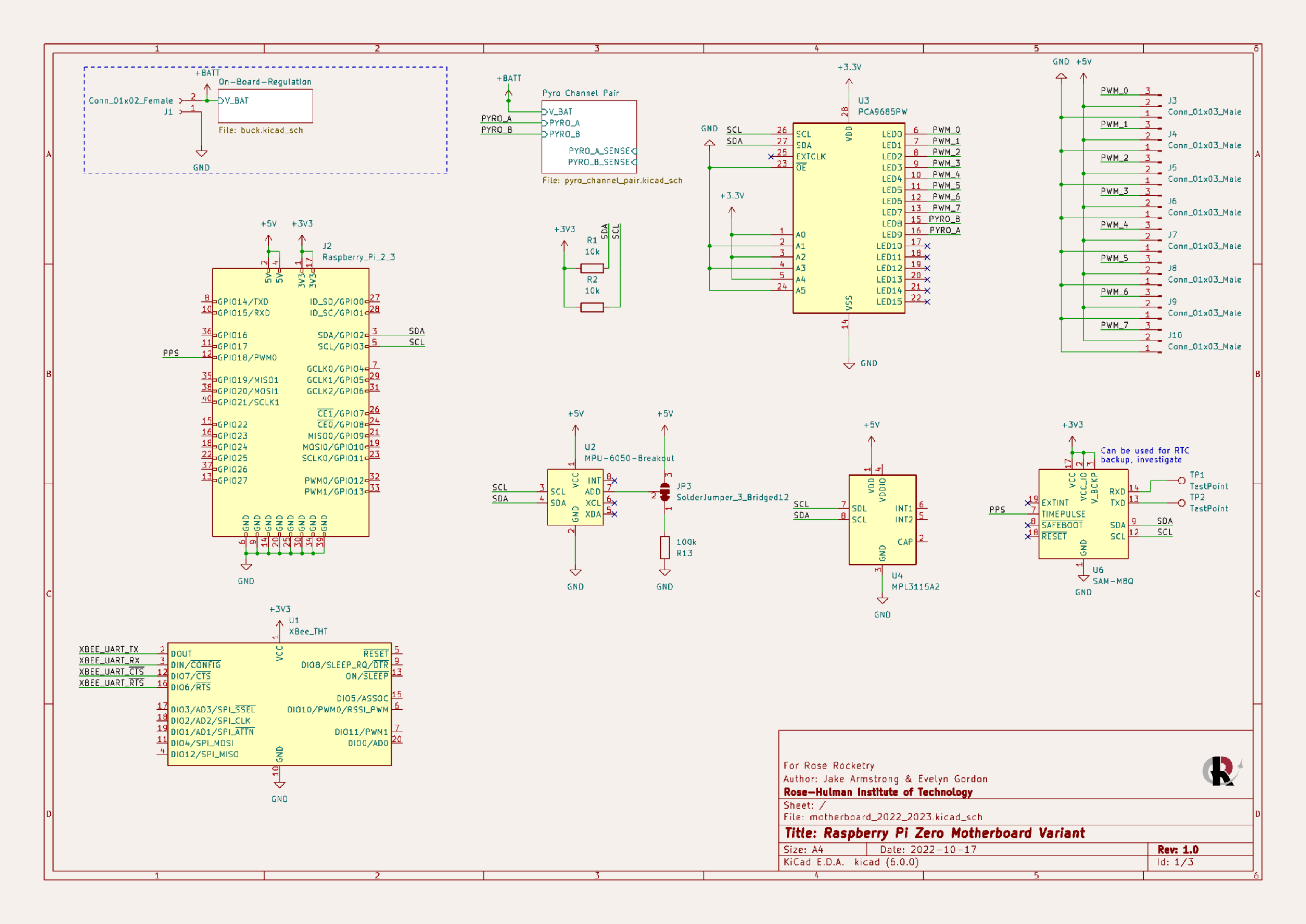


Figure 6.30: Main Schematic of Raspberry Pi Motherboard

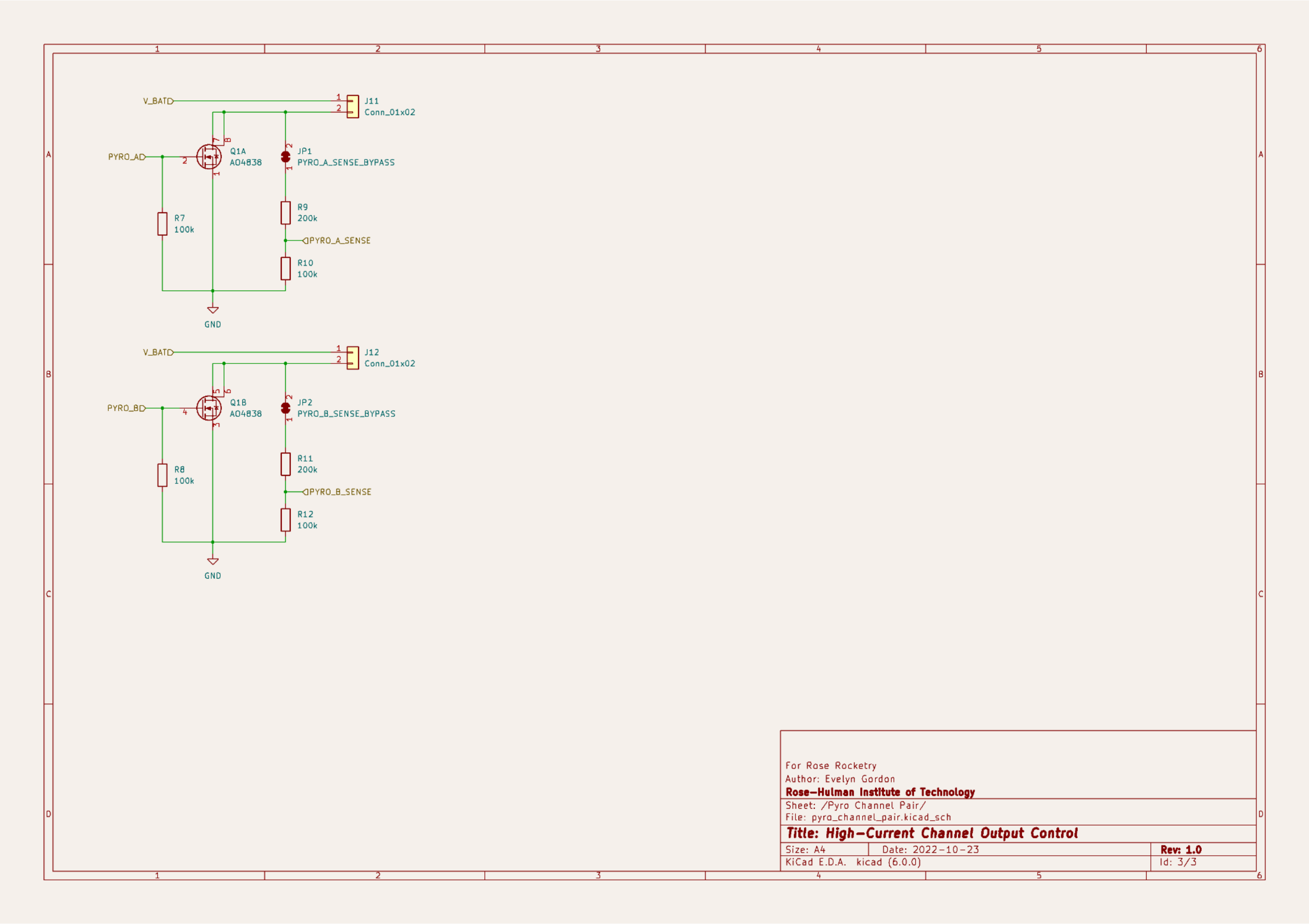


Figure 6.31: Schematic of High-Current Channel Output Control

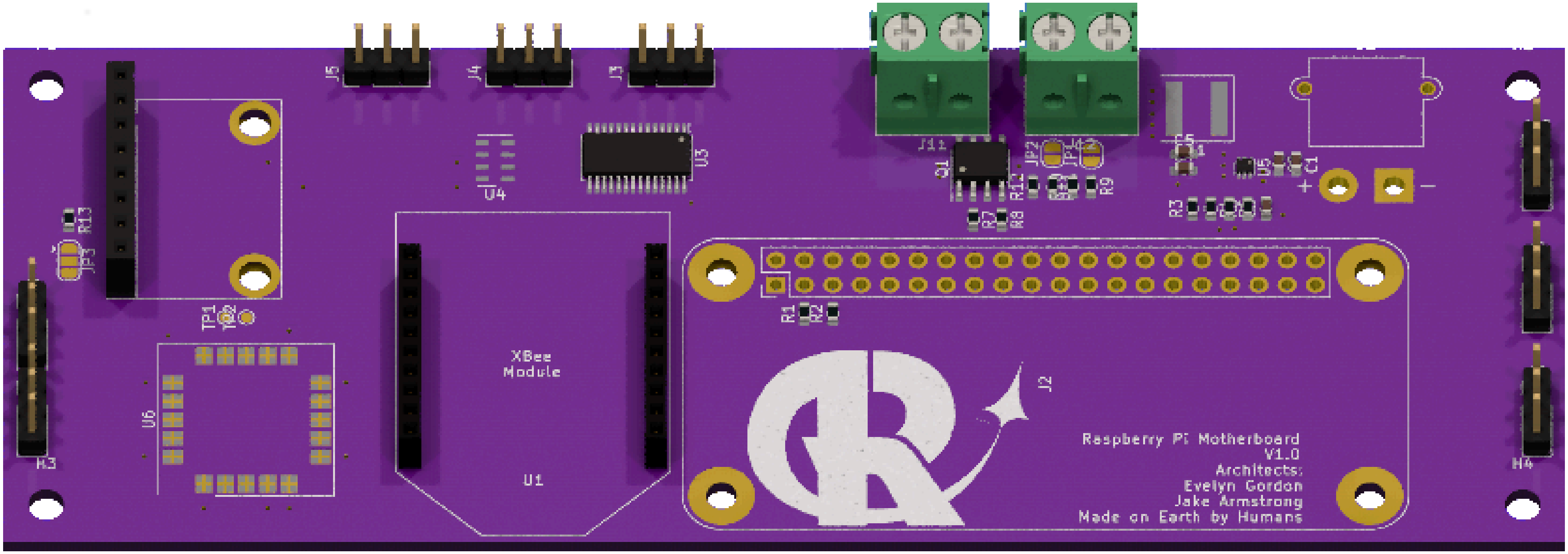


Figure 6.32: 3D Render of the Motherboard

6.5.2. Mechanical

After evaluating alternatives, the team chose the mechanical component leading design with the justifications used in Table 6.21. Their interfacing with each other and the chronology of the system is discussed in this section.

Table 6.21: Leading designs for mechanical payload components

Vehicle Characteristic	Choice	Justification
Leg Support	Simple Rotating Legs	● Mechanically simple ● Easy to actuate ● Sturdy
Rotating Section Control	3D Printed Bearing & 360 degree servo	● Customizable ● Easy to replace ● More control
Bay Door Deployment	Spring-loaded Commercial Off The Shelf (COTS) Hinges	● Known Strength ● Less deployment time ● Decreased development time
Camera Deployment	Scissor Lift	● Easy to integrate into payload sled and camera rotation ● Space efficient
Camera Stabilization	Passive Gimbal	● No actuators needed ● Compact ● Simple and cheap to manufacturer
Camera rotation	Direct Drive 360-degree Servo	● Space efficient ● Does not need gear system
Quick Release	Cord Quick Release	● Stronger material ● Less development time
Electronics Sled	3D Printed Sled	● Customizable ● Easy access and assembly ● Support for deployable structures

With the main components chosen, we moved forward with a complete design in the form of a CAD model. Figures 6.32 and 6.33 show the rotating section of the air frame containing the electrical components and all deployable elements except for the support legs.

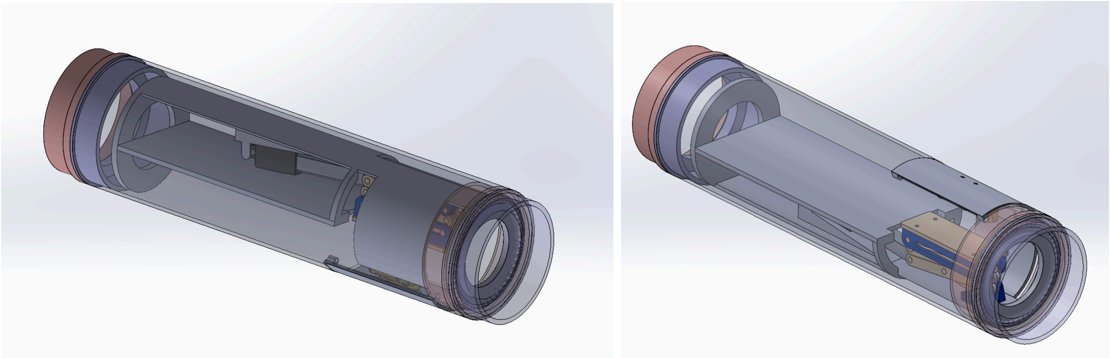


Figure 6.32a and b: The preliminary CAD for the Payload airframe

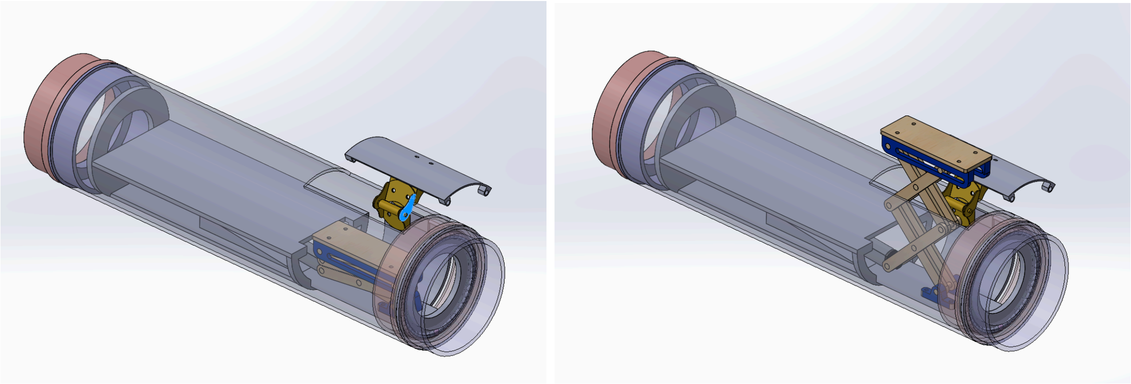


Figure 6.33: The stowed and deployed states of the bay doors and lift mechanism

The CAD shows the airframe as a translucent cylinder. The custom bearings are shown in orange on either end while the payload sled is the gray structure in the middle. Figure 6.32a shows the backside of the sled where the battery will be. The upper side (Figure 6.32b) will hold all the main electrical components. The payload is attached to the airframe using screws through the bearing structure (not pictured). The nose cone and airframe that attach to either side fit over the bearing (as a coupler). Figure 6.33 shows the order in which the payload will deploy. This CAD does not include the support legs, but they will be located outside the rotation section of the airframe.

The full chronology the payload deployment follows and is reiterated in Figure 6.34. The scissor-lift mechanism lifts the bay door with help from the spring loaded COTS hinges. The camera rotation system is an implemented direct-drive 360 degree servo mechanism mounted onto the camera. This combination of mechanical payload components create a compact, customizable system that will ensure proper deployment of the camera system. The electronics sled will be 3D printed to meet our needs and allow for easy access to the primary components seated on the sled.

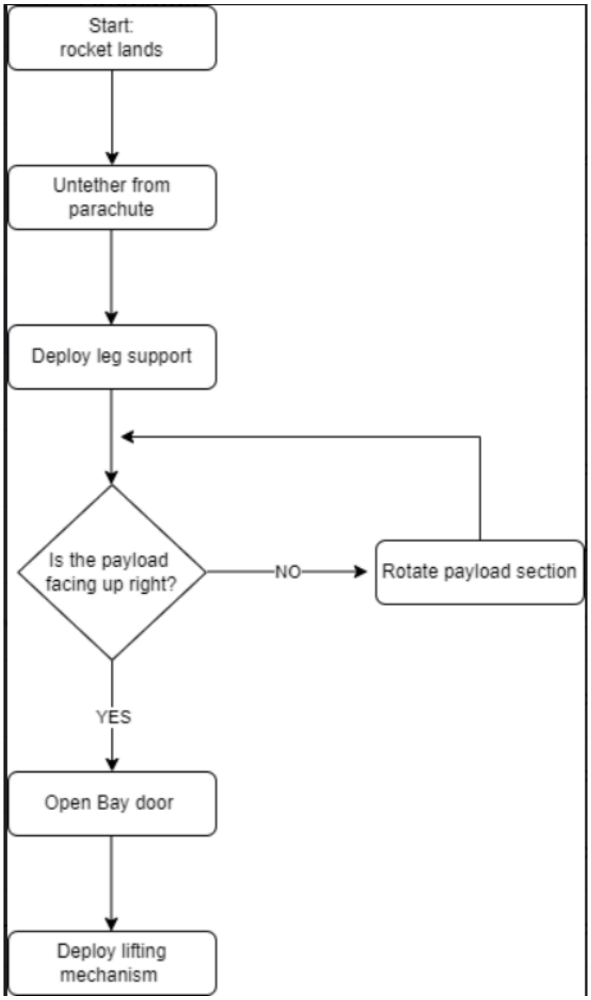


Figure 6.34: Chronology of payload deployment

6.6. Payload and Vehicle Integration

There are several ways in which the vehicle will accommodate the payload. The primary interaction will be a rotating section of the payload tube which will house most of the payload. There will be openings cut into the airframe for rotational supporting legs on either side of the airframe. In the rotating section, there is a bay door for the camera to deploy. Dimensions will be communicated to vehicle systems in order that these modifications to the airframe will be effective in supporting the payload.

7. Safety

7.1. Project Component Risks

Project Kirkpatrick consists of several different milestones as part of the NASA SL competition, and each milestone has similar components. The milestones all consist of writing the documentation, manufacturing prototypes/final systems, subscale systems, and full-scale systems, testing manufactured components, and finally launching the vehicle. This breakdown is summarized in Figure 7.1 below.

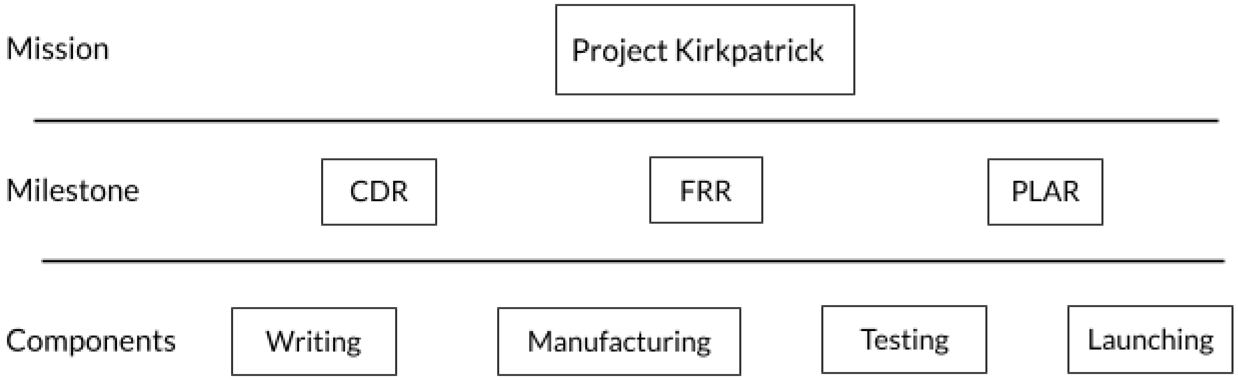


Figure 7.1: Breakdown of major mission components

Each component of the project has been assessed for the different risk factors or specific delays that could impact its timely completion. Where applicable, the specific causes of these risks and delays have been listed, and where there are many potential causes, common examples have been given.

The unmitigated risk to the project is assessed on a severity scale of 1-5 using the criteria in the Table 7.2 below. Potential mitigations have been given for the project planning stage, and a best-case scenario for the mitigated risk is evaluated. The goal of this analysis is not to present a formal mitigation plan, but to assess how easily these setbacks can be dealt with via project planning. Project delays whose severity cannot be effectively mitigated in project planning should ideally be prevented with robust design or operational procedures.

Table 7.2: Definitions of mission impact severities

Category	Value	Mission Impact
Negligible	1	No disruption

Marginal	2	Day to Week Delay
Moderate	3	1-4 Week Delay
Critical	4	Major Restructuring of Project
Catastrophic	5	Non-recoverable

Risks such as a launch cancellation or delay, motor failure, supply chain issues, or COTS manufacturing error cannot be efficiently mitigated. Most other risks/delays can be mitigated through project planning including clear communication, teaching proper handling or manufacturing techniques, or making backup plans for the most severe of delays (launch delay or cancellation being the critical example). The rest of the risks that can be mitigated can be done so using procedures, checklists, and documentation

7.1.1. Writing

Table 7.3: Risk factors or delays involved in the writing component of the mission

Risk Factor or Delay	Cause	Impact to Project	Pre-Risk	Mitigations	Post-Risk
Critical Team member absent	-Illness -Large academic workload -Personal crisis	-Delay in writing document -Gaps in information or documentation -Loss of progress	3	-Spread out workload to ensure no member is solely responsible for one aspect of the documentation	1
Lack of writing from the required team members	-Poor project management or communication	-Writing of document slow and behind -possible late submission	3	-Plan writing ahead of time -Clear communication on who is responsible for what	2
Misunderstanding of deadlines	-Poor project management -Misreading of Guidelines	-Late submission or document	2	-Redundant eyes on deadlines -Calendar with all important dates available	2

7.1.2. Manufacturing

Table 7.4: Risk factors or delays involved in the manufacturing component of the mission

Risk Factor or Delay	Cause	Impact to Project	Pre-Risk	Mitigations	Post-Risk
Parts don’t arrive on time	-Supply chain issues -Problems in component acquisition	-Delay in vehicle manufacturing	3	-Follow up with Treasurer on ordering of critical components -Order parts far in advance	2
Critical team members absent	-Illness -Large academic workload -Personal crisis	-Delay in vehicle manufacturing -Loss of information in design or construction	3	-Teach new members and create documentation detailing construction and design techniques early	2
Part damaged or broken during manufacturing	-Improper construction techniques -Miscalculation of loads sustained	-Delay for reordering or remanufacturing	3	-Order extra critical components -Teach proper construction techniques	2
Critical tool unavailable or broken	-Improper usage or storage	-Delay in construction until tool is found or replaced	2	-Have replacements for critical tools -Teach proper storage and usage	1

7.1.3. Testing

Table 7.4: Risk factors or delays involved in the testing component of the mission

Risk Factor or Delay	Cause	Impact to Project	Pre-Risk	Mitigations	Post-Risk

Damage to testing equipment	-Improper use of equipment -Carelessness	-Delay for reordering or retesting	3	-Read/understand all spec sheets prior to testing -Test with multiple eyes on the setup	2
Loss of component	-Improper testing -Ignorance in component specifications or usage	-Repeat manufacturing	3	-Read/understand all spec sheets prior to testing -Test with multiple eyes on the setup	2
Failed test	-unknown or incorrect reported specifications	-Restructuring of a system or design -Need to order or retest components	3	-Test early so delays are less of an impact	3

7.1.4. Launching

Table 7.5: Risk factors or delays involved in the writing component of the mission

Risk Factor or Delay	Cause	Impact to Project	Pre-Risk	Mitigations	Severity
Motor failure on launch pad	-Manufacturing error -Assembly error	-Loss of a section or entire vehicle	2	-Double check motor assembly	2
Launch cancellation	-High winds -Low cloud cover	-Delay in launching ranging from a week to a month	4	-plan ahead with the expectation of launch delays or cancellations -Be in contact with multiple NAR clubs to	3

				have different launch options	
Vehicle Loss	-Failure to deploy parachute -Motor failure -Motor retention failure -Black powder charges insufficient	-Repeat ordering, manufacturing, and testing of vehicle	5	-Redundant eyes on recovery preparation -Testing of black powder charges	5
Launch equipment malfunction	-Careless operation -Nominal degradation of equipment	-New launch day scheduling -Hours delay for fixing	3	None since equipment is managed by NAR club	3

7.2. Preliminary Personal Hazard Analysis

The goal of this section is to highlight some hazards to personnel and their mitigations. A hazard is an origin of injury (human impact), loss (equipment impact), or mission delay (mission impact). These are categorized by the impact and the probability described in Tables 7.6 and 7.7. The following tables also include preliminary mitigations. Throughout the project going forward, we will implement these mitigations to decrease the probability of the hazards.

Table 7.6: Definitions of severity of hazards

Category	Value	Human Impact	Equipment Impact	Mission Impact
Negligible	1	Minor or none	Minor or none	No disruption

Marginal	2	Minor injury	Minor damage	Proceed with caution
Moderate	3	Moderate injury	Repairable equipment failure	Flight delayed until event resolved
Critical	4	Serious injury	Partially irreparable equipment failure	Flight does not proceed until system removed
Catastrophic	5	Life threatening or debilitating injuries	Failure resulting in total loss of system or equipment	Flight canceled or destroyed

Table 7.7: Mapped Risk Assessment Matrix

Category	**Negligible**	**Marginal**	**Moderate**	**Critical**	**Catastrophic**
Improbable	1	2	3	4	5
Unlikely	2	4	6	8	10
Possible	3	6	9	12	15
Likely	4	8	12	16	20
Probable	5	10	15	20	25

Table 7.8: Hazards and preliminary mitigations

Hazard	Causes	Effects	Preliminary Mitigations	Reference (if any)
Fire in workspace	- Mishandling of equipment - Improper wiring	- Severe burns - Loss of part or project	-Mentor is the one the handle all black powder and motors -Wiring should be double-checked before powering	
Fire on the launch field	-Motor misfire -Accidental Black Powder ignition	-Loss of part of all of vehicle -Injury to personnel ranging from minor burns	-Adhere to NAR guidelines for minimum distance -Listen to RSO	
Airborne particle exposure	- Sanding dust - Metal shavings - Paint - Aerosols -Machining composites	- Skin laceration or irritation - Eye damage - Respiratory distress	- Use dust booths to exhaust particles - Use appropriate PPE (safety glasses, dust masks, gloves, etc.)	
Pinching	-Rapid spring movement -Rapid assembly of airframe sections	-Temporary pain -Bleeding	-Communicating pinch points to all team members	
Rocket launch failure	-Launch Equipment Failure	-Rocket striking personnel	-Adhere to NAR and RSO guidelines	NAR Safety Code

	-Motor failure	-Rocket striking objects		Number 5 [49]
Parachute Deployment failure	-Failure to communicate failed parachute deployment	-Death or excessive damage to object struck -Destruction of rocket	-Preflight Inspection -Follow all NAR safety guidelines for safe distances	
Improper use of power tools	-Negligence -Improper Power Tool Usage -Lack of Training	-Injury to appendages or person -Death	-Wear proper PPE, including safety glasses, long pants, and close-toed shoes -Make sure team members are properly trained to use power tools -Maintain a safe distance from all powered machinery	
Chemical Irritation	-Improper handling of epoxy and its resulting fumes	-Local skin irritation	-Utilize proper Personal Protective Equipment, including long pants, closed-toed shoes, and safety glasses.	
Improper use of Burn wire	-Carelesshandling of burn wire	-Burns -Lacerations	-Wear proper PPE, including safety glasses, long pants, and close-toed shoes -Use manufacturer recommendations for how to handle burn wire	

Battery electrical fire	-Improper handling of battery -Short-circuit wiring -Battery rupture	-Minor damage to battery -Burns to personal -Destruction of components	-Keep the battery in a fireproof container -Visually inspect batteries after each launch	[47]
Tripping	-Blocked walkways -Cluttered workspace	-Minor Injury -Broken bones -Delay in project	-Adhere to 5S principles	[48]
Compressed air injuries	-improper usage and handling of pneumatics	-injury to skin and sensitive parts of the body -Destruction of component(s)	-Do not use pneumatics in design -Wear proper PPE -Be aware of surroundings and others during usage	
Splinters from composite materials	-Handling of machining shards from composites -Handling of freshly cut composite stock	-Laceration or skin irritation	-Wear gloves when handling non-deburred parts -Paint or otherwise condition surfaces for flight-ready vehicles	
Activated Energetics	-Members working with open flame near energetics -Accidental energization of	-Severe burns -Kinetic impact with personnel -Destruction of rocket and/or work environment	-Keep open flames away from motors -Motors stored in fire cabinet -Fire cabinet access limited	NAR Safety Code Number 3 [49]

	igniter while handling		-Igniters installed only when vertical on pad -Using COTS motors	
120V Electrocution	-Misuse of power extension cables -Misuse of power connection -Exposed mains voltage on 3D printers	-Severe Burns -Death	-Proper use of electrical equipment -Use of fuses/circuit breaker and/or GFCI protection -Maintenance of device	
Epoxy Allergy	-Repeated skin exposure to epoxy	-Sensitivity, rash, burn around epoxy	-Correct PPE usage, limit exposure to epoxy	
Soldering burns	-Misuse of tools -Carelessness	-Minor Burns	-Properly train and work with experienced members	
Premature firing of separation charges	-Electronics misfire -Incorrect altimeter reading -Accidental ignition of black powder -Faulty e-matches	-Death -Severe injury -Severe damage to vehicle and systems	-Fully dissimilarly redundant systems -Testing recovery systems and altimeters	
Black Powder accidental ignition	-Heat near black powder -Black powder spillage	-minor burn injury	-Black Powder should only be handled by the mentor -Proper PPE and caution should be used around black powder	

Personal Injury from Terrain	-Uneven ground from clods of dirt, ditches, or puddles	-Sprained or broken ankles or hands	-Traveling in groups -Communication of seen hazards -Awareness of surroundings	
Untrained personnel in workspace	-Students allowing friends into restricted areas -Campus tours pass near work areas	-Chemical irritations -Injury due to power tools -Burns -Damage to vehicle	-Locking up irritants after use -Putting tools away after use -Tape line to discourages unauthorized entry into work area	

Table 7.9: Risk assessment of all hazards in 7.8

Identified Hazard	Risk (Probability/Severity/ Total)		
Fire in workspace	2	5	10
Fire on the launch field	2	4	8
Airborne particle exposure	2	4	8
Pinching	3	2	6
Rocket launch failure	1	5	5
Parachute Deployment failure	4	5	20
Improper use of power tools	3	4	12
Chemical Irritation	2	2	4
Improper use of Burn wire	2	3	6
Battery electrical fire	1	3	3
Tripping	4	2	8
Compressed air injuries	2	2	4
Splinters from composite materials	2	2	4
Activated Energetics	1	5	5

120V Electrocution	1	5	5
Epoxy Allergy	2	3	6
Soldering burns	3	1	3
Premature firing of separation charges	2	4	8
Black Powder accidental ignition	2	3	6
Personal Injury from Terrain	4	2	8
Untrained personnel in workspace	2	3	6

7.3. Failure Modes and Effects Analysis (FMEA)

In contrast to Section 7.2, Section 7.3 reports failure modes from one of the systems. These are hazards that specifically impact the project due to some source within a main system.

7.3.1. Vehicle

Table 7.10: Vehicle Failure Modes and Effect Analysis

Hazard	Causes	Effects	Preliminary Mitigations
Failure of recovery system deployment	-Avionics failure -Recovery entanglement -Battery depletion -Broken screw switches	-Severe damage to or loss of vehicle Risk to personnel and equipment on ground	Fully dissimilar redundancy for both drogue and main deployment Adhere to arming checklists
Motor ignition failure	-Ground equipment failure -igniter failure	-Delay in launch of vehicle	-Follow consistent procedures for igniter installation

			-Have spare igniters available at all launches
Failure of fin joints	-Weak epoxy bond -Disturbance of epoxy while setting	-Severe damage to or loss of vehicle -Risk to people due to unstable flight	Follow consistent and safe procedures for use of epoxy, use fin jig to hold fins stable while epoxy sets
Failure of airframe joints	-Improper testing of airframe strength -Improper simulation	-Rapid unscheduled disassembly of launch vehicle	Use simulation techniques to model the stresses on the frame and the strength of the frame -Test rocket airframe strength using
Tangling of parachute	-Improper packing of parachute -Improperly implemented recovery rigging	-Severe damage to or loss of vehicle -Risk to personnel and equipment on ground	-Ground-test all packing techniques used in flight -Minimize unnecessary components attached to recovery system -Follow consistent procedures in recovery preparation
Loss of aerodynamic stability during flight	- Incorrect weight balance - Damage to control surfaces - High winds	- Incorrect trajectory - Payload or vehicle damage to to impact or	- Preflight inspection - Check balance during construction - Test flights with accurate weight
Failure of airframe structure	-Improper motor class for frame -Inaccurate simulation	-Loss of rocket section(s) - Loss of components within damaged selection(s)	-Prelaunch inspection -Testing of yield strength of materials

	-Damage during construction		-Cross-check simulations to manufacturer specifications
Early detection of payload landing	-Sensor failure -Software failure -Improper programming	-Violating of NASA guidelines -Damage to deployed payload on impact -Failure to complete mission	-Software in the loop and hardware in the loop testing -Use different, redundant sensors to determining landing
Shear pin fails to shear	-Incorrect calculation of shear pin strength or black powder amount	-Vehicle segment(s) fail to separate -Loss or severe damage to vehicle on impact -Danger to personnel and property	-Ground test separation systems
Motor retention failure	-Unknown weakness in retention system due to manufacturing error	-Severe damage to vehicle	-Ensure motor retention system is robust by performing tests and redundant tests during construction
Excessive Vehicle Drift	-Early deployment of main parachute -Improper or inaccurate simulation	-Failure to meeting NASA requirements	-Use several different and redundant simulation techniques -Test Full-scale vehicle with plenty of time for retesting

Table 7.11: Vehicle failure modes risk assessment

Identified Hazard	Risk (Probability/Severity/ Total)		
Failure of recovery system deployment	3	5	15
Motor ignition failure	1	5	5
Failure of fin joints	1	5	5
Failure of airframe joints	1	5	5
Tangling of parachute	3	3	9
Loss of aerodynamic stability during flight	2	4	8
Failure of airframe structure	1	5	5
Early detection of payload landing	3	4	12
Shear pin fails to shear	3	5	15
Motor retention failure	1	5	5
Excessive Vehicle Drift	3	3	9

7.3.2. Payload

Table 7.12: Payload Failure Modes and Effect Analysis

Hazard	Causes	Effects	Preliminary Mitigations
Electrical Short	Human Error In- flight error/movement	- Loss of power to electronics -Electrical Fire	-Good solder joints and review -Ground testing -Mitigation in design
Punctured Battery	-Hard Landing -Misuse	-Potential explosion -Battery Fire	-Mitigate through design choices and awareness
Short Circuit on Battery	-User unaware of hardware design	-Life threatening or debilitating injuries -Failure resulting in total loss of system or equipment -Flight canceled or destroyed	-Label polarity
Flight Computer Resource Exhaustion	-CPU overloading -Memory swapping -Lack of disk space	-Software crash or freeze -Inability to process incoming signals or images	-Measure CPU, memory, and disk usage while testing to ensure proper headroom -Use memory-safe languages when feasible
Software crash or freeze	-Bug in software -Temporary hardware disconnect leading to software freeze	-Failure to perform payload tasks	-Extensive testing of software -Use proper exception handling

			-Use of systemd watchdog timers to detect and restart failed units -Failure-tolerant design for non-mission-critical units
Rf signal received is too weak	-Insufficient antenna -Bad antenna connection -Interference with signal from terrain or rocket parts	-Unable to decode APRS -failure of payload mission -Poor competition performance	-Antenna placement near top of rocket -Raise rocket above small terrain -Testing?
Gimbal Failure	-Breakage of supports -Breakage of gimbal -Angle of rocket too large	-Camera obscured by supports -Camera falls off the gimbal -Camera skew instead of horizontal view	-Provide enough support and gimbal material to prevent breakage -Provide enough clearance for gimbal roll and pitch
Camera rotational failure	- Servo failure -Disconnected wires -Breakage of servo Supports	-Gimbal and camera system has no yaw -Camera unable to deploy	-Provide enough support material to prevent breakage -Make sure servo wires remain connected -Make sure servo supports are connected properly
Electrical Connection Broken	-Loosely fitting connectors slipping -G-Forces pulling wire off	-Actuation of servos may not occur -Power may not be delivered to electronics	-Securing wires using one of the following: hot glue, bundling, or clamp.
Failure of springed hinge deployment	Servo release mechanism not activating	-Camera would not be able to deploy	-Proper and extensive testing prior to flight

		-Potential damage to camera	
Damage to rotation bearings	-Stress of launch and flight -poor caretaking of rocket	-Airframe could not rotate leading to no camera deployment	-Proper handling and caretaking of the rocket -Proper and extensive simulations
Burn wire failure	-Electrical failure	-fFailure of camera deployment	-Proper handling and caretaking of the rocket
Servo motor failure	-Improper motor winding	-Camera deployment will be unsuccessful	-Proper testing of the servo motor prior to flight
Hinge failure	-Weak hinge	-unsuccessful camera deployment	-Use stronger hinge -proper testing with hinge
Scissor lift failure	-Parts binding -Pivot Pin comes out during flight -Part breaks under load from launch, flight or landing	-Camera deployment unsuccessful	-Properly secure scissor lift for launch -Make sure strength is a design consideration
Orientation sensor mis-calibration	-Improper function -Breakage of supports	-Unsuccessful deployment of the scissor lift mechanism	-Rigorous testing to ensure proper sensor function
Sled failure	-High impact upon landing -Structure fracture due to inefficient design	-Electronics misplace -Servo malfunctioning	- Adding fillet / chamfer - using strong material for 3D printing -Hardware Testing
Stability leg deployment malfunction	-Burn wire doesn't break -Binding between parts of mechanism	-Payload will lack ability to effectively self-right	-Assemble legs to reduce friction and binding points -Design legs to reduce binding points

			-Test legs in adverse conditions to confirm ruggedness
Stability leg deployment fails	-Legs deploy but don't increase friction of non-rotating section of payload -Payload lands high centered	-Payload will lack ability to effectively self-right	-Design legs long enough to reach the ground in adverse landing positions

Table 7.13: Payload failure modes risk assessment

Identified Hazard	Risk (Probability/Severity/ Total)		
Electrical Short	3	3	9
Punctured Battery	2	3	6
Short Circuit on Battery	2	3	6
Flight Computer Resource Exhaustion	1	5	5
Software crash or freeze	3	4	12
RF signal received is too weak	2	5	10
Gimbal Failure	3	2	6
Camera rotational failure	3	3	9
Electrical Connection Broken	3	3	9
Failure of springed hinge deployment	3	4	12
Damage to rotation bearings	2	4	8
Burn wire failure	2	3	6
Servo motor failure	2	3	6
Hinge failure	3	3	9

Scissor lift failure	3	4	12
Orientation sensor mis-calibration	3	3	9
Sled failure	2	5	10
Stability leg deployment malfunction	2	3	6
Stability leg deployment fails	2	3	6

7.3.3. Payload Integration

Table 7.14: Payload Integration Failure Modes and Effect Analysis

Hazard	Causes	Effects	Preliminary Mitigations
Leg mechanism damage	-Spring lock mechanism deploys unexpectedly during flight -Spring lock mechanisms are unable to deploy	-Damage to and possible failure of legs -Failure of camera to orient upwards	-Mechanical and audio feedback for when payload legs are properly stowed
Failure of screws	-Improper simulation -Failure of materials	-Partial or total loss of the vehicle	–Testing of materials -Redundant simulation
Failure of bulkhead	-Improper simulation -Improper manufacturing or testing	-Partial or total loss of the vehicle	-Testing -Redundant simulation

Table 7.15: Payload failure modes risk assessment

Identified Hazard	Risk (Probability/Severity/ Total)		
Leg mechanism injury	2	3	6
Failure of screws	2	5	10
Failure of bulkhead	2	5	10

7.3.4. Launch Support Equipment

Table 7.16: Launch Support Failure Modes and Effect Analysis

Hazard	Causes	Effects	Preliminary Mitigations
Launch pad tipping or flexure	-Insufficient rail size -Insufficient pad counterweight -Pad placed on unsafe ground -Pad not secure	-Reduced margin of stability due to low launch speed -Reduced altitude due to launch angle -Increased downrange distance	-Inspect pad before launch -Ensure ground around pad is firm before mounting vehicle -”Shake test” vehicle on pad to ensure sufficient strength with installed rail
Ignition Control Failure	-Bad wiring to ignition control -Misinput to launch control	-Early or late motor ignition -Failure to ignite motor	-Check appropriate and accessible wiring

Table 7.17: Launch Support failure mode risk assessment

Identified Hazard	Risk (Probability/Severity /Total)		
Launch pad tipping or flexure	2	3	6
Ignition Control Failure	3	3	9

7.3.5. Launch Operations

Table 7.18: Launch Operations Failure Modes and Effect Analysis

Hazard	Causes	Effects	Preliminary Mitigations
Rocket caught on rail	- Rail button(s) broken - Damage to rail	- Reduced launch velocity - Launch failure	-Inspect all rails and rail buttons before launch -Ensure sufficient liftoff speed margin to account for minor rail drag
Insufficient personnel at launch	-Launch date conflicts with school deadlines -Lack of communication	-Failure to meet prep-time requirements -Expiration of launch waiver	-Early communication -Early planning of launches

Table 7.19: Launch operations failure mode risk assessment

Identified Hazard	Risk

	(Probability/Severity/Total)		
Rocket caught on rail	1	3	3
Insufficient personnel at launch	4	3	12

7.4. Environmental Hazards

Table 7.20: Environmental Hazards

Hazard	Causes	Effects	Preliminary Mitigations
Transmission of harmful RF interference to atmosphere	-Improper shielding -Excessive transmit power or duty cycle	-May interfere with other radio communications or rockets -Legal action from fcc	-Do not transmit on or near 145Mhz -Use COTS radio hardware with build-in shielding -Limit power and duty cycle in software
Damage to launch field terrain	-High kinetic energy impact with launch field	-Property damage to launch field owner	-Follow launch day procedures to ensure successful launch and recovery
Frozen Actuators	- Extreme low temperatures	- Mechanical system failure	- Choose components rated for very low temps - Test components in bad weather
Water damage	- Condensation on cold surfaces on/in components - Weather / dew	- Short circuits - Corrosion of mechanical parts	- Visual inspection of electronic components / housings / seals

			- Use waterproof housings / components
Harm to wildlife	- Failure of parachute deployment - Entanglement with parachute rigging	- Damage to vehicle - Harm to wildlife - Death to wildlife	- Check launch site before launching - Use consistent and proper practices for preparing recovery systems
Wildfire ignition due to rocket	-Rocket landing in flammable materials -Exhaust plume igniting flammable grasses	-Potential death -Potential property and infrastructure damage -Air Pollution -Use of government money to put fire out	-Launch in a clear safe area where fire danger is low
Airspace Misuse	-Improper Simulation -Failure to check air for obstacles	-Collision causing damage to rocket or aircraft -Potential death	-Check airspace before launch -Proper motor selection -Rocket inspection prior to launch
Non-recovery of vehicle	-Loss of visual tracking -Loss of GPS signal	-Inability to refly vehicle -Pollution of environment due to composite materials and electronic waste	-Test range and GPS lock of all tracking solutions before flight -Do not fly in adverse environments such as thick fog or heavy corn
Low Visibility Weather	-Weather patterns -Time of Day -Visibility of Rocket	-Failure to recover rocket	-Have vehicle ready in time for multiple back-up launches -High visibility decals and/or reflectors on rocket

Heavy winds/ Tornado	Poor weather	Damage to rocket	Inspect weather in advance and keep proper storage of the rocket
Dirt inside the rocket	-Rocket getting buried due to high impact force -Parachute dragging rocket	-Potential damage to mechanical and electrical components	-Traverse the launch site terrain with caution
Battery Failure	-Physical damage to battery -Overcurrent or other electrical fault	- Can start wildfire - Can release corrosive acids	-Structurally protect batteries from impact -Simulate and test power draw of all components
3D printed parts litter	-not recycling the plastic parts -being wasteful -printing out unnecessary parts	-ends up in landfills or oceans -killing wildlife -microplastics	-printing out parts sparingly -Use environmentally friendly filaments
High Rocket Temperature	-Weather -High temperatures	-Parts becoming warped -Servo malfunction	-Choose components rated for high heat -Test materials in high heat
Electronic Waste	-Broken Boards -Ordering boards we don't use	-Release of lead solder to environment -Release of long lasting, man-made materials into environment	-Mount boards securely -Prototyping circuits prior to ordering
Non-trained members accessing workspace	-Other competition teams letting students into workspace -School tours bringing untrained	-Broken components -Hurt members	-Create restrictive signage to the space -Put away breakable components -Put away hazardous tools or materials

Table 7.21: Environmental hazards risk assessment

Identified Hazard	Risk (Probability/Severity/ Total)		
Transmission of harmful RF interference	1	1	1
Damage to launch field terrain	3	1	3
Frozen Actuators	2	3	6
Water damage	3	3	9
Harm to wildlife	1	3	3
Wildfire due to rocket	1	5	5
Airspace Misuse	1	5	5
Non-recovery of vehicle	3	4	12
Low Visibility Weather	3	3	9
Heavy winds/ Tornado	1	5	5
Terrain	2	3	6
Battery Failure	2	4	8
3D printed parts litter	4	1	4
High Heat	2	3	6

Electronic Waste	3	3	9

7.5. Project Risks

Table 7.22: Projects risks

Risk	Causes	Effects	Preliminary Mitigations
Machine Outages	-Rocketry uses machines used by other on-campus organizations, and may not always be operable -Rocketry owned machines may not always be operable	-Critical components may not be able to be manufactured under time constraint -Lead time on components may delay interconnected aspects of project	-Secondary manufacturing methods using other machines -Manufacturing parts ahead of time when machines are known to be operable
Shipping Errors	-Delays in acquisition of or loss of materials	-Delays in manufacturing of components and systems -Delays in testing operations -Delays in flight operations	-Closely monitor status of deliveries -Use reputable shipping companies when possible -Order materials as soon as reasonably possible
Deadline missed	-Poor communication	-Large score decrease -Potential prohibition from launching	-Early deadline communication -Timeline for completion of milestone
Emotional Burnout	-Stress -Academic workload	-Low quality of work, possible mistakes	-Talk to a therapist

			-Distribute work evenly among team -Communicate feelings
Loss of important information or experience	-Sudden member departure -Lack of adequate documentation	-Redoing of work -Redesigning of lost system information	-Transferable knowledge through proper documentation
Lack of testing	-Poor organization of a timeline -Lack of commitment to timeline and deadlines	Failure of components	-Incentivizing meeting deadlines and sticking to the timeline -Usage of proper timeline softwares
Loss of code or configuration files	-Storage failure -Damage to flight computer	-Large time setback -Failure to meet deadlines	-Store all code in a central VCS -Deploy code and configurations to the flight computer through declaratively build disk images
Lack of funds	-Unable to secure sponsors or donations -Major Unplanned expenses (replacing full scale if it's destroyed)	-Unable to bring all team members to the competition. -Degraded competition performance -Withdrawal from competition	-Maintain a reserve budget -Secure vehicle and payload funds by Subscale flight -Secure all travel funds by full scale launch
Vehicle Damage or Destruction in Test Flight	- Any of FMEA hazards listed above	- High cost to repair/rebuild rocket - High time commitment to rebuild rocket	Follow all FMEA mitigations listed above

Vehicle Damage or Destruction in Building	- Improper tool use -Carelessness in handling of materials - Material defects	- Potential high cost of replacement parts - Loss of time due to waiting for new parts, rebuilding	- Follow standard safety procedures for tool use - Follow safe handling procedures for materials - Test materials for durability before attaching to launch vehicle
Procrastination	-Thinking the deadline is still far away -Prioritizes other activities	-Fails to finish rocket on time -Withdrawal from competition	-Set up personal deadlines and stick with them
Inadequate transportation	-Driving members otherwise occupied -Lack of access to a large van for rocket transportation	-Delay of launch	-Plan launches ahead of time to ensure driving members can come -Make alternate vehicle arrangements (e.g renting)
Illness	-Allergies -Global pandemic	-Delays on deliverables and vehicle fabrication	-Have members work remotely when feeling unwell -Use proper PPE and hygiene
Insufficient personnel at launches	-Conflicts with other activities -Lack of communication	-Fewer checks on procedure -Not enough hands to prep the rocket in reasonable time	-Plan launches far in advance -Announce launches at general meetings
General member loss	-Lack of interests in club events -Lack of possible involvement	-Not enough active members to compete	-Organize engaging sections

			-Encourage and reward members with their progress -Be upfront with expectations
Scheduling Conflicts	-Members taking on too many commitments	-Members not being able to attend meeting or launches	-Encourage members to refrain from taking on too much work. -Have members rank their priorities

Table 7.23: Project risk assessment

Identified Hazard	Risk (Probability/Severity/ Total)		
Shipping Errors	4	4	16
Deadline missed	2	4	16
Vehicle Damage or Destruction in Test Flight	3	5	15
Machine Outages	2	3	12
Loss of important information or experience	3	4	12
Lack of testing	3	4	12
Vehicle Damage or Destruction in Building	3	4	12

Lack of funds	2	5	10
Emotional Burnout	3	3	9
Inadequate transportation	3	3	9
General member loss	3	3	9
Scheduling Conflicts	3	3	9
Loss of code or configuration files	2	4	8
Procrastination	4	2	8
Insufficient personnel at launches	2	4	8
Illness	3	2	6

8. Project Plan

8.1. Requirements Verification

8.1.1. Vehicle

Table 8.1: Vehicle requirements verification

No.	Requirement	Justification
Vehicle		
V.1	The team will only launch at club launch sites our mentor has access to	-Easy presence of club members and mentor
V.2	Vehicle must have a Factor of Safety of 4 or greater for all stresses	(HB 2.3) Vehicle must be recovered in reflyable condition
V.3	The launch vehicle will have three sections	-(HB 2.4) The vehicle will have no more than four sections -Complexity and risk is reduced -Team already has experience with 3-section vehicles -Team sees no reason for fourth section to achieve goals
Airframe		
AF.1	Vehicle will be constructed from 4-inch tube	-(M.3) Vehicle will be sized to reach the target altitude on a K-class motor -(HB 2.15) The launch vehicle will have a minimum thrust to weight ratio of 5:1 -4-inch tubes are commercially available and at reasonable cost
AF.2	Vehicle will be constructed from 4-inch fiberglass tubing	(1.4) Vehicle will be constructed from 4-inch tube (1.7) Vehicle must be built to withstand all forces of flight (2.8) -Fiberglass is strong and commercially available

Aerodynamics		
AD.1	The target altitude for the launch vehicle will be 5,000 feet	-(HB 2.1) The vehicle will deliver the payload to an apogee altitude between 4,000 and 6,000 feet above ground Level -Provides as much margin in each direction as possible -(M.3) Reachable on a K-Class motor
AD.2	The launch vehicle will use fins to provide aerodynamic stability	-(HB 2.14) The launch vehicle must have a static stability margin of at least 2.0 at rail exit
AD.3	The launch vehicle will use a trapezoidal fin design	-() The launch vehicle will use fins to provide aerodynamic stability -(HB 2.3) Vehicle must be recovered in reflyable condition
AD.4	The fins will be constructed from fiberglass	-(HB 2.3) Vehicle must be recovered in reflyable condition -(AV.4)) The launch vehicle shall be recoverable in a state sufficient to allow failure analysis in the event of a complete loss of electrical power -Fiberglass is commercially available at a reasonable cost and has proven in past flights to survive failed landings without significant damage
Motor		
M.1	The launch vehicle will use a common and reliable igniter	-(HB 2.7) The launch vehicle will be capable of being launched by a standard 12-volt direct current firing system. -(HB 2.9) Each team shall use commercially available ematches or igniters. -Reduce chance of motor failure or off-nominal ignition sequence
M.2	The motor will use an ejection charge	-Backup and redundancy for recovery system -In the event of a total failure of avionics, the motor ejection charge will ensure the vehicle is recovered using at least a drogue
M.3	Vehicle will not fly on a motor larger than a K-class	-(HB 2.12) total impulse will not exceed 5,120N s -L-class motors have no ejection charges

8.1.2. Recovery

Table 8.2: Recovery requirements verification

No.	Requirement	Justification
Descent Control		
DC.1	The parachute will be of toroidal design	-Highest drag coefficient of parachute options -Lightest for the required performance
DC.2	72in maximum parachute diameter	-The next size up will exceed the descent time and/or drift requirements depending on wind at the launch site.
DC.3	59.8in minimum parachute diameter	-Calculations show that minimum diameter to achieve less than 55 ft lbf on the heaviest section is 59.8in
DC.4	The vehicle will not descend faster than 21.3ft/s under main	(DC.9) Each section of the vehicle will not exceed 55 ft lbf of kinetic energy on landing (HB 2.3) Vehicle must be recovered in a reusable condition
DC.5	The vehicle will descend from apogee to the ground in under 80 seconds	(HB 3.11) Teams whose launch vehicle descent, as verified by vehicle demonstration flight data, stays under 80 seconds will be awarded bonus points. -Gives margin if vehicle is lighter than expected -Reduces possible drift
DC.6	The vehicle will not descend faster than 170 ft/s under drogue	-Ensures integrity of main parachute at deploy -Reduces jerk on payload
DC.7	The drogue parachute will be no smaller than 10in	(DC.6) Vehicle will not descend faster than 170 ft/s under drogue
DC.8	The drogue parachute will be no larger than	(DC.5) Vehicle will have a descent time of less than 80 seconds

	24in	
DC.9	Each section of the vehicle will not exceed 55 ft lbf of kinetic energy on landing	(HB 3.3) Teams whose heaviest section of their launch vehicle, as verified by vehicle demonstration flight data, stays under 65 ft-lbf will be awarded bonus points. -Gives ample margin to achieve bonus points -Ensures that an unexpected reduction in parachute performance will still result in landing under the kinetic energy limit of 75 ft lbf
Avionics		
AV.1	The avionics sled shall be 3D printed	-(HB 3.3) To minimize the total weight of the vehicle, which will ensure the kinetic energy of the vehicle will not exceed 75 ft-lbf. -Team had trouble with a wooden bay in previous competitions -Electronics locations can be integrated much more easily -Will be printed as one piece, increasing structural strength -Ease of manufacturing
AV.2	The launch vehicle will have batteries capable of supporting flight for 4 hours	-(HB 2.6) The launch vehicle and payload 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 -Gives extra time -Accounts for any battery decay that may appear
AV.3	The launch vehicle will use lithium-ion batteries.	(HB 2.5) The launch vehicle will have batteries capable of supporting flight for at least a two-hour delay -Li-Po batteries are commercially available -Li-Po batteries will fit our size constraints
AV.4	The launch vehicle shall be recoverable in a state sufficient to allow failure analysis in the event of a complete loss of electrical power.	-Complete-power-off failure in a past flight caused complete destruction of the vehicle and electronics, making analysis of the cause of the failure difficult.
Separation		

System		
SS.1	The separation system will be black powder	(HB 2.3) Vehicle must be recovered in reflyable condition -Black powder has proven to be reliable -Black powder is commercially available -The team has experience with black powder separation

8.1.3. Payload

Table 8.3: Payload requirements verification

No.	Requirement	Justification
APRS Antenna		
AA.1	The antenna must be deployed so that it is angled at least 40 degrees from the positive Z direction.	In testing, leaving the antenna stowed within the rocket, parallel to its length, leads to lousy reception if the vehicle lands aimed toward the transmitter. Angling the antenna up ensures that this is not possible.
APRS Radio		
AR.1	We want to have a radio packet loss rate of less than twenty five percent.	NASA will broadcast the commands every two minutes, and we do not want to …
Single Board Computer		
SC.1	A flight computer's software must be able to be set up from scratch within 30 minutes.	If any part of the flight computer breaks, like an SD card, EMMC flash, or SBC, we need to be able to easily set up a new flight computer quickly and ensure that we know precisely how to do it. We also want to create multiple, identical flight computers easily.
SC.2	All software components must be able to be automatically restarted in case it freezes or becomes unresponsive.	In some of our testing, various components froze during exceptional conditions and did not recover unless manually restarted.

Camera Payload		
CP.1	The main avionics sled plate will have a maximum width of 95% of the total airframe diameter.	To prevent any component damage that may arise and ensure a snug fit with the airframe. This prevention also allows for vertical space along the length of the rocket for daughter boards.
CP.2	Maximum runtime of 20 seconds between picture capture commands.	We want to ensure that we have plenty of time to meet the handbook's 30-second limit, so we will ensure that we have a decent safety factor in case of any unexpected interference or lag.
Bay Door Deployment		
DD.1	The bay door must open to at least 100 degrees.	This is to ensure the camera can pass through the airframe unimpeded. This would also ensure the bay door would stay open after the actuation has been completed.
Camera Deployment		
CD.1	The payload shall be separated from the airframe after landing.	From previous experience, the parachute often catches the wind and drags the rocket after landing. We also don't want the payload dragged to keep the camera in the orientation defined in HB 4.2.1.1.
CD.2	All deployable mechanisms shall be mechanically secured during flight.	This ensures that the payload can make it to its deployment phase in its proper orientation. Improper securing could result in unpredictable aerodynamics.
CD.3	Ejecting a tethered payload from the launch vehicle shall not be an option.	If the payload is ejected (while still tethered to fulfill HB 4.2.4), we determined that the risk of interfering with recovery was too significant.
CD.4	The camera shall be deployed 3-4 inches above the airframe	The camera has a clear field of view of its surroundings and so the lens is not obscured by the airframe or bay door.
CD.5	All burn wire must be mounted within one inch of the airframe	To ensure that it is kept away from electronics and sensitive hardware near the center of the rocket.

Camera Stabilization		
CS.1	The camera must come to rest within 10 degrees of the horizon. Zero degrees is defined as the horizon in the center of the camera frame.	NASA requires the images to be “close to level showing a good balance of sky and ground using the horizon as a center line,” so we set a qualitative limit based on what we could count as level.
CS.2	Derived requirement CS.1 shall be met for every point within the 360 degrees of rotation.	A level camera is defined as the horizon line that will be within 450 pixels on the Y-axis of the camera.
CS.3	The camera shall be mounted on a gimbal stabilization platform to allow for rotational control along the x and y axis parallel to the ground.	This is to ensure the camera will be level with the horizon according to our requirement (the one two above this)

8.2. Funding Plan

The Rose Rocketry USLI Team currently has budgeted $17,368.09 for the 2023 competition season with $12,830.00 currently secured from our school's Student Government Association, innovation centers, and outside donations. The team has the necessary funds to continue project development and has ordered 51 of our 94 line items, excluding travel items. A summary of anticipated expenses by category is included below. Currently funding represents only a low project risk; continuing without raising additional funds would lead to a decrease in students traveling to competition. There are currently sufficient funds to send an adequate launch crew to competition. However, the team would prefer to bring all students to competition who want to attend.

Table 8.5: Team Budget

Consumable Supplies:	**$780.46**
General Tools:	**$964.22**
Full Scale Vehicle:	**$911.77**
Full Scale Motors:	**$1,014.48**
Subscale Vehicle:	**$490.98**
Subscale Motors:	**$154.73**
Payload Mechanical:	**$758.99**
Payload Electrical:	**$758.99**
Travel and Lodging:	**$12,042.50**
Total:	**$17,368.09**

8.3. Funding Acquisition Plan

The team receives a baseline level of yearly funding through a university program which supports various competition teams, as well as the Student Government Association (SGA). These are requested during the prior academic year, and take effect September of the following year. The team also applies for individual project funding via a "one-time funding request" process, which allots additional SGA funds on a case-by-case basis. In addition, we have been raising outside funds through alumni donations, social media donations

Table 8.4: Team Budget and Funding Sources

Budget Total:	**$17,368.09**	**Future Spending:**	**$15,339.50**	**Funding Secured Total:**	**$12,830.00**
To-date Spent:	**$2,028.59**	**Future spending without Travel:**	**$3,297.00**	**Remaining Funds to Secure:**	**$4,538.09**

8.4. Material Acquisition Plan

Rose-Hulman Institute of Technology has specific workflows to follow, depending on the source of funding being used to acquire materials. All material orders, regardless of funding source, start by placing the desired item, link to purchase, price quantity, and other related information into a spreadsheet which is also maintained by our treasurer. To ensure parts are ordered in a reasonable time for mission success, the treasurer compiles purchase requests from the master spreadsheet every Monday and Wednesday. It is the responsibility of the treasurer to set intermediate purchasing deadlines for internal deadlines, e.g subscale vehicle materials. The subteam leads are responsible for final decisions on component choices and their entry into the master spreadsheet.

After the team treasurer compiles a purchase request it is sent to the innovation center office where the funds are pulled from the specified account and the order is placed. When a manufacturer sends the team material it is first delivered to the university mailroom, then the innovation center, and finally the team workspace. The compiling of purchase orders from the treasurer, communication with the innovation center, and shipping through campus mail, can add multiple days of overhead to material acquisition.

The twice weekly purchase request and enforcement of ordering deadlines by the team treasurer ensure the team will always have the materials necessary for project success. For example, all subscale vehicle parts were ordered on October 4th. Upon checking on the order status October 19th, the team learned a miscommunication within the innovation center resulted in the order never being placed. However, the subscale vehicle materials were ordered the following day on October 20th, with confirmation, and will still arrive within the allotted time frame to construct and launch on November 12th.

8.5. Line Item Budget

Table 8.6: Line item budget

Item	Unit Cost	Quantity	Tax %	Shipping and other fees (e.g hazmat)	Total Cost	Vendor	Area of use	Status
36" X 48" fiberglass sheet	$185.00	1	8.00%	$10.00	$209.80	Composite Warehouse	Consumable Supplies	Received
Black 18 AWG wire 100'	$34.06	1	8.00%	$0.00	$36.78	Digikey	Consumable Supplies	Received
Black wire 100'	$21.46	1	8.00%	$0.00	$23.18	Digikey	Consumable Supplies	Received
Blue 18 AWG wire 100'	$34.06	1	8.00%	$0.00	$36.78	Digikey	Consumable Supplies	Received
Blue wire 100'	$21.46	1	8.00%	$0.00	$23.18	Digikey	Consumable Supplies	Received
ESD Bags	$0.22	10	8.00%	$3.00	$5.38	Digikey	Consumable Supplies	Not Ordered
Green 18AWG wire 100'	$34.06	1	8.00%	$0.00	$36.78	Digikey	Consumable Supplies	Received
Green wire 100'	$21.46	1	8.00%	$0.00	$23.18	Digikey	Consumable Supplies	Received
Header pins	$6	1	8.00%	$0.00	$6.48	Amazon	Consumable Supplies	Received

Orange 18AWG wire 100'	$34.06	1	8.00%	$0.00	$36.78	Digikey	Consumable Supplies	Received
Orange wire 100'	$21.46	1	8.00%	$15.00	$38.18	Digikey	Consumable Supplies	Received
Red 18 AWG wire 100'	$34.06	1	8.00%	$0.00	$36.78	Digikey	Consumable Supplies	Received
Red wire 100'	$25.38	1	8.00%	$0.00	$27.41	Digikey	Consumable Supplies	Received
Screw switch	$7.00	10	8.00%	$4.50	$80.10	CS Rocketry	Consumable Supplies	Received
Shear pins	$8.88	1	8.00%	$0.00	$9.59	Amazon	Consumable Supplies	Not Ordered
Whilte wire 100'	$25.38	1	8.00%	$0.00	$27.41	Digikey	Consumable Supplies	Received
White 18 AWG wire 100'	$34.06	1	8.00%	$0.00	$36.78	Digikey	Consumable Supplies	Received
XT30	$12	2	8.00%	$0.00	$25.92	Amazon	Consumable Supplies	Received
Yellow 18AWG wire 100'	$34.06	1	8.00%	$0.00	$36.78	Digikey	Consumable Supplies	Received
Yellow wire 100'	$21.46	1	8.00%	$0.00	$23.18	Digikey	Consumable Supplies	Received
Full Scale motor (approx)	$165.19	5	8.00%	$0.00	$892.03	Wildman Rocketry	Full Scale Motors	Not Ordered
Full Scale motor case	$113.38	1	8.00%	$0.00	$122.45	Wildman Rocketry	Full Scale Motors	Not Ordered
1/8" fiberglass sheet	$19.80	4	8.00%	$0.00	$85.54	Wildman Rocketry	Full Scale Vehicle	Not Ordered

2.1 1 ft Fiberglass Motor Tube	$15.84	1	8.00%	$0.00	$17.11	Wildman Rocketry	Full Scale Vehicle	Not Ordered
Aeropack retainer	31	2	8.00%	$5.00	$71.96	Wildman	Full Scale Vehicle	Not Ordered
Airframe tube (5ft)	$128.43	2	8.00%	$15.00	$292.41	Wildman Rocketry	Full Scale Vehicle	Not Ordered
Coupler tube	$2.86	36	8.00%	$0.00	$111.20	Wildman Rocketry	Full Scale Vehicle	Not Ordered
Drogue chute	$31.95	1	8.00%	$0.00	$34.51	Wildman Rocketry	Full Scale Vehicle	Not Ordered
Fullscale nose cone	$75.90	1	8.00%	$0.00	$81.97	Wildman Rocketry	Full Scale Vehicle	Not Ordered
Main chute	$139.00	1	8.00%	$0.00	$150.12	Wildman Rocketry	Full Scale Vehicle	Not Ordered
Motor retainer	$31.00	2	8.00%	$0.00	$66.96	Wildman Rocketry	Full Scale Vehicle	Not Ordered
128GB Micro SD Card	$17.00	1	8.00%	$0.00	$18.36	Amazon	General Tools	Received
128gb sd card (2 pack)	$26.00	1	8.00%	$0.00	$28.08	Amazon	General Tools	Received
eevblog multimeter	1	130	8.00%	$10.00	$150.40	Eevblog	General Tools	Not Ordered
Eggfinder antenna kit	$12.00	2	8.00%	$0.00	$25.92	Eggtimer	General Tools	Not Ordered
Eggfinder Kit	$80.78	2	8.00%	$0.00	$174.48	Eggtimer	General Tools	Received
Eggfinder Mini Kit	$59.50	1	8.00%	$0.00	$64.26	Eggtimer	General Tools	Received
Eggtimer Proton	$80.78	1	8.00%	$0.00	$87.24	Eggtimer	General Tools	Not Ordered

ESD Mat	$80.00	1.00	8.00%	$10.00	$96.40	Esdmat	General Tools	Not Ordered
ethernet adapter	$13.00	1	8.00%	$0.00	$14.04	Amazon	General Tools	Ordered
Key switch	$14.52	2	8.00%	$0.00	$31.36	Digikey	General Tools	Received
M3 screws of different sizes	$11.00	1	8.00%	$0.00	$11.88	Amazon	General Tools	Ordered
More flat jumper wires	$7.00	2	8.00%	$0.00	$15.12	Rose Hulman	General Tools	Ordered
RPi Pico	$4.00	1	8.00%	$0.00	$4.32	Digikey	General Tools	Received
rrc3 data cable	$25.00	1	8.00%	$0.00	$27.00	Animal Motor Works	General Tools	Received
rrc3 lcd display	$40.00	1	8.00%	$10.00	$53.20	Animal Motor Works	General Tools	Ordered
RTL-SDR	$29.95	2	8.00%	$0.00	$64.69	Amazon	General Tools	Not Ordered
SD cards x5	$17	2	8.00%	$0.00	$36.72	Amazon	General Tools	Ordered
Soldering magnifier	$45.99	1	8.00%	$0.00	$49.67	Amazon	General Tools	Ordered
Tweezers	$10.25	1	8.00%	$0.00	$11.07	Amazon	General Tools	Ordered
25x Female SMA connector	$10.99	1	8.00%	$0.00	$11.87	Amazon	Payload Electrical	Ordered
BuckConverter	$1.85	3	8.00%	$0.00	$5.99	Digikey	Payload Electrical	Not Ordered
Capacitors	$0.01	100	0.00%	$0.00	$1.00	Rose-Hulman	Payload Electrical	Not Ordered
Inductors	$3.35	3	8.00%	$0.00	$10.85	Digikey	Payload Electrical	Not Ordered
long sma cable (2 pack)	$10.00	1	8.00%	$0.00	$10.80	Amazon	Payload Electrical	Not Ordered

Nichrome MOSFETS	$0.80	6	8.00%	$0.00	$5.18	Digikey	Payload Electrical	Not Ordered
Oshpark PCB (3 pack)	$65.00	2	8.00%	$10.00	$155.60	Oshpark	Payload Electrical	Not Ordered
PWM Extension (LED Driver)	$2.94	5	8.00%	$0.00	$15.88	Digikey	Payload Electrical	Not Ordered
raspberry pi zero 2 w	$90.00	2	8.00%	$0.00	$194.40	Amazon	Payload Electrical	Not Ordered
Resistors	$0.01	100	0.00%	$0.00	$1.00	Rose-Hulman	Payload Electrical	Not Ordered
rubber ducky antenna	$12.00	1	8.00%	$0.00	$12.96	Amazon	Payload Electrical	Not Ordered
Screw Terminal Block	$6.88	1	8.00%	$0.00	$7.43	Amazon	Payload Electrical	Not Ordered
short sma cable (4 pack)	$13.00	1	8.00%	$0.00	$14.04	Amazon	Payload Electrical	Not Ordered
sma adapters	$13.00	1	8.00%	$0.00	$14.04	Amazon	Payload Electrical	Not Ordered
SMT Breakout PCB for SOIC-28 or TSSOP-28	$4.95	1	8.00%	$4.00	$9.35	Adafruit	Payload Electrical	Not Ordered
SMT Breakout PCB for SOIC-8	$2.95	1	8.00%	$0.00	$3.19	Adafruit	Payload Electrical	Not Ordered
Super-elastic Signal Stick: SMA male	$25.00	2	8.00%	$8.00	$62.00	Signal Stuff	Payload Electrical	Received
Wide Angle Pi Camera	$19.99	2	8.00%	$4.00	$47.18	Arducam	Payload Electrical	Ordered
XBee®-PRO 900HP/XSC RF Modules	$65.44	2	8.00%	$0.00	$141.35	Digikey	Payload Electrical	Not Ordered

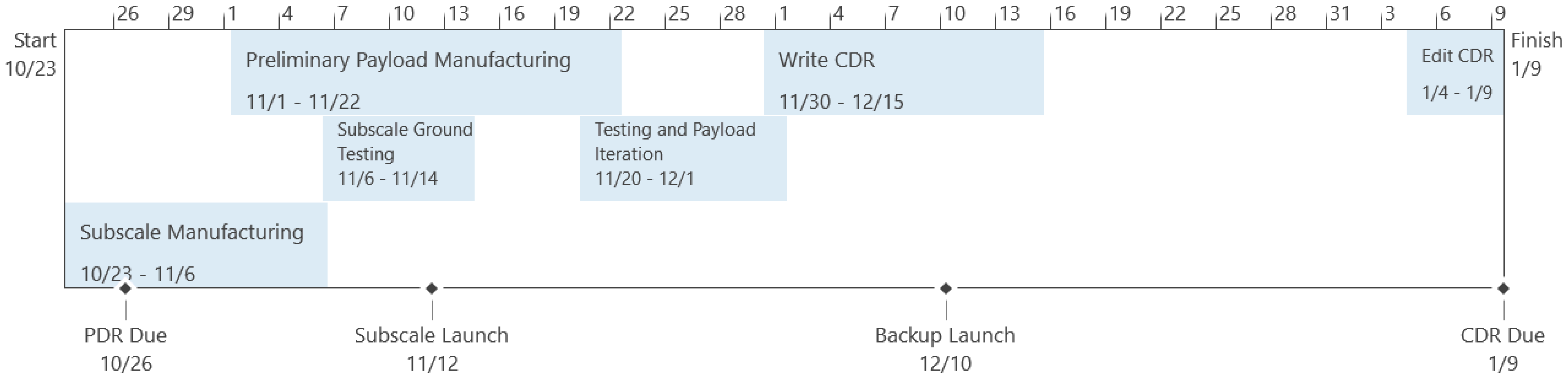
2" Stroke Linear Servo	$30.99	1	8.00%	$0.00	$33.47	Amazon	Payload Mechanical	Not Ordered
25 kg*cm Servo	$16.00	2	8.00%	$0.00	$34.56	Amazon	Payload Mechanical	Received
5mm Steel Rod	$6.00	1	8.00%	$0.00	$6.48	Amazon	Payload Mechanical	Received
Ball Bearing	$6.75	1	8.00%	$0.00	$7.29	McMaster-Carr	Payload Mechanical	Not Ordered
Burn wire	$9	1	8.00%	$0.00	$9.72	TEMCO	Payload Mechanical	Not Ordered
Sample quick release 1	$26.44	1	8.00%	$0.00	$28.56	Amazon	Payload Mechanical	Not Ordered
Sample quick release 2	$14.99	1	8.00%	$0.00	$16.19	Amazon	Payload Mechanical	Not Ordered
Sample quick release 3	$25.04	1	8.00%	$0.00	$27.04	Amazon	Payload Mechanical	Not Ordered
Servo 5V	$10	1	8.00%	$0.00	$10.80	Amazon	Payload Mechanical	Received
Servo Chucky	$14	1	8.00%	$0.00	$15.12	Amazon	Payload Mechanical	Received
Spring Loaded Hinges	$2.50	4	8.00%	$0.00	$10.80	Mcmaster Carr	Payload Mechanical	Received
Springs	$7.85	1	8.00%	$0.00	$8.48	Mcmaster Carr	Payload Mechanical	Received
Thrust bearing	$12.76	1	8.00%	$5.00	$18.78	Mcmaster Carr	Payload Mechanical	Received
Torsional Springs	$6.00	1	8.00%	$0.00	$6.48	Mcmaster Carr	Payload Mechanical	Received

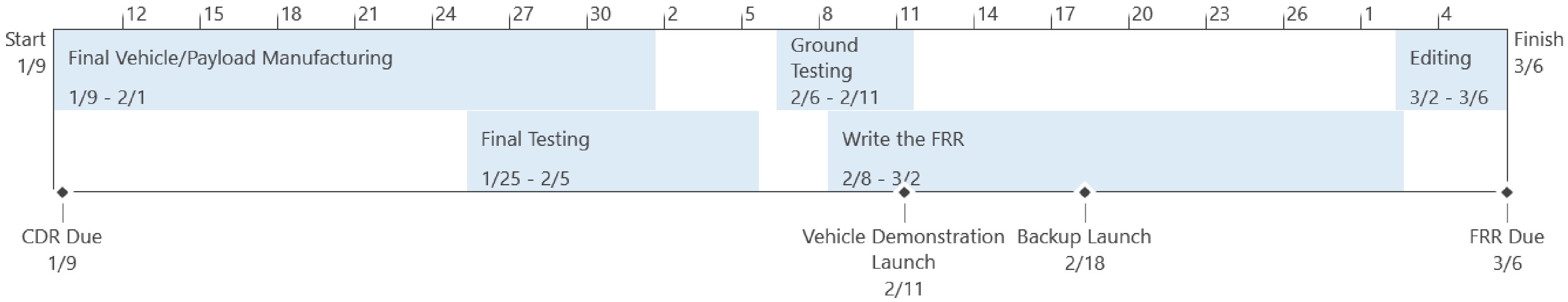
Torsional Springs	$6.00	1	8.00%	$0.00	$6.48	Mcmaster Carr	Payload Mechanical	Not Ordered
J760WT	$115.49	1	8.00%	$30.00	$154.73	Wildman Rocketry	Subscale Motors	Not Ordered
1/4" eyebolts	$5.37	10	8.00%	$0.00	$58.00	Wildman Rocketry	Subscale Vehicle	Ordered
2.1 1ft Fiberglass Motor Tube	$15.84	1	8.00%	$15.00	$32.11	Wildman Rocketry	Subscale Vehicle	Ordered
3.0 13" Fiberglass Coupler	$2.54	13	8.00%	$0.00	$35.66	Wildman Rocketry	Subscale Vehicle	Ordered
3.0OD 5ft Fiberglass Airframe	$112.81	1	8.00%	$0.00	$121.83	Wildman Rocketry	Subscale Vehicle	Ordered
Harness set for 3" rockets	$64.00	1	8.00%	$0.00	$69.12	Wildman Rocketry	Subscale Vehicle	Ordered
Kevlar strap	$4.50	1	8.00%	$0.00	$4.86	Wildman Rocketry	Subscale Vehicle	Ordered
Recon Recovery 60" Parachute	$91.95	1	8.00%	$0.00	$99.31	Wildman Rocketry	Subscale Vehicle	Ordered
Wildman Nosecone 3.0 5-1	$64.90	1	8.00%	$0.00	$70.09	Wildman Rocketry	Subscale Vehicle	Ordered
Meals (Per Person)	15	60	0.00%	$0.00	$900.00	N/A	Travel and Lodging	Not Ordered
Mentor Hotel (Per night)	135	5	0.00%	$0.00	$675.00	N/A	Travel and Lodging	Not Ordered
Mentor Van Rental (Per 5 Days)	600	1	0.00%	$0.00	$600.00	N/A	Travel and Lodging	Not Ordered

Mileage Reimbursement (1000 mile trip at 20 MPG and $3.95 per gallon)	197.5	5	0.00%	$0.00	$987.50	N/A	Travel and Lodging	Not Ordered
Mileage Reimbursement (1000 mile trip at 20 MPG and $3.95 per gallon)	630	1	0.00%	$0.00	$630.00	N/A	Travel and Lodging	Not Ordered
Student Hotel (Per 5 nights at $150 per night)	750	7	0.00%	$0.00	$5,250.00	N/A	Travel and Lodging	Not Ordered
Van Rental (Per 5 Days)	600	5	0.00%	$0.00	$3,000.00	N/A	Travel and Lodging	Not Ordered

8.6. Timeline

Project Kirkpatrick is broken down into the NASA milestones provided as well as self-imposed sections seen in Figures… All launch dates are determined by when our home club, Indiana Rocketry Inc., has High-Power launches nominally. The blue boxes show tasks to be completed while the diamonds on the bottom represent important dates and deadlines.





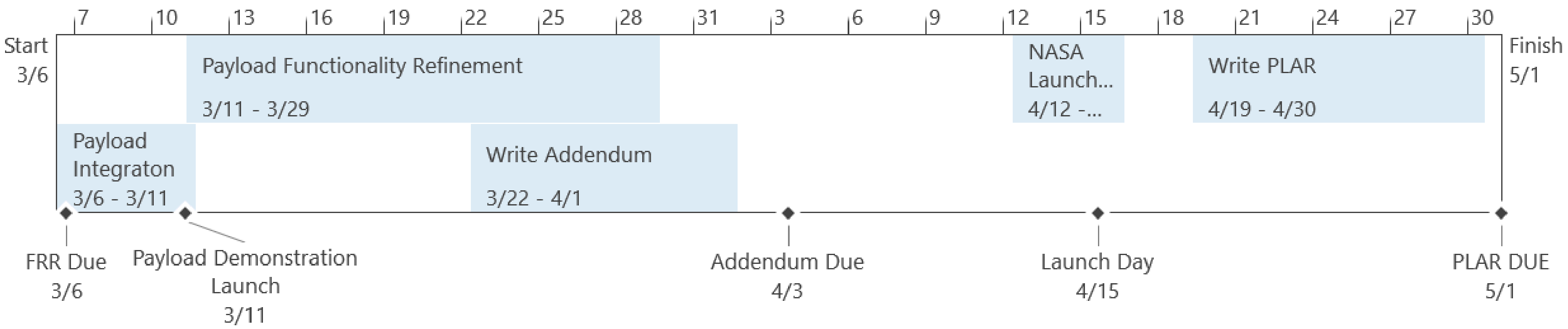


Figure 8.1: Timeline of main competition components from the PDR to the PLAR

The weekly schedule is present below; this schedule applies for normal working periods, and is modified to accommodate upcoming milestones. General Meetings are meetings for the entire club and consist of announcements and updates from all the subteam leads about progress from the last week and problems they may have encountered. All subteam meetings are only for the subteam members and the subteam lead of the subsystem. System Integration Meetings are designed to facilitate decision making between subteams by bringing a topic that is relevant to all the subteams and discussing it in the context of subteam integration.

Table 8.5: Weekly Rose Rocketry Schedule

Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
6-7pm - System Integration Meeting 7-9pm - General Meeting	6-8pm - ECE Payload subteam Meeting	5:00 pm - Vehicle Systems subteam meeting 7:30-pm - ME Payload subteam Meeting			5:00 pm - Vehicle Systems subteam Meeting	3 -4pm - Officer Meeting 4-8pm - Work time

9. STEM Engagement

As part of the NASA Student Launch STEM Engagement requirement, the team has a plan with a combination of activity types to educate students in STEM related concepts. The breakdown of activities are as follows:

- Direct Education Engagement from hands-on activities in Scouting Merit Badges and Middle and High School Activities
- Indirect Education Engagement from the After School Matters program
- Direct Outreach Engagement from USLI Team Presentation
- Indirect Outreach Engagement from the Career Fair Presentation Table.

9.1. Scouting Merit Badges

The team consists of Merit Badge Counselors (MBCs) who mainly teach STEM based courses. The breakdown of requirements are described below from individual Merit Badge Pamphlets. Through a mixture of large merit badge events and small, local, troop-wide merit badge workshops, a significant portion of the STEM Engagement requirement will be met. The team plans on registering MBCs for the 2023 Merit Badge University on February 25, 2023, at York High School in Elmhurst, IL through the Three Fires Council. One MBC from Troop 100 within the team has contacted the troop in doing the following Merit Badges:

9.1.1. Space Exploration

Requirement 3: The team plans on having each scout build, launch, and recover his or her own model rocket as well as identify and explain the parts of a rocket. The rockets will be built to meet NAR safety codes and safety standards will be explained to the scouts.

9.1.2. Engineering

Requirement 1: The team plans on having each scout select a manufactured, household item and investigate the inner workings of the item. The scouts will discuss with the MBCs what engineering activities were involved in creating the item.

Requirement 5: The scouts will do one of the following

a. Using the systems engineering approach to make step-by-step plans for a campout by listing alternative ideas for items such as program schedules, campsites, transportation, and costs. The scouts will then describe what choices and improvements they made.
b. Making an original design for a piece of patrol equipment by using the systems engineering approach and drawing plans for it. The scouts will show the plans to the MBCs and explain the design process.

Requirement 6: The scouts will do one of the following

a. Using common materials or a construction set, the scouts will make a simple model that will demonstrate motion and explain how the model uses basic mechanical elements like levers and inclined planes to demonstrate that motion. The scouts will then describe an example where the mechanism is used in a real product.
b. Discussing with MBCs the differences in strength and heat conductivity in wood, metal, and plastic by doing experiments tests on the materials.
c. Describing to MBCs what energy is and how energy is converted and used in surroundings by doing an experiment to show how mechanical, heat, chemical, solar, and electrical energy may be converted among each other.
d. Entering a project in a science or engineering competition and discussing with MBCs what the scouts' projects demonstrated and how well they were able to answer visitors' questions.

9.1.3. Robotics

Requirements 4 and 5: The scouts will design, build, and test a robotic system, of at least 2 degrees of freedom, including programming and sensor feedback, to complete a chosen task. The design process, accomplishments, and tests will be documented in a robot engineering notebook along with suggestions on improving the robot. The robotic system will be demonstrated to the MBCs and the scouts will present their robot engineering notebook.

9.1.4. Aviation

Requirement 2: We plan on providing the scouts aeronautical charts to learn and read. The scouts are instructed to measure and establish a true course on the chart and correct it for magnetic variation, compass deviation, and wind drift to determine a compass heading. Then, using a flight simulator software package available for computers, the scouts will "fly" the course and heading they established. Rose-Hulman Institute of Technology has a Design-Build-Fly team that we can collaborate with to secure resources such as flight simulation software to provide the scouts to use.

Requirement 3: The scouts will do one of the following

a. Building and flying a fuel-driven or battery-powered electric model airplane. The scouts will describe safety rules for building model airplanes such as glue, paint, plastics, fuel, and battery pack, as well as flying them.
b. Building and organizing a model FPG-9 competition to test the precision of aircraft flight and landing.

9.2. FIRST Robotics Competition Activities

9.2.1. Downtown Trick or Treat

FIRST is a national non-profit who hosts robotics competitions for students, most notably high school students through FIRST Robotics Competition (FRC). FRC's and NASA SL's STEM engagement program share a common mission of engaging the community and Rose Rocketry will be partnering with our local FRC team to host a STEM booth with rocketry and robotics demonstrations at our community's downtown trick or treat event.

9.3. Middle and High School Activities

9.3.1. USLI Team Presentation

We will visit middle school classrooms to present about Rose Rocketry and talk about the engineering process as well as our member's experiences as part of the team. During our visit, we will share our progress designing this year's competition rocket and present last year's rocket and electronics sleds. In September, our team members presented at Sarah Scott Middle School. We engaged students and answered questions such as our successes and failures of last year's design and how our presented members personally developed an interest in rocketry. Students will learn about the engineering design process and future career paths within STEM.

9.3.2. OpenRocket Simulation

When visiting middle and high schools, the plan is to teach and have the students simulate a model rocket that they design. The team will use the EDGE method here to explain why simulation is important when doing a preliminary design, the tools required to carry those simulations, and how that specifically applies to rocket design. The team will then demonstrate to the students how to build a rocket using OpenRocket and guide the students in generating a simple altitude prediction on a rocket that each student builds. The team then effectively enables the students to carry out simulations on their next model rockets.

9.3.3. Physics Demonstrations

We will visit middle school classrooms to provide an overview of physics and topics including Newton's Laws, Inertia, Linear and Angular Momentum, and Centrifugal force. Students will learn these concepts through demonstrations using simple objects and will then do the demonstrations themselves. This presentation will give students a greater understanding of physics concepts and be able to connect real world systems to the physics behind them.

9.3.4. Egg Drop Challenge

The egg drop challenge demonstrates the engineering process using household items. As part of this activity, students will have time to brainstorm, construct, and test a container for an egg that will be dropped from a certain height. Successful containers will prevent the egg from cracking or breaking after being dropped. This is a friendly competition between students with a small prize for the student with the lightest successful container. This project gives students hands-on experience of the engineering design process and develops their creativity.

9.3.5. Snap Circuits

Snap Circuits is an electronic kit containing several science experiments for students to try. We will visit a classroom and explain basic electronics concepts including voltage, current, power, resistance and how circuits, resistors, capacitors, and LEDs work. Students will gain an understanding of electronics and be able to conceptualize how electronics function.

9.3.6. After School Matters

After School Matters is a Chicago-based non profit organization which provides teens with skills learned during paid after-school programs. We will visit the Advanced Audio Electronics program to showcase Rose Rocketry and share our knowledge of working with radio frequency hardware at an engineering level. Students will gain a greater understanding of the electrical and computer engineering process as applied to rocketry.

9.4. University Presentation Tables

9.4.1. Career Fair

On career fair day, we set up a table showcasing last year’s competition rocket and subscale, hardware, and software. We presented our current progress to students and employers, the significant growth of the club, and spoke about our achievements and shortcomings throughout last year's competition. Additionally, each member had the opportunity to share their roles and projects within their subteams. Visitors left with an understanding of Rose Rocketry’s mission to increase the interest and presence of aerospace on campus and Indiana.

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