University of Notre Dame
2018-2019

NOTRE DAME ROCKET TEAM
FLIGHT READINESS REVIEW

NASA STUDENT LAUNCH 2019
UAV AND AIR BRAKING PAYLOADS

Submitted March 4, 2019

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Notre Dame, IN 46556

Contents

List of Tables

List of Figures

Table 1: List of acronyms

Acronym	Meaning
ABS	Air Braking System
ACCST	Advanced Continuous Channel Shifting Technology
AGL	Above Ground Level
CFD	Computational Fluid Dynamics
CPU	Central Processing Unit
CRAM	Compact Removable Avionics Module
DSM	Digital Spectrum Modulation
ESC	Electronic Speed Controller
FEA	Future Excursion Area
FMEA	Failure Modes and Effects Analysis
FPS	Frames Per Second
FPV	First-Person View
IMU	Inertial Measurement Unit
LED	Light Emitting Diode
LiPo	Lithium Polymer
NDRT	Notre Dame Rocket Team
OpenCV	Open Source Computer Vision Library
OPTO	Optoisolator
PCB	Printed Circuit Board
PDB	Power Distribution Board
PID	Proportional-Integral-Derivative
PLA	Polylactic Acid
PWM	Pulse-Width Modulation
RC	Radio Controlled
RF	Radio Frequency
UAV	Unmanned Aerial Vehicle

1 Summary of FRR Report

1.1 General Information

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Team Name: Notre Dame Rocketry Team

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1.2 Mission Statement

The mission of the Notre Dame Rocketry Team (NDRT) for the 2018-2019 NASA Student Launch competition is to independently design, build, and launch a high power rocket to an altitude of 4,700 feet. The mission shall be successful if the rocket safely descends under a parachute before landing without causing damage to the vehicle, surroundings, or spectators. After landing, a semi-autonomous unmanned aerial vehicle (UAV) will deploy and execute a mission to deliver a beacon to a target area.

In addition, NDRT's mission includes building a program centered around NASA's experiential learning project that will offer 60+ undergraduates opportunities to grow as engineers by developing technical and professional skills not available in a traditional undergraduate curriculum. Finally, the team aims to inspire young minds in the South Bend community through hands on activities promoting STEM education and rocketry.

1.3 Launch Vehicle Summary

1.3.1 Launch Vehicle

For the 2019 Student Launch competition, the launch vehicle's final design is a variable diameter body with fore and aft diameter of 7.75 and 6.125 inches respectively and a total length of 144 inches. Table 2 gives additional general vehicle dimensions.

The motor selected for this launch vehicle is the Cesaroni L1115. This motor is at the higher end of total impulse for L-class motors. When taking the most conservative estimates for payload and component masses, this motor will exceed the target altitude, as specified below, allowing the effective use of an Air Braking System. More detailed information, including motor thrust curves, can be found in Section 3.1.1. Additionally, the vehicle will utilize a 12 foot 1515 launch rail.

The target altitude selected for this year's competition vehicle is 4,700 ft. This altitude was specified at PDR, and confirmed in this report. Mission performance predictions indicate that the selected motor allows the vehicle to achieve an altitude between 5,000 and 5,100 ft. This range allows for the effective use of drag inducing tabs to reduce the apogee of flight to the targeted altitude. Figure, 1, shows the as-constructed dimensions of the launch vehicle.

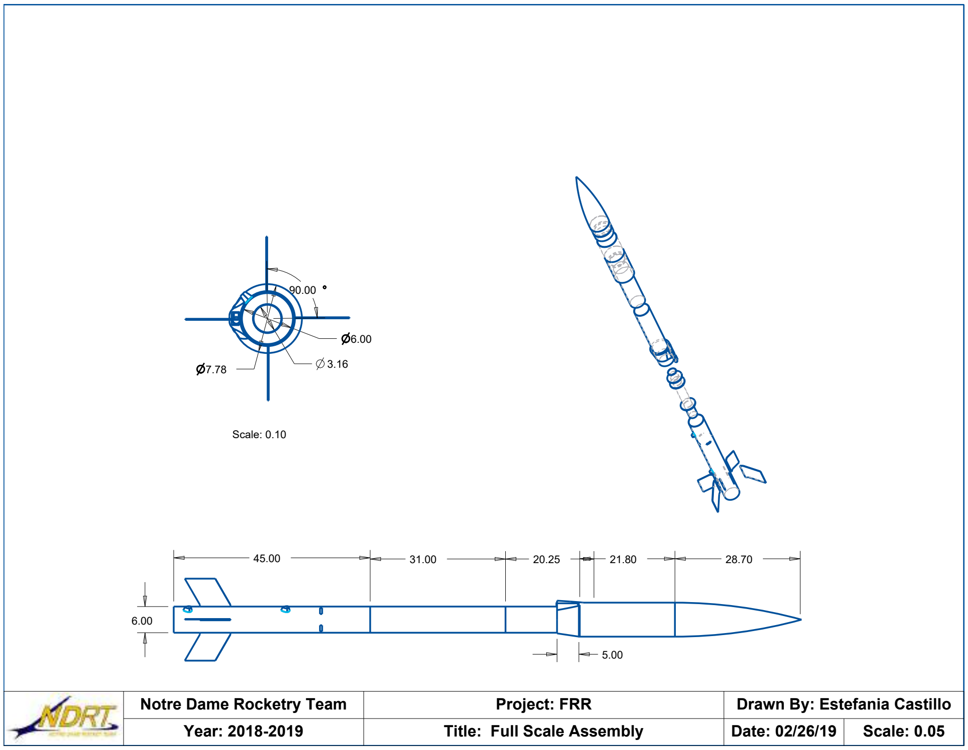


Figure 1: Full Scale Vehicle Dimensions.

Table 2: Concise Size and Mass Statement

Characteristic	Dimension
Total Length (in.)	144
Fore Diameter (in.)	7.75
Transition Length (in.)	4
Aft Diameter (in.)	6.125
Number of Fins	4
Fin Root Chord (in.)	6.75
Fin Tip Chord (in.)	6.75
Fin Sweep Angle (°)	30
Fin Height (in.)	6
CG Position from Nose Cone (with motor) (in.)	86.13
Total weight without Motor (oz.)	685
Total weight with Motor (oz.)	791
Stability Margin without Motor	4.17
Stability Margin with Motor	2.72

1.3.2 Recovery System

The recovery system will use a drogue parachute and main parachute which will be ejected simultaneously at apogee. The main parachute will be held tied up until main deployment at 500ft AGL, at which point a system of redundant chute releases will allow for full deployment. The ejection of the main and drogue parachutes will be accomplished through the use three independent and redundant black powder charges. The secondary and tertiary charges will be ignited at 1 and 1.5 seconds after apogee, respectively. The estimated descent time for the launch vehicle is 87.68s. The maximum drift radius in 20mph winds is estimated to be 2491ft. The Raven 3 Featherweight altimeters will be used for all deployment charges, and will be powered by 9V DC alkaline batteries.

1.4 Payload Summary

1.4.1 Air Braking System Summary

The purpose of the Air Braking System (ABS) is to implement a system to control the apogee of the rocket to reach the target of 4,700 ft. Four drag control surfaces, hereby called drag tabs, will be extended from the side of the vehicle body after motor burnout has occurred to induce a drag force downward due to airflow and control the ascent speed after motor burnout. The drag tabs are controlled by a mechanical system driven by a servo motor and controlled autonomously by on-board avionics. These electronics will implement a closed loop PID control algorithm using feedback from on-board sensors whose data is passed through a Kalman filter to reduce noise. The necessary drag force to bring the vehicle to the designed apogee is calculated, and the drag tab mechanism actuates accordingly until retracting the tabs fully when apogee is detected.

2 Changes Since CDR

2.1 CDR Action Items

- Concerning the wiring diagram for the recovery system, it can be found in Section 3.3.3.
- Concerning the tertiary black powder charge added to the recovery system, the deployment system was redesigned to include 3 independent recovery charges, as described in Section 3.3.

2.2 Changes to Vehicle Criteria

The team has changed the length of the transition section from 4" to 5" to decrease the flow angle to prevent separation. The transition was also altered to allow space for a camera housing.

2.3 Changes to Recovery System

The team has decided to transition to black powder as a means of separation of the rocket and deployment of the parachute, due to difficulty in implementing a backup black powder charge into the original mechanical deployment system. The team will use similar testing procedures to years past, which includes basic electronics testing, E-match testing, and black powder testing. The altimeters and batteries were changed to Raven 3 Altimeters and 9V DC alkaline batteries, respectively.

2.4 Changes to Payload Criteria

- The UAV frame design was changed in order to better accommodate the beacon deployment mechanism. This allowed for the Raspberry Pi to be located on the bottom section of the drone. Additional changes allowed for the prop arms to be locked perpendicular to the body when deployed.
- The method for extending the prop arms was changed from a pulley system to spring extension. The springs allow for all arms to be folded toward the middle of the UAV body. This allowed for simplified integration of the UAV into the airframe to accommodate the length requirement.
- The motor driving the linear transport mechanism was changed from a stepper motor to a gear motor. This was largely driven to reduce weight in the payload deployment subsystem.
- The finalized video streaming frequency was chosen to be 5.8 GHz in order to prevent latency that would have appeared in the 900 MHz range.

2.5 Changes to Project Plan

The initial project timeline established during the Critical Design phase of the project has slipped by the order of a couple weeks. The following are primary drivers of this and how they have affected the timeline of the project:

- Components for both payloads were required to be CNC milled in the Student Fabrication Lab at Notre Dame. The lab is run and overseen by the University and as a result, the ability of the team to complete construction was inhibited by the availability of lab personnel. This pushed back vehicle integration testing and caused the planned vehicle demonstration flight on February 9, 2019 to be scrubbed entirely.
- The Critical Design review revealed errors in the design of the mechanical recovery system and integration of the UAV payload. The team responded with an internal review of the vehicle payloads at a system level. This review and analysis delayed the start of construction and component testing from January 25, 2019 until February 5, 2019
- The team partners with Michiana Rockety to conduct launches in Three Oaks, Michigan. The next nearest accessible launch sites accessible are in Tab, Indiana, Brighton, WI, or Jackson, MI. Targeted vehicle demonstration flights on February 16 and February 24, 2019 were scrubbed due to weather conditions. However, the team was able to conduct a launch on March 2, 2019 with a ballasted UAV payload and inactive Air Braking System.

3 Launch Vehicle Technical Design

3.1 Design and Construction of Vehicle

3.1.1 Propulsion

The propulsion system consists of the motor and its corresponding support systems, including a retention system and a centering/mounting system. This motor was selected because it gave the necessary impulse and apogee, as well as a more consistent thrust curve, which has proven to be reliable in the past. The specifications and the commercially published thrust curve for the L1115 are shown below in Table 3 and Figure 2, respectively.

Table 3: Cesaroni Technologies L1395

Property	Value
Length (in)	24.4
Diameter (in)	2.95
Peak thrust (lbf)	405
Average thrust (lbf)	329
Total Impulse (lbf*s)	1100
Total weight (oz)	152
Burn time (s)	3.34
Thrust to Weight	8.19

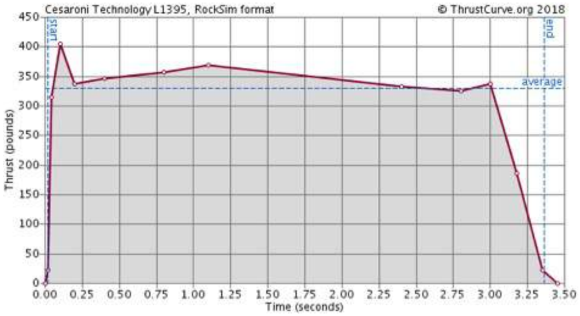


Figure 2: Cesaroni L1395 Motor Thrust Curve

3.1.2 Structural Elements

Airframe:
The airframe of the rocket is made of both carbon fiber and fiberglass. The UAV bay is composed

of fiberglass while the main body tube is made of carbon fiber. Carbon fiber is stronger and stiffer than fiberglass, which makes it a more ideal material for the airframe, as it will remain intact after ground impact and retain its shape. This is important in keeping the aerodynamic forces acting upon the rocket constant during different flights. However, fiberglass must be used for the UAV bay because of its dielectric permeability, meaning that electrical signals can travel through it whereas they can't travel through carbon fiber. A drawing of the fin can and the slots cut into it is shown in Figure 3

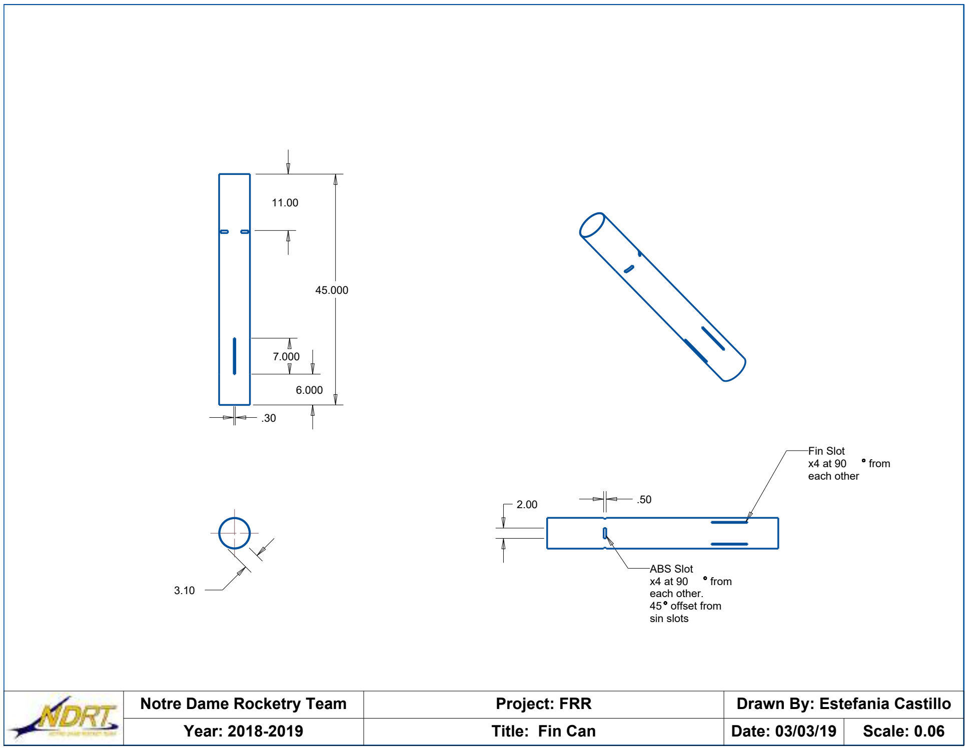


Figure 3: Fin Can Drawing.

Nose Cone:

The tangential-ogive-shaped nose cone being used was purchased from Public Missiles Ltd and is composed of 0.071-inch-thick G10-fiberglass resulting in a high durability for its weight of 36.6 ounces as well as allowing signal transmission from the the GPS unit located within the nose cone. The nose cone has been measured to have an exposed length of 29.0 in. and a shoulder length of 4.0 in. The nose cone is secured to the UAV Bay via the bulkhead connected to the locked lead screw of the track system used to deploy the UAV after landing.

Transition Section:

The transition section of our rocket has a variable outer diameter that transitions from 6 to 7.9 inches over a height of 5 inches. This part is made out of acrylonitrile styrene acrylate plastic (ASA) which has a tensile strength yield of 29 MPa in the XZ axis and 27MPa in the ZX axis. Due to its mechanical strength and outdoor resistant qualities the transition section is able to undergo all forces experienced during flight. In order to transition from diameters the 6 inch body tube of our rocket extends 4 inches into the 7.71 inch diameter UAV bay. Two centering rings aid the transition and will bear all of the load from the fore part of the rocket. Because of these, the ASA transition section is a non-load bearing component. A 2.3 by 1.4 by 0.64 inch camera is hosted in the transition section. The camera is secured to the ASA plastic with a threaded rod, washers, and nuts. A drawing of the transition section can be found below, in Figure 4

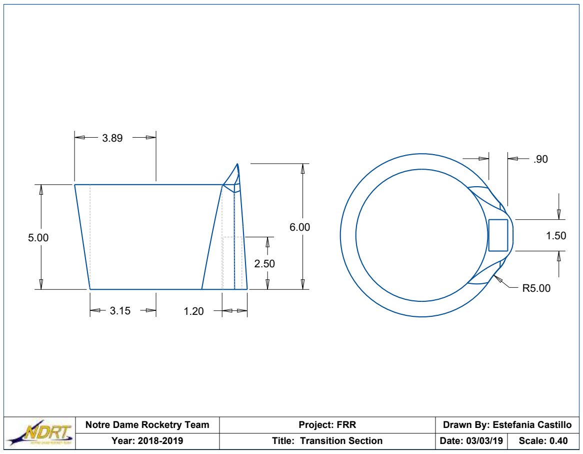


Figure 4: As-Built transition section drawing.

Couplers:

Two couplers are used in the assembly of the rocket. One provides the connection between the recovery tube and the parachute bay, and the other connects the parachute bay to the fin can. Each coupler is made of carbon fiber, which ensures that they will not fail due to any stresses that the rocket experiences during flight because of the material's high strength. The carbon fiber also ensures that the weight of the rocket is minimized while meeting the required strength for a load-bearing component. The couplers are secured permanently to the inside of the aft end of the recovery tube and the aft end of the parachute bay with epoxy, which provides a strong connection to ensure that these components do not break apart. The end of the coupler that protrudes from the recovery tube slides into the parachute bay, and the connection is secured by shear pins extending through the walls of both tubes. This design allows the black powder charges to separate the recovery tube from the parachute bay by causing the shear pins to fail. The coupler that extends out from the parachute bay slides into the fin can, and five 1" diameter steel screws are used to secure the connection. Each screw extends through the walls of the fin can and the coupler. This design will allow the team to remove the fin can from the rest of the rocket in order to access ABS by removing the screws, while also ensuring that the fin can remains secured to the rocket during flight. The maximum shear stress that the screws will experience during flight will occur during separation, with a worst-case acceleration of 35g. In order to keep the fin can secured to the parachute bay during this event, the screws will need to withstand a shear stress of 6,950 psi at one shear plane per screw. The yield shear strength for the steel used in the screws is 38,000 psi, which ensures that the screws will withstand the stress applied at separation with a Factor of Safety of 2.45.

Centering Rings and Bulkheads:

For this rocket in particular, centering rings are used to secure and center the motor mount inside the fin can and also to center and secure the 6 inch body tube inside the 7.75 inch UAV bay. Bulkheads are also used in the rocket to bear the weight of interior components and separate different parts of the rocket. The centering rings and bulkheads are made of fiberglass, which provides many benefits and ensures the structural integrity of the rocket. For one, fiberglass' mechanical strength will allow the centering rings to hold under high stresses, as the motor mount thrusts upwards and the gravitational forces push the rocket down. Fiberglass is also incombustible, which prevents any damage that high heat from the motor may cause to other materials, and as fiberglass heats up, it does not release any toxic fumes which may cause harm to the team. Fiberglass is also highly dimensionally stable, which means that it is not sensitive to changes in temperature or atmosphere and resists any changes in shape due to these changes in environment. In comparison to carbon fiber, fiberglass was selected because while carbon fiber has a yield strength of $9.0x10^4 - 2.0x10^5$ psi, a stiffness of $1.0x10^7 - 5.0x10^7$ psi, and a density of 0.05 lb/in^3 and fiberglass has a yield strength of $3.0x10^4$ psi, a stiffness of $1.2x10^6$ psi, and a density of 0.055 lb/in^3, fiberglass is cheaper per pound and provides enough strength and stiffness for the rocket to remain structurally sound.

Fins:

Four fins are aligned symmetrically around the rocket at the fin can to provide stability during flight. The fins serve to position the CP aft of the CG such that any destabilizing moments during flight are corrected by aerodynamic forces. The design and placement of the fins will ensure that the angle of attack during flight will remain vertical, as desired.

The fins are made of carbon fiber, providing enough strength to withstand any aerodynamic or impact forces that they will experience in a successful flight. During the subscale flight, one of the plywood fins failed on impact during landing, so the choice of carbon fiber ensures that the fins will not experience the same impact failure. The carbon fiber also ensures that the increase in the weight of the rocket is minimal while still meeting the necessary strength of the fins.

The planform shape of the fins is a parallelogram with a sweep angle of 30°, shown in Figure 5. This shape will result in low induced drag for the low Reynolds numbers in the expected range of speeds at which the rocket will fly. The ideal airfoil shape for subsonic speeds is a rounded leading edge and a pointed trailing edge, which were sanded onto each fin.

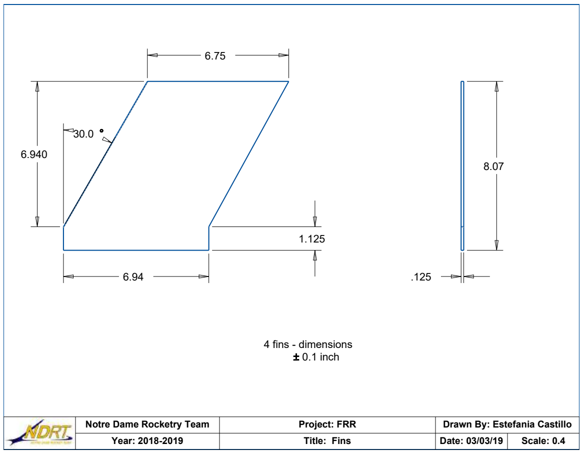


Figure 5: As-Built drawing of vehicle fins

Motor Mount and Retention:

The motor mount is composed of the cylindrical motor mount tube, three centering rings, and a motor retainer. The motor mount tube is made of fiberglass-wrapped phenolic, and is centered within the fin can by the fiberglass centering rings such that the motor remains parallel to the fin can, helping the vehicle fly straight. The metal motor retainer covers the end of the motor mount tube and keeps the motor in place during flight.

Rail Buttons:

The purpose of the rail buttons is to guide the rocket along the rail while it is still in contact with the launching pole so that the rocket travels straight up. The pole will be long enough to put the rocket on the correct trajectory. There are two airfoiled rail buttons on the rocket that were purchased from Apogee Components. The rail buttons are 1.26 inches long. There are two offsets, one for each rail button, that are 3D printed and shaped like the rail buttons. The offsets are 0.9 inches thick. The offsets are larger than the rail buttons and are attached directly to the rocket, holding up the rail buttons. The purpose of the offsets is to space the rail buttons far enough away from the rocket so that the rail buttons can effectively attach to the rail without the fins or the upper part of the rocket obstructing the access. The diameter of the upper part of the rocket that is above the transition section is 7.5 inches, where the diameter of the rocket below the transition section is 6 inches. Therefore, the offsets are necessary for the rocket to clear the rail. The rail buttons are mounted on the offsets, which allows the rail buttons to slide along the rail without the upper part of the rocket obstructing their access. This addition of the offsets allows the rocket to clear the rail during the launch. The total weight of the two rail buttons, the two offsets, and the epoxy and nails used to attach them to each other and the rocket is 1.5 oz. Figure 6, below, shows the as-printed dimensions of the rail button offsets.

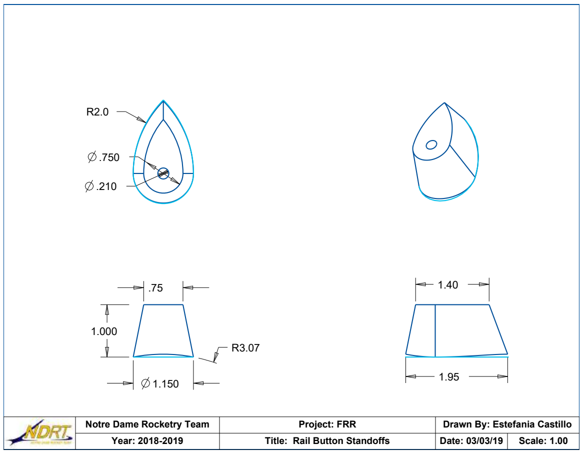


Figure 6: As-Printed rail button standoffs

3.1.3 Construction Process

3.1.3.1 Epoxying

Proper epoxying technique is required to ensure the strength of connections between components. Prior to epoxying any two parts, each was sanded to score the material and increase the contact area for the epoxy. Each part was also filleted, creating a round in between the two contact points. This technique was utilized for any epoxied surface.

3.1.3.2 Fins

The fins were cut from a sheet of carbon fiber by a technician in the Physics Department on campus at Notre Dame. Once cut, the leading and trailing edges of each fin were sanded down through the use of two sanding blocks. One block was specifically designed for the broader, rounded leading edge and other for the sharper, pointed trailing edge. Once fitted with sandpaper, the fins were run back and forth across the blocks, giving the fins a cross section that is more of an airfoil rather than a flat plate to decrease profile drag. The fins were then wet sanded in order to smooth out roughness created from the sanding process. The fin sanding blocks can be found in Figure 7, with closer views seen in Figure 8

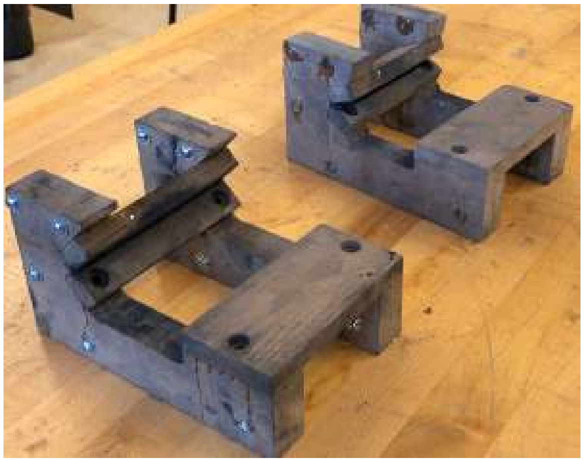


Figure 7: Fin Sanding Blocks

Figure 8: Leading Edge Block (Left), Trailing Edge (right)

3.1.3.3 Fin Can

The fin can construction process began with sanding and epoxying the two foremost centering rings onto the motor mount tube. The third, aft-most centering ring was intentionally left off in order to allow access to where the rail button wooden blocks would be attached, as well as filleting the fins to the motor mount, as will be discussed later. The interior of the fin can was then scored by sanding. Once fully cured, the motor mount with its two foremost centering rings was inserted into the fin can and epoxied at the point of contact between the interior of the tube and the outermost edge of the centering rings. Epoxy was spread around the circumference of the fin can to fillet the fore edges of the centering rings, and then epoxy was filleted on the aft edges. Once the motor mount was cured with two centering rings, the fins were mounted. Laser-cut fin alignment rings were used to ensure alignment of the fins which were then epoxied in place at three points of contact: one at the motor mount tube and one on each side of the fin can tube. The first fin was given 2 hours to soft set, and then the fin can was rotated 90° to affix the second. 2 hours after this, the third fin was epoxied, leaving the last empty fin can slot to the bottom. After 4 hours of drying, the last fin was epoxied. The longer wait was to account for a more complete cure on the first fin that would be in an inverted position. The alignment rings can be seen in Figure 9 Next, holes were drilled for the rail buttons. This is addressed in detail in Section 3.1.3.6. After the rail buttons were set, the final centering ring was epoxied at the point of contact with the motor mount tube and with the fin can, and finally, the motor retainer was epoxied onto the end of the motor mount tube.

Figure 9: Fin Alignment Mechanism.

3.1.3.4 Transition Section

Two centering rings were sanded to fit between the UAV bay and the 6 inch body tube. These were then epoxied to the 6 inch body tube. To ensure that they were perpendicular to the body tube we used a level before applying the epoxy, during the setting time of epoxy we watched for them not to shift out of place. Next, the 6 inch body tube was epoxied to the UAV bay. Epoxy was applied to both edged of the two centering rings as well as inside the UAV bay were these were to be attached. To get epoxy at the right distance from the UAV bay edge we measured the corresponding distances in a stick that was used to evenly apply epoxy around the inside. The 6 inch body tube was slid in and allowed to set. Figure 10 shows the centering rings drying on the 6" body tube.

Figure 10: Transition centering Rings

The ASA transition section was 3D printed with dissolvable support to allow for a smooth finish on the outside as well as inside the camera housing area. Then epoxy was applied to the centering rings, and the transition section was slid on over the epoxy and the edges were filleted. The camera was secured to the transition section using a screw and lid mechanism. First, a wooden top was cut to fit the size of the housing hole a hole was cut for the lens area. A long screw was screwed into a second hole in the wooden piece and drilled into the further end of the ASA piece. The transition section is shown below in, Figure 11. The mounted transition section is depicited in Figure 12.

Figure 11: Transition Section.

Figure 12: Mounted Transition Section

3.1.3.5 ABS Tie Rods

To mount the ABS in the fin can, it is slid onto threaded rods that are set inside. These rods were first cut to length, and 4 holes were machined out of a bulkhead. Using the thrust plate on the motor mount as a starting point, the rods were set so that the ABS would line up with the slots cut out of the fin can airframe. Washers and nuts were epoxied at a corresponding height, with ABS on the rods to ensure that the rods cured straight. This is shown in Figure 13.

Figure 13: ABS Initial Drying

Once the first part was set, the system was remeasured, again to ensure that the ABS tabs were perfectly in-line with the pre-cut slots. Once this was confirmed, the bulkhead was epoxied in with fillets to the fin can. ABS was once again placed on the rods to verify that the rods would dry correctly. This can be seen in Figure 14.

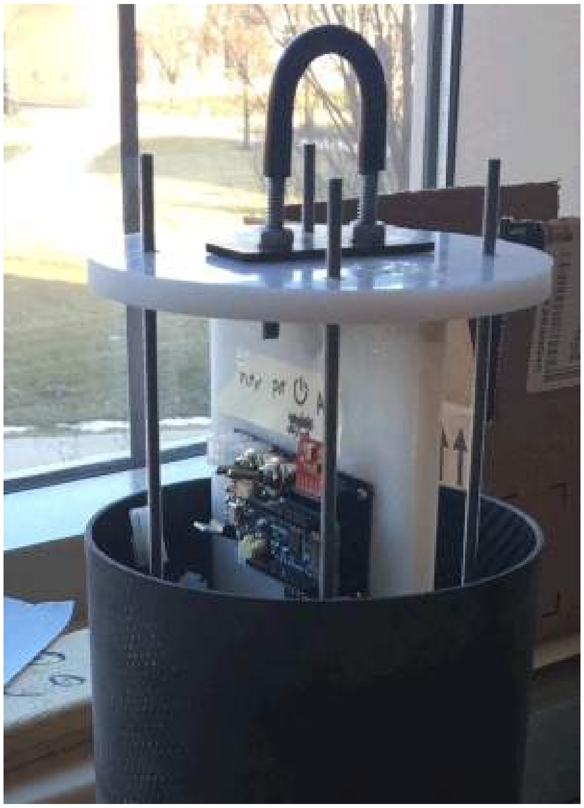


Figure 14: ABS Mount drying inside body tube.

3.1.3.6 Rail Buttons

The rail buttons were bought from an Apogee Components, and the offsets were 3D printed with ASA. In order to ensure that the rail buttons were both in line with each other as well as equally spaced between two of the fins, a few methods were used. The fin can was first placed against the door frame, which allowed a straight line to be drawn along the fin can. This line was used as a preliminary marker in order to test various ways of positioning the rail buttons. Next, the distance between the two fins was measured, and the midpoint was found. Then, by using a rail, another line was drawn onto the fin can. After checking the line's position multiple times, two holes were drilled into the fin can, one at the bottom and the other at the top of the motor mount. Two pieces of 2x4 wood that had been cut and sanded down to size were epoxied into place on the interior of the fin can. These pieces were used when the two rail buttons and conjoining offsets were drilled into the fin can. Each rail button system consists of the rail button itself, the 0.9 inch offset for the fore body tube to clear the launch rail, a wood anchor block in between the fin can and the motor mount, and a screw. Epoxy was spread between all the joints and then drilled together. The rail button mounting can be seen below in Figure 15.

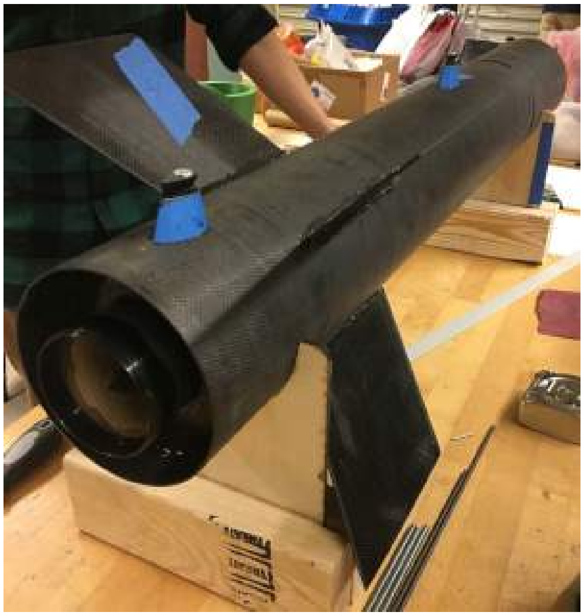


Figure 15: Rail Button Alignment

3.1.4 Differences from Designed to Constructed Vehicle

As a result of weight changes from payloads, the in-flight separation point had to be switched from near the fin can, to the fore separation. Due to the design, there were no differences in the outer airframe, as one side needs to be accessible on the ground. The screw access points has changed to be at the aft separation point, with shear pins in the fore section. The only other design change was the transition section, which changed to accommodate a shroud for the camera. As a result, the transition has changed from 4 to 5" so there is more space for the camera.

3.2 Air Braking Subsystem

3.2.1 Overview

The Air Braking System, abbreviated ABS, consists of four flat plate drag tabs that deploy from the vehicle body. The drag tabs extend a distance of one inch providing approximately 2 in^2 of area per tab, or 8 in^2 total exposed to the airflow to induce drag. The ABS deploys these tabs symmetrically via a single servo motor to maintain the stability of the vehicle. The ABS assembly also contains mounting for the servo motor and control electronics. The full assembly is housed in the fin can of the vehicle during flight where the tabs deploy from slots cut in the fin can at the approximate center of pressure as of the time of manufacturing. An exterior view of the fully assembled Air Braking System is shown in Figure 16.

Figure 16: Full Assembly of Air Braking System

3.2.2 Mechanical Design

The mechanical design consists of a Hitec D980TW servo motor, a 0.25" diameter shaft, the crosspiece with set screw, and the four drag tabs with their respective tie rods. The servo motor turns the shaft, which in turn rotates the crosspiece. The drag tabs are attached to the crosspiece via four tie rods and are constrained to a slot that ensures linear displacement throughout the rotation of the crosspiece. The shaft transfers torque to the crosspiece via a #5-40 set screw.

The drag tabs, crosspiece, and tab support plates are made of Delrin to provide a low coefficient of friction and high yield stress rating to withstand the forces experienced during flight. The drag tabs are cut from a 0.25” thick sheet of Delrin corresponding to their thickness, while the support plates and crosspiece are cut from a 0.5” thick sheet. The motor mount and lower bearing plates are cut from a 0.25” sheet of polycarbonate which was chosen for its transparency which aids in assembly and monitoring the mechanism for damage during testing. The lower bulkhead and electronics mounting decks are produced from 0.5" and

0.375" HDPE respectively which was chosen for being a cheap yet reliably strong plastic.

3.2.2.1 ABS Manufacturing

The primary structural components of the Air Braking System were designed in Autodesk Fusion 360. This was used for both the CAD and CAM processes to export NC files for manufacturing. Under the supervision of staff in the Student Fabrication Lab in Stinson-Remick hall, the drag tabs, crosspiece, support plates and associated bulkheads were cut using a Techno LC Series 4848 CNC router using a combination of 1/8" and 1/4" bits. The Student Fabrication Lab was also used for cutting 3/32" key stock for transfering torque to the shaft potentiometer, tapping a hole for the crosspiece set screw, and installing 3mm screw threads for the drag tabs and crosspiece. The manufactured crosspiece with set screw and 3mm screw hole visible is shown in Figure 18.

(a) Techno Router Manufacturing (b) Finished Parts

Figure 17: ABS Manufacturing

Figure 18: ABS Crosspiece

3.2.2.2 Drag Tab Design Modification

A possible point of failure of the original drag tab design was recognized prior to manufacturing while working with the CAD models. Upon full retraction, the inner side of the tie rods would jam with an adjacent drag tab, preventing full retraction and risking damage to the system. To avoid this collision a small arc was cut out from the tab to ensure that the link would slot in, and avoid the collision. The drawing of the revised drag tab is shown in Figure 19.

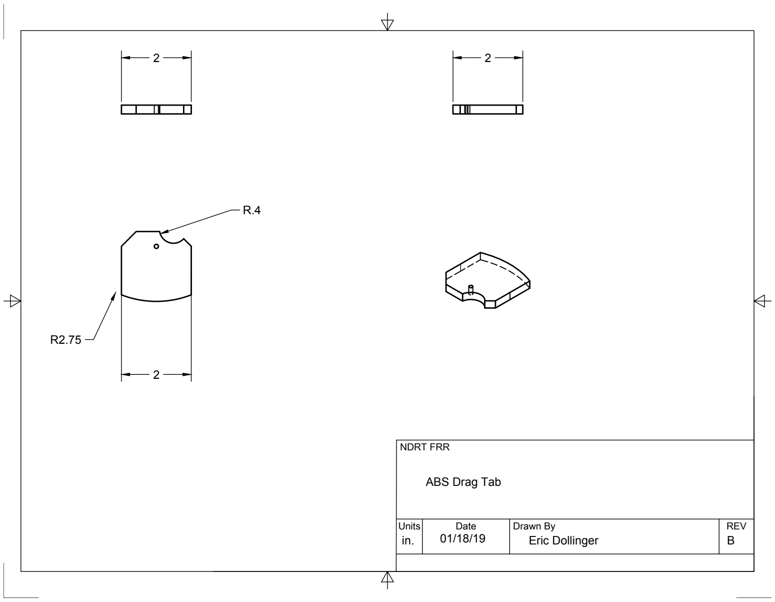


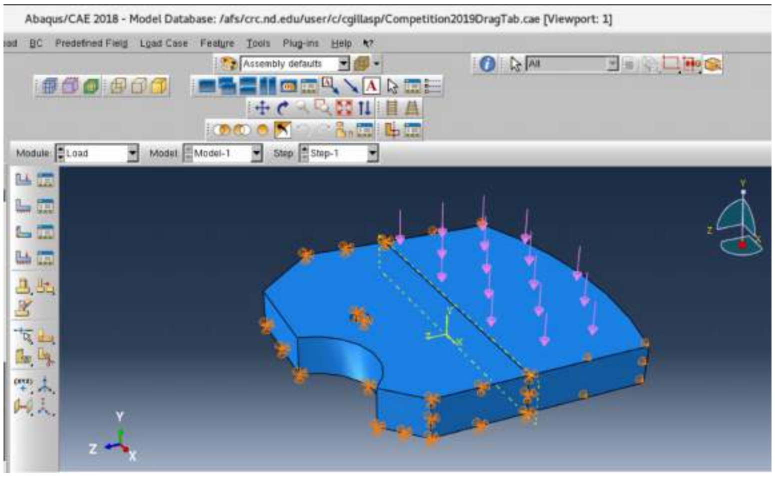
Figure 19: Drag Tab Revision

3.2.2.2.1 Revised Drag Tab Finite Element Analysis

As a result of the drag tab modification, a new Abaqus Finite Element Analysis was performed on the modified tab to get the new displacements and stresses, to ensure the integrity of the Delrin tabs under the expected forces. The Finite Element Analysis was run for pressures of 20 psi on the area of the tabs, which is higher than the expected 8.5 psi that the tabs would experience. The following constraints were placed on the tab for the analysis:

- Sides of the tab that are exposed to air are only permitted to move in the y and z directions.
- Sides of the tab within the mechanism support plates and not exposed to airflow are constrained in the x,y, and z directions.
- The hole for connecting the tie rod is pinned (constrained in x,y, and z directions).
- The bottom of the tab within the mechanism support plates which is not exposed to airflow is constrained in the x,y, and z directions.

The FEA constraints are displayed in Figure 20, the von mises stress plot is shown in Figure 21, and the displacement plot is shown in Figure 22.


Abaqus/CAE 2018 - Model Database: /afs/crc.nd.edu/user/c/cgillasp/Competition2019DragTab.cae [Viewport: 1]

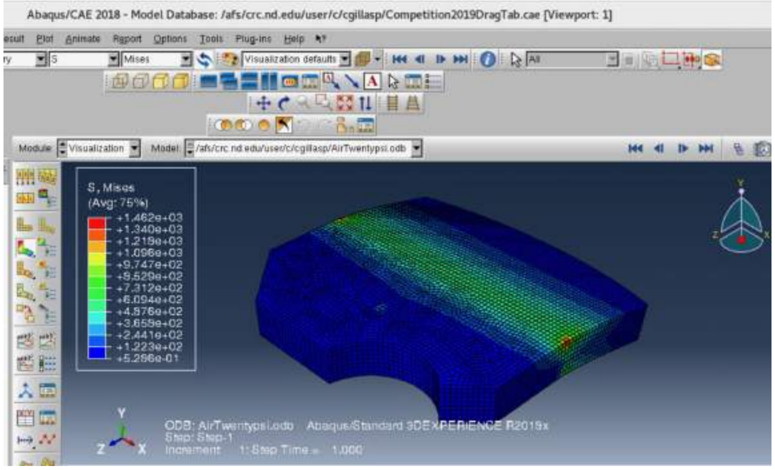
Assembly defaults

Module: Load

Model: Model-1

Step: Step-1

Figure 20: Drag Tab FEA Constraints


Abaqus/CAE 2018 - Model Database: /afs/crc.nd.edu/user/c/cgillasp/Competition2019DragTab.cae [Viewport: 1]

S

Mises

Visualization defaults

Module: Visualization

Model: /afs/crc.nd.edu/user/c/cgillasp/AirTwentypsi.odb

ODB: AirTwentypsi.odb Abaqus/Standard 3DEXPERIENCE R2019x

Step: Step-1

Increment 1: Step Time = 1.000

Figure 21: Drag Tab FEA Von Mises Stress

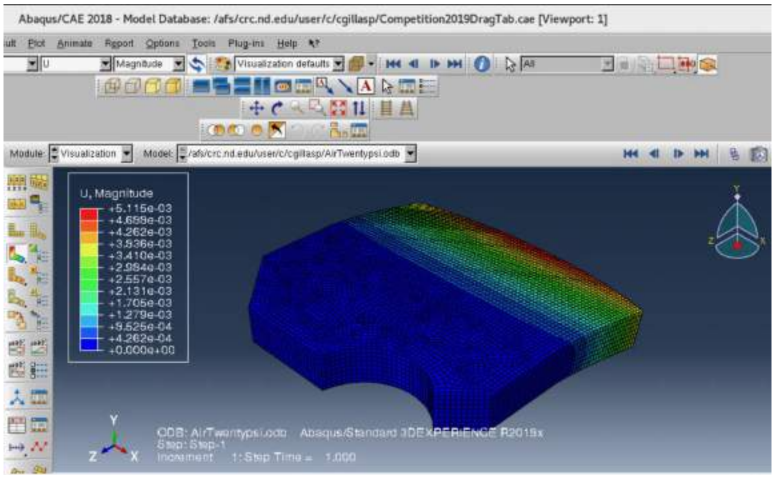


Figure 22: Drag Tab FEA Displacements

The conclusion is that the cutout of the tab had a slight effect on the displacements and stresses experienced under the maximum load conditions, but is still well within acceptable ranges. The maximum simulated stress of 1,480 psi is well below the yield stress of Delrin (5,200 psi), with a safety factor of about 3.7, while the maximum displacement was simulated at 0.0051 inches or 2% of the 0.25" thick tab. This is a small but noticeable change from the drag tab at CDR, where the maximum stress was 1,197 psi, and the maximum displacement was 0.0054". Given this factor of safety while simulating at higher than expected forces, the tab are expected to perform without being damaged. The final Drag Tabs upon manufacturing is shown in Figure 23.

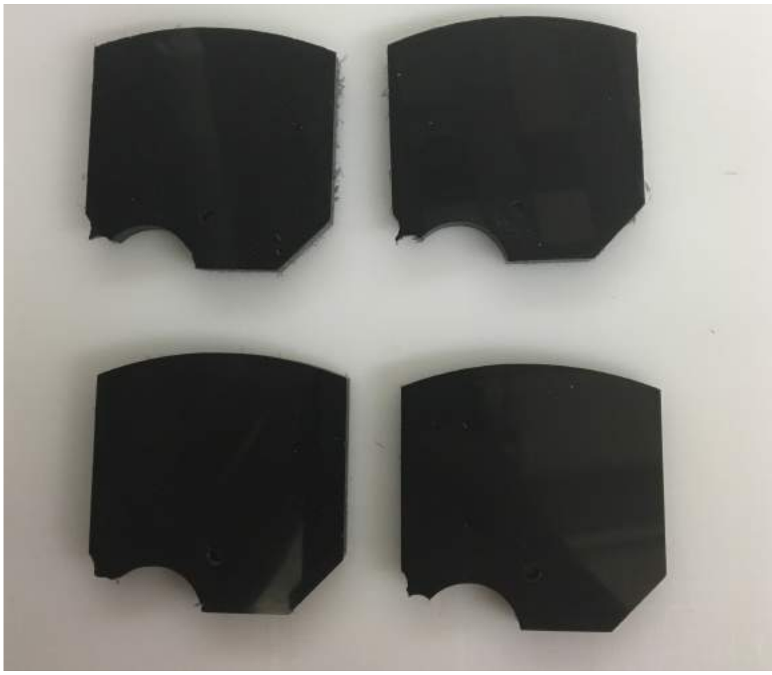


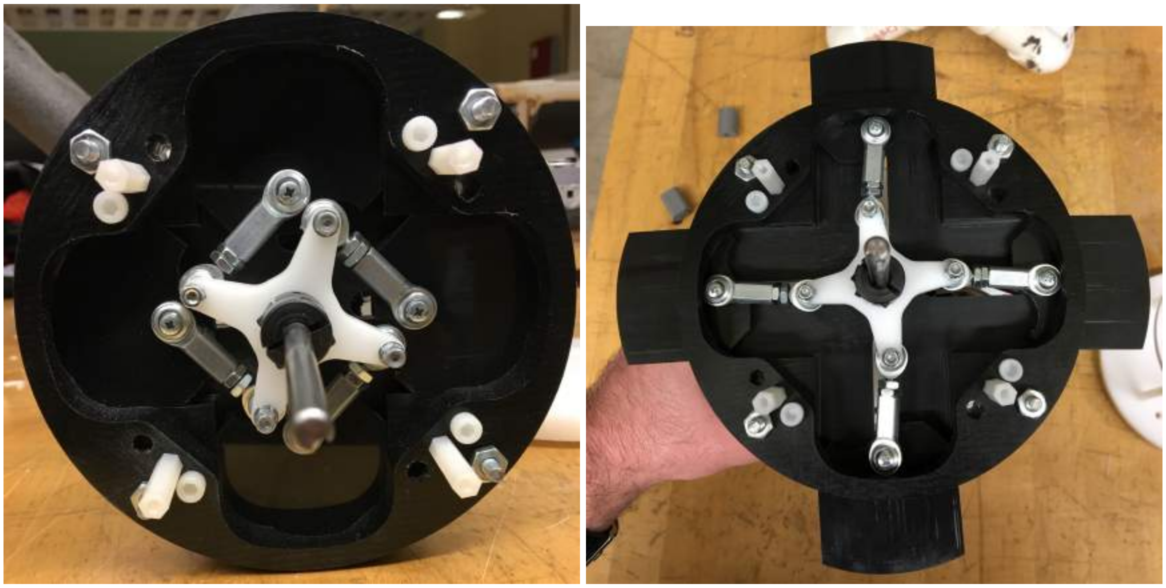
Figure 23: Final Drag Tabs

3.2.2.3 Tab Deployment Mechanism

The mechanism for deploying the drag tabs from the fin can was successfully assembled without any required design changes from the design put forth at CDR. The Associated Delrin support plates and polycarbonate bearing plates were manufactured with a CNC router, and the 0.25" shaft, tie rods with ball joint ends, and 2-piece shaft collar were supplied from McMaster Carr, while the lower bearing for the shaft was supplied from Servo City.

The assembled mechanism is shown below in Figure 24, and the motor mount and shaft potentiometer mount is shown in Figure 25. Shaft collars are used to maintain the height of the crosspiece along the shaft. 3 mm screws are used for securing the tabs to the tie rods and the tie rods to the crosspiece. #10-32 steel bolts are used to secure the two Delrin support plates together. Additionally, the plates are held together by the nylon screws connecting to nylon standoffs which secure the motor mount plate and lower bearing plate above and below the tab enclosure.

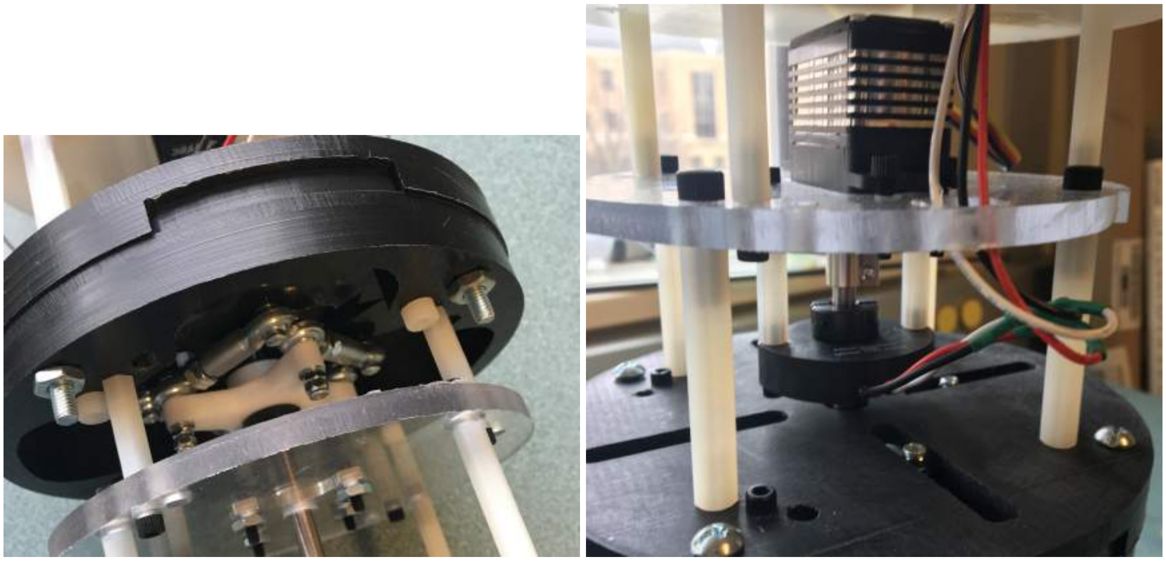
The drag tabs shown in Figure 25 are not flush with the support plates. This is normal and a result of a minor amount of additional space between adjacent tie rods during retraction, which allows the tabs to slightly retract farther than flush until the tie rods touch if the motor over-retracts. This has been deemed not to be an issue during testing, and will additionally be controlled and avoided by sending positional feedback from the potentiometer to the motor control algorithm.



(a) Retracted

(b) Extended

Figure 24: ABS Mechanism



(a) Mechanism & Lower Bearing Plate (b) Motor and Potentiometer

Figure 25: ABS Mounting

3.2.3 ABS Electrical Design

The top-level electronics system consists of an Arduino MKR Zero microcontroller, a Tenergy 7.4V Li-Po battery, an Adafruit branded Bosch BNO055 Inertia Measurement Unit accelerometer, Sparkfun branded Freescale MPL3115A2 altimeter, a Honeywell 640CS103A06NAAY hollow shaft potentiometer to detect shaft rotation, and Hitec D980TW motor. The system is interconnected with a custom-design printed circuit board (PCB) designed using Autodesk Eagle and manufactured from OSH Park. The printed circuit board and components were assembled by members of the team using a Weller #WTCPT soldering station and fume absorber as shown in Figure 26.

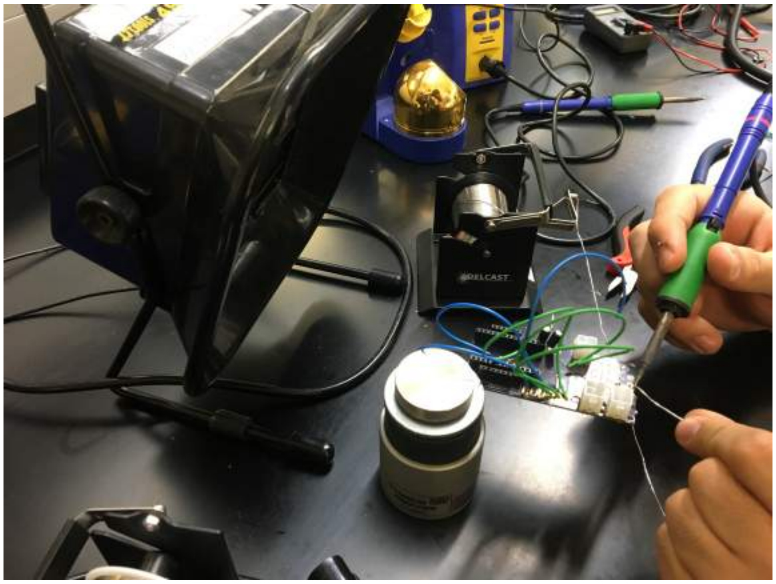


Figure 26: ABS PCB Soldering

3.2.3.1 Printed Circuit Board Revisions

The PCB has a footprint of 85x40mm with mounting holes in each corner to connect to the payload assembly. An emphasis was placed on direct connections between components to limit the amount of wiring that could become tangled, shorted, or disconnected. Two switches were soldered directly to the board to arm and control power of the system. In addition to the physical switches, the user interface includes 8 colored LEDs to signal various system states for the purposes of testing and pre-launch information. The motor, potentiometer, and battery leads are easily connected to the circuit using molex connectors. The shaft potentiometer measures motor rotation and will be read to calculate current tab extension and detect motor jams.

As a result of initial failed electronics testing, a second revision of the PCB was manufactured. This resolved issues with sensor pin mapping and incorrect routing of the decoupling capacitors on the voltage regulator. The new design meets requirements and has passed the required test #AT2, as well as allowing operation for other ABS tests.

The final ABS electronics assembly is shown in Figure 27. Clay was used to assist in pressure sealing the wire hole in the lower electronics bulkhead. The final PCB design is shown in Figure 28.

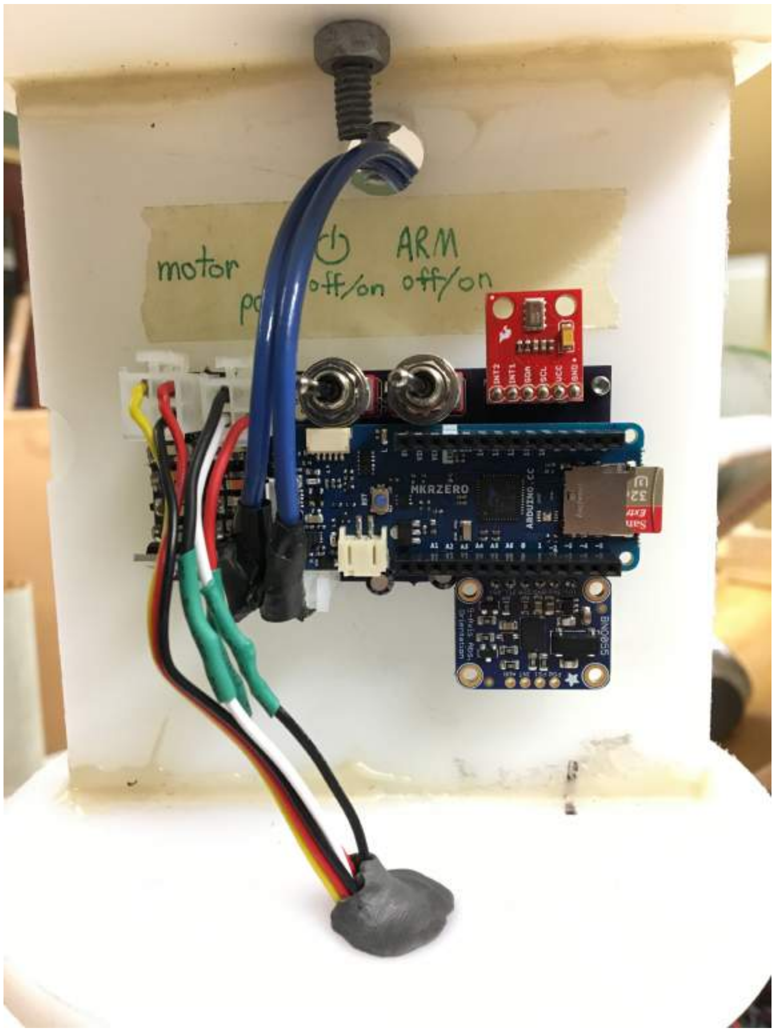


Figure 27: ABS Electronics Assembly

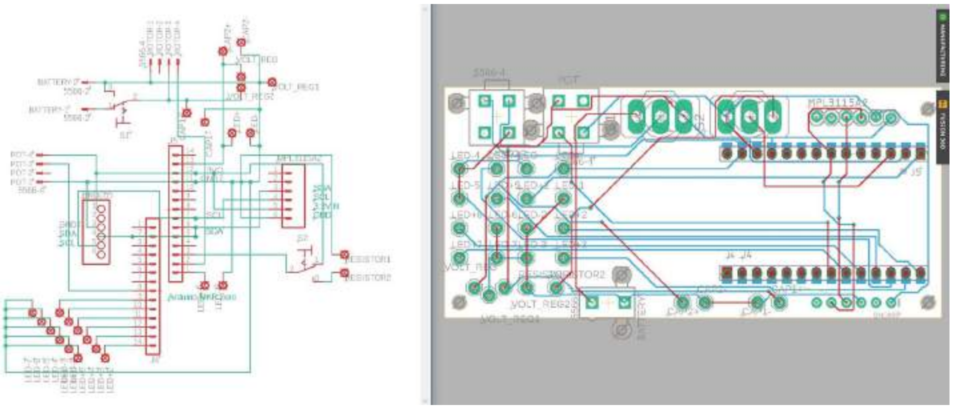


Figure 28: Final ABS PCB Schematic

3.2.4 ABS Control System Design

The ABS system has a functioning state machine that transitions between the proper flight states based on comparisons of our acceleration and altitude to various acceleration and altitude flags as described in Table 4.

Table 4: ABS Control System Stage Descriptions

Stage	Transition
ARMED	The control code will initialize in this state.
LAUNCHED	A transition to this state from ARMED occurs if an acceleration threshold or a height threshold of 100 ft. is broken.
BURNOUT	A transition from LAUNCHED to this stage occurs when the net acceleration becomes negative.
APOGEE	A transition from BURNOUT to this stage will occur if the altitude is decreasing and the velocity value is negative.
LANDED	A transition from transition from APOGEE to this stage occurs once altitude drops below its initial threshold and velocity is less than a defined threshold.

A Kalman filter is utilized to dynamically correct sensor noise and error. Prior simulations of position, velocity, and acceleration will be used with sensor data and estimated noise to calculate a Kalman gain. The Kalman gain will be used with the sensor data to estimate the current position, velocity, and acceleration of the rocket. At this point the error covariance matrix is updated based on the Kalman gain factor. Finally, the Kalman filter projects an estimation of the state of the rocket and the associated error covariance into the next time step, to be used in the next iteration of the filter. The desired output is then coverted to a signal to the servo motor via a PID controller. The Kalman filter is currently being improved by adjusting gain factors by using test data from the March 2nd test flight to ensure successful filtering before the filtered data is used to make decisions in upcoming test flights before the payload demonstration deadline. Additional information on the status of control code development is outlined in the AT5 test results.

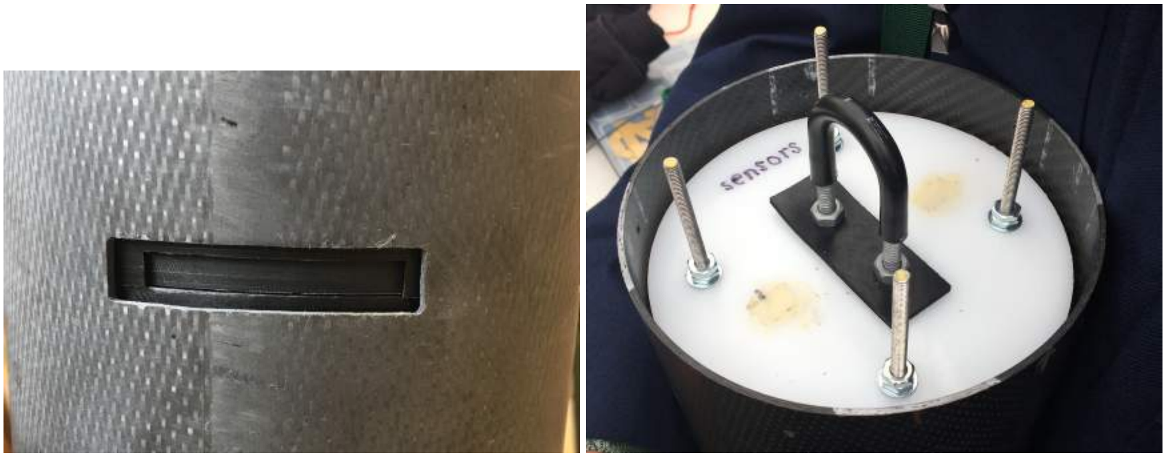
The algorithm works by fully extending the tabs if the sensor determines velocity is found at any point to be above the “best flight” velocity at the same altitude from a computer generated flight to exact apogee. Similarly, the servo motor attempts to retracts the tabs at any points in flight where the rocket is below or near its flight velocity.This algorithm has been tested by augmenting flight code and inputting simulated flights and visually inspecting the tabs and comparing their extension to real time data presented on the serial monitor. We found that the tabs extended and retracted correctly as the test flight matched to velocity values that differed from our “best flight” projection. This algorithm was chosen because wind tunnel testing was not available at this time to experimentally confirm the effectiveness of our tabs, so the tabs braking power will not be experimentally confirmed until we run a full extension flight.

3.2.5 Integration

The ABS is integrated and secured into the fin can of the vehicle using four #10-32 steel threaded rods. The rods are epoxied to a fiberglass bulkhead which is then epoxied into the fin can at the appropriate height and rotational angle to ensure the drag tabs align with the slots previously cut in the fin can during manufacturing. The ABS then slides down these rods which run through holes precisely cut in the ABS parts during the manufacturing process to maintain alignment. The ABS is then secured using a #10 washer and two hex nuts on each of the four rods. A U-bolt at the attached to the top bulkhead of the ABS allows for easy removal by a team member. Pictures of the ABS integration and tab-slot alignment is shown in Figure 29.

The fully assembled Air Braking System (without the integration rods) weighs 64.9 oz. this represents a 0.43% weight increase from the 64.62 oz approximation made at CDR. The negligible increase can be attributed to minor inaccuracies between the material densities used in the Fusion 360 approximation and the actual material used.

The drag tabs are designed to be placed near the center of pressure to ensure stability during flight. As of the March 2nd test flight, the center of pressure was found to be 2" fore of the drag tab slots in the fin can. This distance between the tabs and center of pressure was deemed to be acceptable for vehicle stability as it fell within the 4 inch target outlined in ABS requirement #AB-1. The tabs were not active during the March 2nd flight and the distance between the tabs and center of pressure will be reevaluated at future test flights prior to the drag tabs actuating.



(a) Tab Alignment (b) Rod Integration

Figure 29: ABS Integration

3.3 Recovery Subsystem

3.3.1 Recovery System overview

The recovery subsystem uses black powder charges for the separation and parachute deployment event. Three black powder charges will ignite consecutively at apogee, enabling parachute deployment. Both the main parachute and drogue parachute will be ejected from the vehicle at apogee, and the main parachute will be held from unfurling by Jolly Logic Chute Releases. The vehicle will descend under the drogue chute until it reaches an altitude of 500 ft AGL, at which the main parachute will be allowed to fully unfurl. Recovery staging is outlined in Table 5.

Table 5: Recovery Staging

Stage	Event	Altitude	Description
1	1.1 First Black Powder Charge	Apogee	The black powder in the first PVC pipe ignites
	1.2 Second Black Powder Charge	Apogee + 1 sec	The secondary black powder charge ignites
	1.3 Third Black Powder Charge	Apogee + 1.5 sec	The tertiary black powder charge ignites
2	2.1 Parachute Separation	Apogee	The exploded black powder charges eject the main and drogue parachutes out of the launch vehicle
3	3.1 Jolly Logic Chute Release	Apogee	The Chute Release elastic with a built-in altimeter is wrapped around the folded main parachute, preventing the main parachute from opening up during and after ejection. The rocket descends under the drogue chute until the next stage
4	4.1 Parachute Deployment	500 ft AGL	The latch holding the elastic around the main parachute is released, and the originally tethered main parachute is opened to its full diameter. The rocket descends under the main parachute and the drogue chute until ground

3.3.2 Structural Elements

Both the fore and aft sections of the launch contain a structural bulkhead made out of 3/4in thick plywood. The outer diameter of each bulkhead was machined to match the inner diameter of the body tube. Each bulkhead was attached to the body tube using RocketPoxy.

Shock cords connect the parachute to both sections of the launch vehicle and ensure that the rocket will stay connected when the parachute is deployed. Both sections of the rocket will be secured at an eye bolt in a structural bulkhead epoxied to the body tube. The shock cord will be routed through the recovery system in order to traverse from the parachute to the structural bulkhead. The shock cord will be 9/16in. flat nylon with a breaking strength of 2400 lbs. Nylon shock cords reduce the possibility for zippering because of the extra width of the cord, and the slightly elastic nature of the cord reduces the impulse that the rocket receives during parachute opening. Figure 30 depicts the shock cords that will be used in the rocket. The manufacturer for the shock cords is Fruity Chutes, and the part number is SCN-688.

Figure 30: 9/16in Nylon shock cords

The shock cord will be connected to the eye bolts with 'quick links', which are carabiners with a threaded gate. An example of a quick link is shown in Figure 31, below. Quick links reduce assembly time during launch preparation, allowing sections of the shock cord to be easily clipped in place. The quick links are 2.06 in long, have a 3/8in. opening, are made of 316 stainless steel, and can hold up to 1760 lb. The quick links are manufactured by McMaster-Carr with part number 3711T25. Chosen because of its high yield strength, 316 stainless steel is also corrosion resistant; both of these properties ensure that all recovery hardware is strong and long lasting.

Figure 31: 316 stainless steel quick links used to attach launch vehicle sections to the shock cord

The eye bolts that the shock cords will connect to will be 5/8 -16, forged construction, 316 stainless steel eye bolts. An eye bolt of this type can be seen in Figure 32, below. These eye bolts are attached with a hex nut and RocketPoxy to structural bulkheads and thereby the other components. The manufacturer of the eye bolts is McMaster-Carr, and the part number is 3014T109.

Figure 32: Eyebolt as epoxied into structural bulkheads of launch vehicle

3.3.3 Electrical Components

3.3.3.1 Altimeters, batteries, black powder, connectors

Within the black powder recovery mechanism, there are many different electronics that help to ensure the successful launch and retrieval of the rocket as a whole. The compact removable electronics module (CRAM) contains:

- 3 9V DC alkaline batteries to power the system, connected to the rest of the system via battery boxes that can be turned on and off through the use of an exterior switch
- Raven v3 altimeters to control the detonation of the black powder at apogee, while also gathering flight data
- Electronics matches which cause detonation of black powder charges
- Wago 221 lever nut connectors which ensure that all of the connections between components will be secure

In addition, 2 Jolly Logic Chute Releases are used to keep the main parachute from unfurling until 500 feet AGL.

Each component was tested individually as described in Table 6.

Table 6: Description of recovery electronics tests

Component	Test
9V Batteries	A multimeter was used to verify voltage prior to installation in the CRAM
Raven 3 Altimeters	A simulated launch was run using Featherweight interface software. An LED was used to ensure that the altimeter caused current to flow at the correct time.
Electronic Matches	A simulated flight was run on the altimeters using the Featherweight software to ensure that the altimeters could ignite the electronic matches at the correct time.

Each of the three redundant systems present in the CRAM were wired as shown in Figure 33.

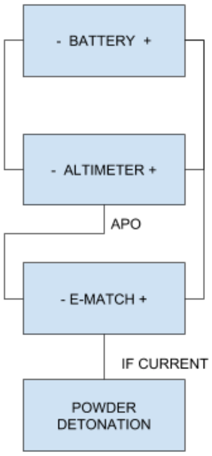


Figure 33: Altimeter wiring diagram

3.3.3.2 Recovery System Testing

The team conducted a variety of tests prior to launching to ensure that the recovery system would work safely and consistently. When the team first assembled the system, LEDs were utilized in lieu of the e-matches. This allowed the team to see when exactly the altimeters were activating, and so there was no concern about explosions that e-matches generate. The results of this test were successful, and confirmed that the wiring of the system was correct. This test was done several times per altimeter, to ensure that all of the altimeters were working properly. The setup of this test can be seen in Figure 34.

Figure 34: LED testing demonstration

After the wiring of the system was confirmed, the team moved on the testing the e-matches to ensure that enough current would be generated by the battery in order to set them off. In this test, the team replaced the LEDs with the e-matches. This allowed for a test of the system without having to deal with the use of extensive energetics. In order to be safe, this test was conducted over a sink to prevent accidental ignition of anything outside of the e-match. This test was performed 6 separate times (2 times per altimeter), and was successful every time. The setup of this e-match test can be seen in Figure 35.

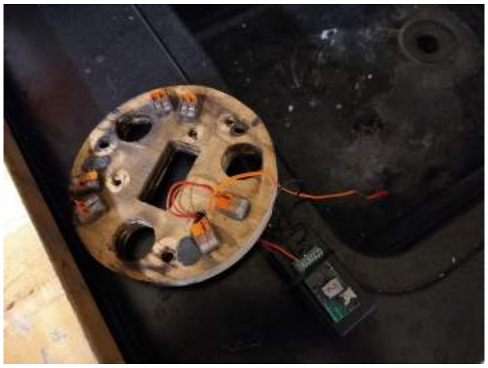


Figure 35: Demonstration of electronic match testing

These e-match tests were then coupled with black powder detonation tests. The team conducted two black powder ground tests prior to the full scale launch to ensure the success of the system. A black powder charge was wired directly to one of the 9V batteries used in the CRAM. The first test was conducted with 4 grams of black powder in one PVC pipe. The black powder was ignited but was not able to separate the the fore section from the recovery tube, due to pressure escaping through unsealed wire holes in the CRAM. These holes, the shock cords hole, and the seam between the bulkheads and the recovery tube were then sealed with high-density, non-hardening duct seal. The amount of black powder in the PVC pipe was increased to 5 grams and the test was performed again. The test successfully separated the fore section from the recovery section of the rocket.The results of these black powder tests are summarized in Table 7.

Table 7: Black powder tests

Test Number	Description	Result	Changes and Test Details
Test 1	4g of black powder used	Failure	No separation induced, due to escaping of pressure through holes in CRAM
Test 2	5g of black powder	Success	Duct seal was added around the top of the CRAM and separation was induced

Based on the results of these tests, three 5g black powder charges were used in the recovery system during launch.

3.3.3.3 GPS tracking system

In order to track the launch vehicle during and after launch, an Eggfinder TX kit was used. This system consists of a transmitter that emits a signal at 911 MHz. The Eggfinder TX transmitter was placed inside of the nose cone, which transmitted to the Eggfinder RX Dongle receiver on the ground. This receiver interfaced with an Android phone using the Bluetooth GPS application. The altimeters were powered using GOLDBAT 7.4V 800 mAh LiPo batteries, which provide a battery life of approximately 5 hours of continuous use. The GPS system was tested separately from the launch vehicle by moving the transmitter to locations at various known distances from the receiver. These tests ensured that the GPS would be able to track the launch vehicle after landing, even if it drifted outside of the allowable drift radius. Figure 36 shows how this system was implemented, and how the signal was transmitted.

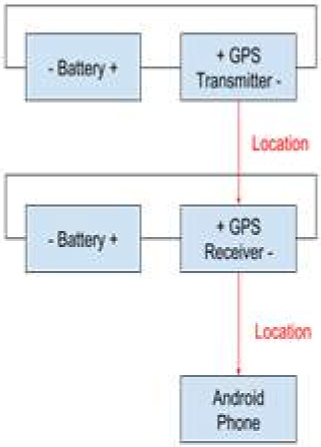


Figure 36: GPS wiring description

3.3.3.4 Redundancy

The recovery system was designed to be at least one fault tolerant, as per NASA requirement 3.6 in the student launch handbook. In the main separation event, this was accomplished through the use of 3 separate altimeters systems. Each Raven 3 altimeter was connected to a separate battery and black powder charge. As mentioned in Section 3.3.3.2, each individual black powder charge was sufficient to separate the rocket.

For main deployment, two independent chute releases were connected in series, as shown in FIGURE 37. These were wrapped around the parachute such that if either chute release deployed, the main parachute would be able to unfurl. Each chute release contains its own altimeter and battery, which are independent from the rest of the recovery electronics.

Figure 37: Redundant Jolly Logic Chute Releases

3.3.4 Parachute Sizes and Descent Rates Predictions

The size of the main parachute was determined based on the minimum kinetic energy requirement of 75ft-lb as set by Requirement 3.3 in the Student Launch Handbook. The maximum descent velocity was found to be 13.71ft/s using formula 1 where m_s is the mass of the heaviest section of the launch vehicle.

$$V_{descent} = \sqrt{2 * KE * m_s} \tag{1}$$

The minimum diameter of the main parachute was then calculated to be 12.35ft based on equation 2 assuming a drag coefficient C_d of 1.85.

$$D = \frac{8W}{C_d \rho V_{descent}^2 \pi} \tag{2}$$

A 14ft parabolic Rocketman parachute made of low-porosity ripstop nylon was chosen, as it satisfies the kinetic energy requirement, but still produces a descent velocity of 88.3% of the maxmimum allowed. This minimizes drift distance and descent time. The Rocketman parachute was also chosen due to its high drag coefficient of 1.85 and its low weight. Characteristics of the Rocketman parachute are shown in Table 8. A picture of the Rocketman parachute is shown in Figure 38.

Table 8: Characteristics of 14 ft Rocketman Nylon Parachute

Characteristic	Value
Nominal Diameter (ft)	14
Drag Coefficient	1.85
Material	ripstop nylon
Maximum descent velocity (ft/s)	12.02
Packing Volume (in^3)	173.3
Weight (oz)	27.2

Figure 38: Rocketman 14ft Standard Parachute

3.3.5 Drogue Parachute Selection

The area of the drogue was calculated in order to satisfy the descent time requirement of 90 seconds as set by Requirement 3.10 in the Student Launch Handbook. Assuming a main deployment at an altitude of 500ft, the time required to descend under the main is 39.4 s. This means that the time to descend to 500ft under the drogue parachute must be less than 48.4371 s. In order to achieve this, a Rocketman 2ft parachute was chosen, as it produces a descent time of 87.68 s. Again, a Rocketman parachute was chosen for the drogue chute as it is lightweight, has a high drag coefficient, and provides a descent time closest to the required maximum, which allows for the highest terminal velocity, and least force on the launch vehicle when the main parachute deploys. The relevant characteristics of the drogue parachute are shown in Table 9.

Table 9: Characteristics of 2 ft Rocketman Nylon Parachute

Characteristic	Value
Nominal Diameter (ft)	2
Drag Coefficient	1.85
Material	ripstop nylon
Maximum descent velocity (ft/s)	85.45
Packing Volume (in^3)	7.96
Weight (oz)	1.5

The predicted descent times and drift distances were calculated using an Euler method simulation, which is outlined in Section 3.4.2.

Because the system uses black powder for ejection, the parachute will be wrapped in Nomex cloth in order to protect the parachutes from burns.

3.3.6 CRAM

All deployment electronics are contained in a component called the Compact Removable Avionics Module, or CRAM. The CRAM consists of several parts; the CRAM body, the CRAM core, and a number of bulkheads. The multi-part design allowed for easier retrieval of the altimeters than a single piece recovery bay would have. The fully assembled CRAM can be seen in Figure 39.

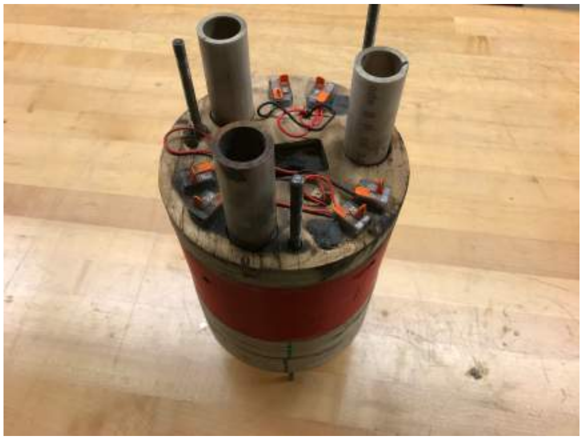


Figure 39: Fully Assembled CRAM, as flown

3.3.6.1 CRAM Body

The CRAM body is a casing that contains the CRAM core and provides a mounting point for the recovery electronics. The body consists of a cylinder with a large, central cutout where the CRAM core, with electronics attached, can slide in and out of the body. 3 0.25 inch by 0.75 inch rectangular ports cut into the side of the CRAM allow for access to the switches that control power to the altimeters, and 3 0.2 inch diameter holes to allow for airflow to the altimeters. 3 0.28 inch holes in the top of the CRAM body, which run all the way through the part, allow for tie rods to secure the CRAM in place against the aft recovery bulkhead. In the bottom of the CRAM is a .4 inch by 1.1 inch rectangular hole in the bottom of the CRAM allows for the shock cord to pass through the CRAM and connect to an eyebolt mounted in the aft recovery bulkhead. The top of the CRAM also features three circular cutouts, where PVC pipes were mounted. The CRAM body was additively manufactured from PLA, which was readily available, cheap, and allowed for the complex geometry required for the CRAM body. An engineering drawing of the CRAM body can be seen in Figure 40

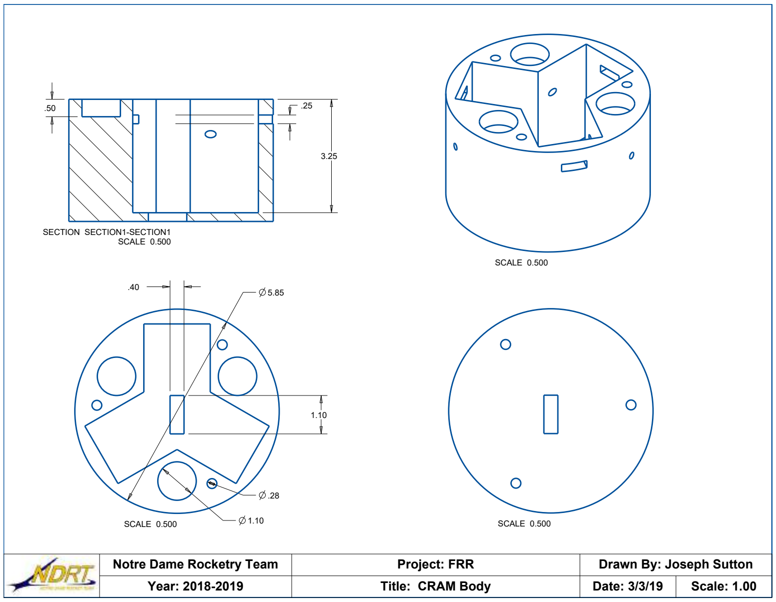


Figure 40: CRAM Body Drawing

Three PVC pipes are mounted to the top of the CRAM body as ejection charge wells, where the black powder charges are be placed during testing and flight. Figure 41

Figure 41: Picture of CRAM Body

3.3.6.2 CRAM Core

The CRAM core is a removable sled to which the recovery altimeters and batteries attach. The removable sled allows easy access to the electronics after recovery, while providing a location for tight attachment of the altimeters and batteries. A 0.35 inch by 1 inch central cutout in the center of the CRAM core allows for the shock cord to pass through the CRAM and attach to the aft recovery bulkhead. A three-part "skirt" on the CRAM core provides a mounting location for the battery boxes and altimeters. Figure 42, below, shows and engineering drawing of the CRAM core.

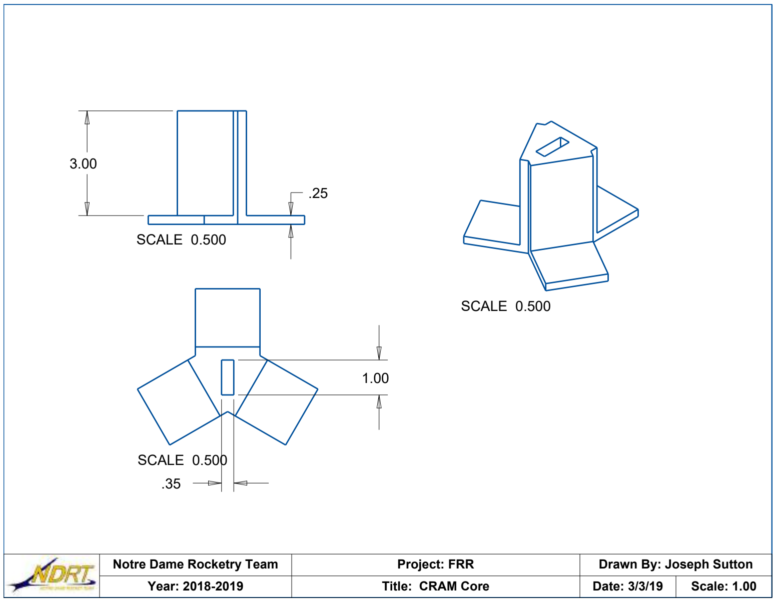


Figure 42: Drawing of CRAM Core

Each of the altimeters is mounted to its respective battery box with a zip tie, and all the battery boxes are mounted to the CRAM core with electrical tape. Clay is used to pack the empty space in between the batteries and the core to reduce vibration. The CRAM core was 3-D printed from PLA, which was cheap, readily available, and allowed for highly accurate manufacturing. Figure 43 is a picture of the bare CRAM core, and Figure 44 is a picture of the core with battery boxes and altimeters mounted.

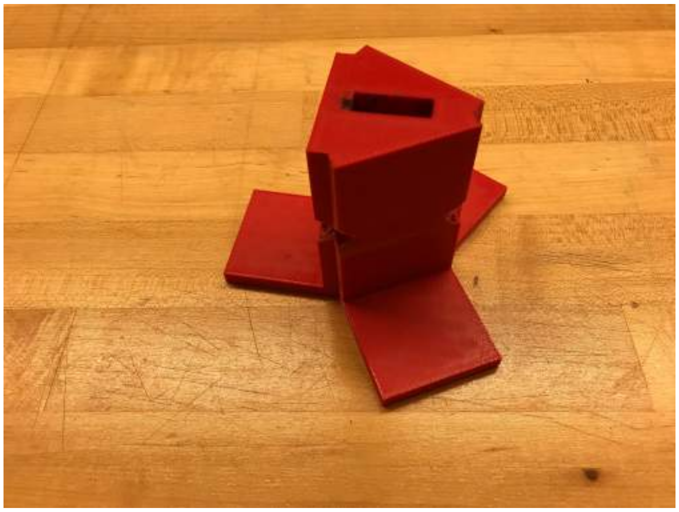


Figure 43: Picture of CRAM Core

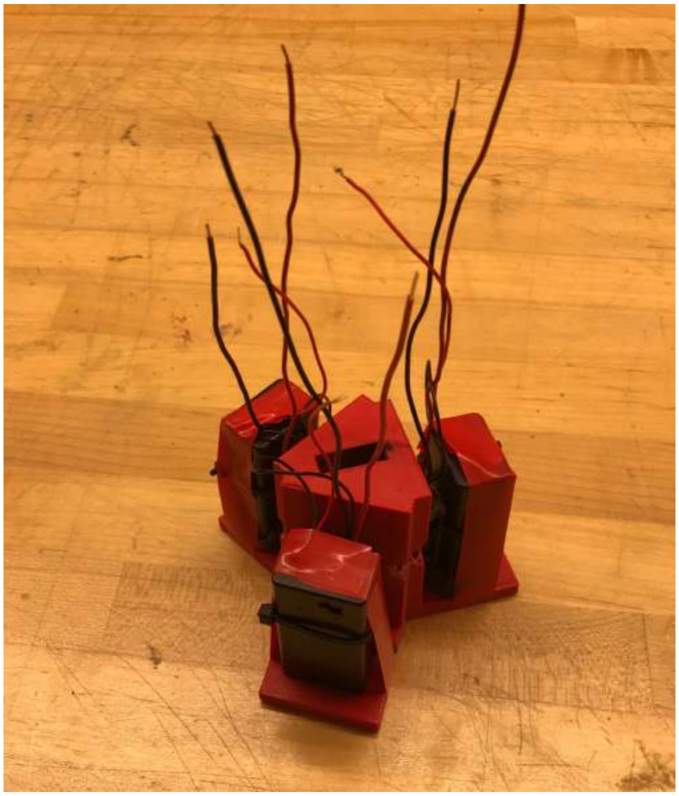


Figure 44: Picture of CRAM Core, with battery boxes and altimeters attached

3.3.6.3 CRAM Upper Bulkhead

The CRAM upper bulkhead acts to retain the CRAM core inside the body and seal the top of the CRAM such make the compartment airtight and protect the altimeters from black powder discharge. The bulkhead features a single 0.4 inch by 1.1 inch rectangular hole for the shock cord to pass through, three 1.1 inch diameter holes that allow for the PVC charge wells mounted to the CRAM body to pass through, three .28 inch holes to allow for tie rods to pass through, and three .25 inch holes to allow for wires to pass through. Six Wago 221 lever nut connectors are mounted to the top of the bulkhead which allow for easier instillation of the black powder charges in the field. The bulkhead was machined out of .75 inch plywood using a CNC router. Figure 45 is a picture of the CRAM upper bulkhead after flight.

Figure 45: CRAM Upper Bulkhead, after flight

3.3.6.4 CRAM Lower Bulkheads

Four lower bulkheads are added to the bottom of the CRAM to provide room for the eyebolt and attaching quick link to reside. The bulkheads feature a large central cutout to allow room for the aft eybolt and quick link. The bulkheads were machined from 0.75 inch plywood. The outer profile was mahcined with a CNC router and the central cutout was machined with a hand router. Figure 46 is a picture of one of the CRAM lower bulkeheads.

Figure 46: CRAM lower bulkhead

The CRAM, and all of the CRAM bulkheads, are attached to the aft recovery bulkhead with 0.25 inch threaded tie rods. 1/4-20 hex nuts and washers are used to lock the CRAM in place.

3.3.7 Shielding

The CRAM will be shielded by carbon fiber on all sides while in the rocket. The body tube of the rocket is made of carbon fiber, and is continuous around the CRAM. Two carbon fiber bulkheads, matching the size of the inner diameter of the body tube, will be cut and placed on either end of the recovery subsystem. The bulkheads will be 1/8in. thick. Carbon fiber is used for shielding the CRAM because carbon fiber is EF opaque, so no electromagnetic waves are able to propagate through it. This ensures that all recovery electronics are not adversely affected from all other electronic devices during flight, as per NASA requirement 3.12 in the student launch handbook.

3.3.8 Changes Needed Based on Test Flight

The test launch was a way of verifying the predictions from simulated flight data. Figure 47 shows a comparison between the actual flight data and the simulated flight trajectory.

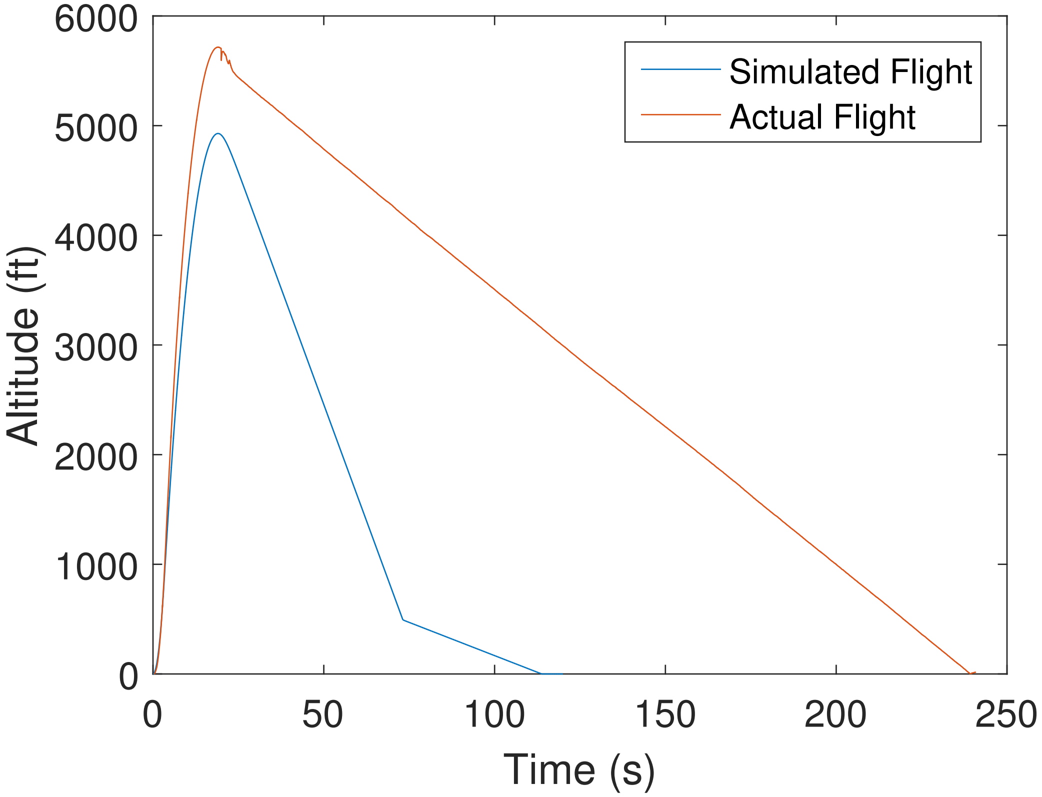


Figure 47: Test launch data compared to simulated flight trajectory

As shown, the two curves are drastically different, for a variety of different reasons. The first of major difference is in the apogee of the flight, which was much higher than previously estimated. This is due to a difficulty in modeling the finish on the outside of the launch vehicle, and the weight estimates used.

The second major difference is in the dual deployment, which is only seen in the simulated flight. This is due to the fact that the chute releases did not hold the main until the predicted 500 ft AGL, and so the main deployed at apogee. Visual confirmation and altimeter data show that the chute releases remained closed until the predicted 500 ft AGL, but the parachute slipped out of them at deployment. In order to remedy this in future launches, less black powder will be used, and the Nomex cloth around them will be packed more tightly.

The final major difference between the simulated flight and the actual flight is the descent velocity under the main parachute. The descent velocity under main for the actual flight was approximately 25ft/s, much larger than the predicted 12.11ft/s. This is due to an incorrect estimation of the exposed area of the parachute. In order to better control the flight of the launch vehicle, a larger main parachute will be used for future launches. This will also bring the kinetic energy at landing under the 75ft lb required by the student launch handbook.

3.4 Mission Performance Predictions

3.4.1 Static Stability

The static stability of the vehicle is a measure of its ability to counteract, or correct for, the conditions that act on it. Specifically, static stability measures how well the vehicle can return to its original position if disturbed. Requirements specify that the vehicle is to have a stability margin of at least 2 calipers. In order to maximize apogee and reach the decided upon altitude, the team's target stability range falls between 2.3-2.8. The vehicle must have a center of pressure that is aft of the center of gravity to prevent the aerodynamic forces from creating a destabilizing moment. Using CAD modeling and OpenRocket simulations, the static stability of the unloaded vehicle was calculated to be 4.12, whereas the stability of the loaded vehicle was calculated to be 2.75 with the Cesaroni L1395 motor.

3.4.2 Flight Profile Simulations

Various simulation techniques were used in order to model the flight of the rocket. The Euler method was used to model the trajectory of the rocket after reaching apogee. The velocity of the launch vehicle was discretized using Equation 3

$$v_i = v_{i-1} - g + \frac{C_d * D^2 * \pi * v_{i-1}^2 * \rho}{8m} * dt \tag{3}$$

where g is the acceleration due to gravity, C_d is the coefficient of drag of the parachute, m is the mass of the launch vehicle, D is the nominal diameter of the parachute, ρ is the density of air, and v is the instantaneous vertical velocity of the rocket. A step size of 0.013s was used. The predicted descent trajectory as a function of time is shown in Figure 48.

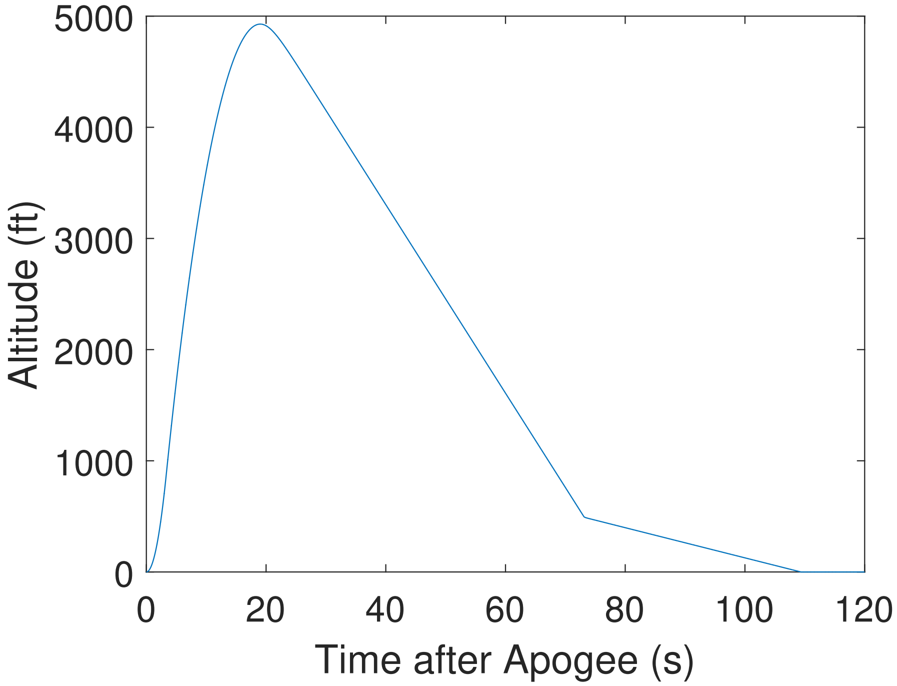


Figure 48: Predicted descent trajectory from the Euler Method

The Euler method was also used to calculate drift distances as various wind speeds. The calculated drift trajectories are shown in Figure 49

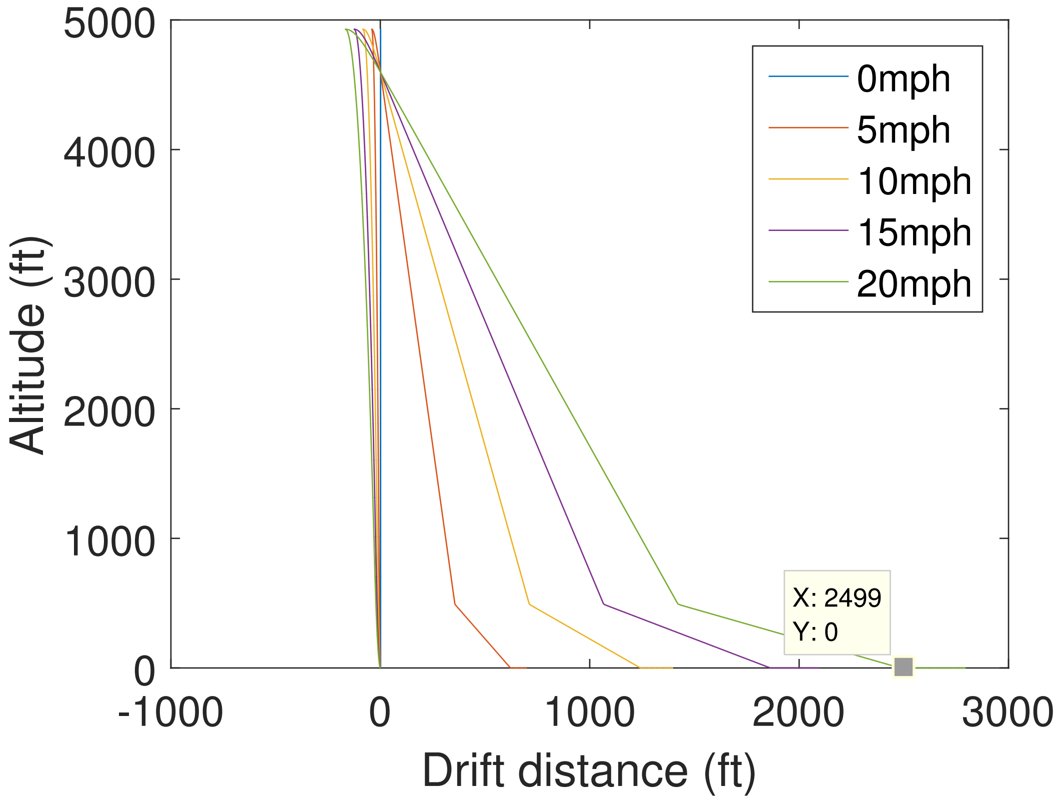


Figure 49: Drift trajectory from the Euler Method

OpenRocket and RockSim models were also used to calculate the trajectory of the launch vehicle. Both programs take into consideration contributions from the launch vehicle body, main and drogue parachutes, and the thrust curve of the motor in order to calculate the overall flight path. The flight predictions for OpenRocket and RockSim are shown in Figures 50 and 51, respectively.

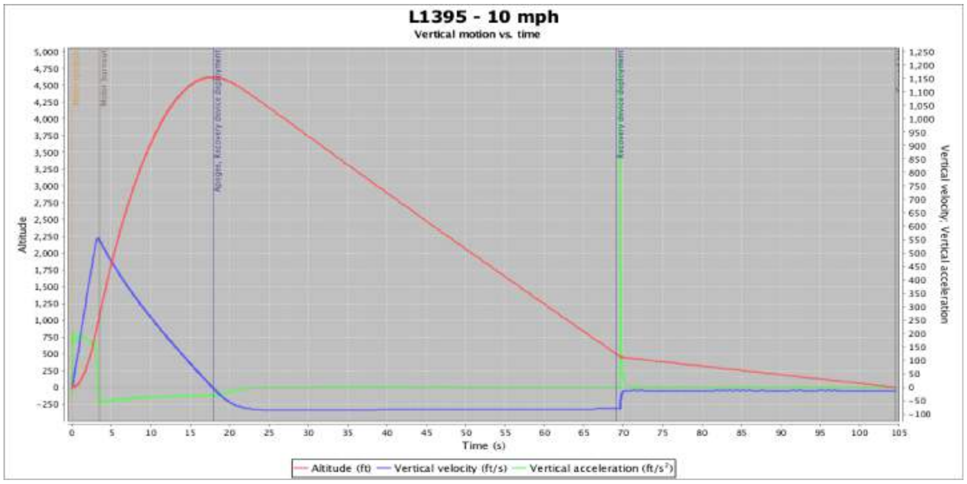


Figure 50: OpenRocket Flight Simulation

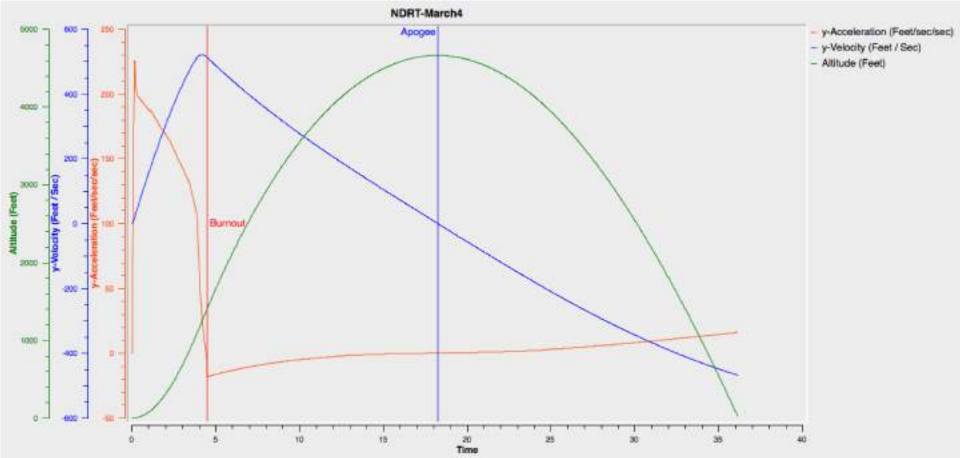


Figure 51: RockSim Flight Simulation

The overall performance predictions from each of the three simulations are summarized in Table 10.

Table 10: Flight Simulations and predictions

Simulation	Apogee(ft)	Kinetic Energy at landing (ft-lb)	Descent Time (s)	Max Drift Radius (ft)
Euler Method	4928	68.6	87.68	2573
OpenRocket	5210	58.2	88	2581
RockSim	5267	30.2	86	2522

The minor differences between values reflect the various considerations of the simulations. However, all of the values are similar enough such that a confident prediction of the flight path can be made. As shown, both the kinetic energy and descent times meet requirements 3.3 and 3.10 in the student launch handbook. The drift radius is slightly larger than the allowed radius of 2500ft. However, this is due to the fact that the simulations ignore weather cocking. Due to the stability margin of the rocket, it will turn into the wind during ascent, and will be well within the drift radius at landing, even flying within 20mph winds.

3.5 Vehicle Demonstration Flight

3.5.1 Launch Conditions

The test launch on March 2nd, 2019 took place in Tab, Indiana with a temperature of 31°F, and an average wind speed of 10 mph.

3.5.2 Flight Comparison

Table 11: Test Launch Flight Comparison.

	Open Rocket Prediction	Actual
Apogee (ft)	5758	5715
Time to Apogee (s)	19.3	18.75
Max Velocity (ft/s)	667	619
Max Acceleration (ft/s^2)	251	290

There is a 1.3% error in the predicted apogee when accounting for the temperature and wind conditions. The leading reason for the difference in the predicted to actual launch is wind gusts at varying altitudes and times during launch. The 10 mph winds that were used for the predictive analysis were based on average speeds, and do not account for the exact wind speeds at launch.

3.5.3 Coefficient of Drag Estimation

The C_D over the launch vehicle was estimated after the test launch using post-flight data. Using flight data post-burnout and apogee data, the required drag force can be calculated to form the parabolic curve. This drag force can then be used to extrapolate the drag coefficient for the entire launch vehicle. A comparison between the simulated data and the launch data is shown in 52. The fact that the simulated data matches almost identically with the actual flight data indicates accuracy in the estimated drag coefficient.

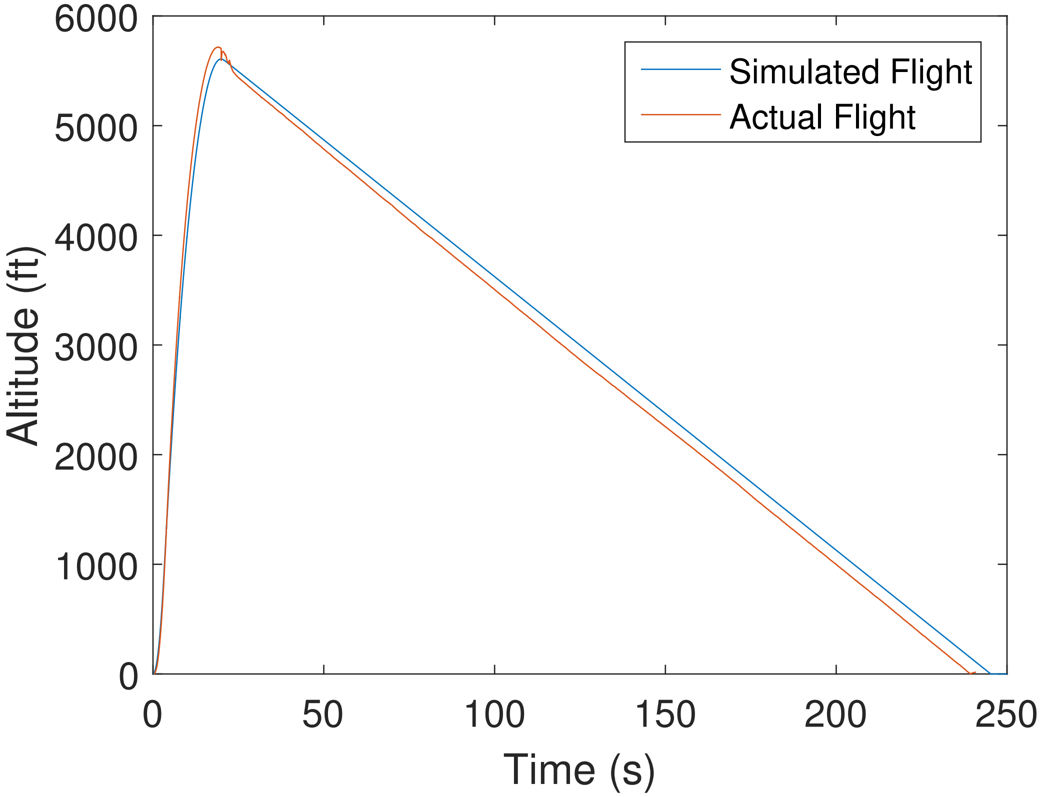


Figure 52: Simulated flight data compared to full scale launch data

Full-scale and Sub-scale Test Similarities and Differences:

The subscale flight test and three full scale test both had very similar predictive errors in apogee estimations. This further proves the simulation accuracy used for mission performance predictions. The subscale was a scaled down model of the full scale, and as such the geometry was the same across both tests. One notable difference is that the subscale transition was scaled based on a 4" long part, but this dimension has been changed to 5". Another difference is the greater deal of precision and lower tolerance levels on the full scale. The components used for the full scale vehicle were machined and produced with a high degree of accuracy, and this would have led to the predictions being much closer to the observed flight. During the subscale launch, the parachute was packed too tightly and this led to the chute release to become tangled and not allow for full deployment of the main parachute. This was improved upon during full scale and the chute release did not get tangled with the main parachute and impede recovery. However, the main parachute deployed at apogee which is not desired, and is being improved upon for the next test launch. Both subscale and full scale had very stable liftoff and overall launches, which verifies the team's construction processes, as well as the fin leading and trailing edge rounding procedures.

4 Safety

4.1 Safety Officer

James Cole is the Safety Officer for the Notre Dame Rocketry Team for the 2018-2019 season. The primary responsibility of the Safety Officer is to ensure the safety of all team members, students, and members of the public involved with any activities conducted by NDRT. To ensure this, the safety officer shall ensure that the team abides by all requirements set for the NASA USLI Competition as defined in Section 5.3 of the NASA SLI Handbook in addition to team-derived safety procedures.

4.2 Safety Analysis

Hazards were evaluated and assigned a level of risk based on their severity and probability of occurrence. This method was applied to every step of the project and team operations, and continues to be used throughout team operations. Each hazard identified was evaluated by the Safety Committee and documented such that the team proactively and promptly became aware of all hazards, and implemented all necessary mitigations. Thus, safety has been an iterative and interactive document that will continue to remain ahead of any and all risks the team may encounter. In order to assist with this, the Safety Committee used a scoring system when evaluating risks. Probability of occurrence was evaluated and designated with a letter between A and E, with E being that the event in question is almost certain to happen under present conditions, and A being that it is improbable that the event will occur. The criteria for this scoring is outlines in Table 12 below.

Table 12: Probability of hazard occurrence classification

Description	Value	Criteria
Improbable	A	Less than 5% chance that the event will occur
Unlikely	B	Between 5% and 20% chance that the event will occur
Moderate	C	Between 20% and 50% chance that the event will occur
Likely	D	Between 50% and 90% chance that the event will occur
Unavoidable	E	More than 90% chance that the event will occur

Probability and severity are evaluated according to present conditions, meaning two assumptions were made. The first is that if the conditions change, the probability and severity will be re-evaluated and changed accordingly. The second assumption is that all personnel involved in the activity have undergone proper training and clearly acknowledged understanding of the rules and regulations outlined in safety documentation. This may include, but is not limited to, the safety manual, compiled MSDS documents, FMEA tables, most recent design review, and lab manual if applicable. The evaluation of occurrence probability will also assume that proper PPE was used, all outlined procedures were correctly followed, and all equipment was inspected before use. Severity of the incident is evaluated on a scale of 1 through 4, where 4 is that the incident will prove catastrophic, and 1 is that the incident will prove negligible. Severity is evaluated according to the incident's impact on personal health and well-being, impact on mission success, and the environment. The score shall be based off of whatever the worst case scenario for the types of impacts being considered. These considerations will be re-evaluated anytime new hazards are identified. The criteria used to evaluate severity of each hazard is outlined are Table 13 below.

Table 13: Severity of hazard classification

Description	Value	Criteria
Negligible	1	Could result in insignificant injuries, partial failure of systems not critical to mission completion, project timeline or outcome possibly affected and might require corrective action, or minor environmental effects.
Marginal	2	Could result in minor injuries, complete failure of systems not critical to mission completion, project timeline or outcome affected and requires corrective action, or moderate environmental .
Critical	3	Could result in severe injuries, partial mission failure, severe impact to project requiring significant and immediate corrective action for project continuity, or severe and reversible environmental effects.
Catastrophic	4	Could result in death, total mission failure, complete failure of project rendering project unable to continue, or severe and irreversible environmental effects.

By combining the severity and probability values, a risk score will be assigned to each hazard. Risk scores will have a alphanumeric designation from 1A to 4E, where the number designates the severity and the letter designates the probability of occurrence. Risk levels can be reduced through mitigating actions which will lower either the severity score or the probability score. Actions will be taken starting with the highest risk level hazards, and will continue through the lower levels until all hazards have been reduced as much as possible. All hazards pose a risk and will not be ignored, but the classifications help the Safety officer prioritize resources to those that require the most immediate attention. Mitigations can take the form of design considerations to reduce severity or probability of failure, verification systems created to ensure proper operating conditions, and better handling procedures to follow. Risk scores and the risk levels that correspond with each score are outlined in the risk assessment matrix shown in Table 14, and the description of each risk level is listed in Table 15.

Table 14: Risk assessment matrix

Probability Level	Severity Level			
	Negligible (1)	Marginal (2)	Critical (3)	Catastrophic (4)
Improbable (A)	1A	2A	3A	4A
Unlikely (B)	1B	2B	3B	4B
Moderate (C)	1C	2C	3C	4C
Likely (D)	1D	2D	3D	4D
Unavoidable (E)	1E	2E	3E	4E

Table 15: Description of Risk Levels and Management Approval

Risk Level	Acceptable Level/Approving Authority
High Risk	Highly Undesirable. Must be approved by team captain, safety officer, and supervising squad lead.
Medium Risk	Undesirable. Must be approved by safety officer and supervising squad lead.
Low Risk	Acceptable. Must be approved by supervising squad lead or safety officer.
Minimal Risk	Acceptable and negligible. Risk level is minimal enough that the safety officer has deemed it negligible. No approvals needed.

In order to properly assess the risk facing the mission, key areas for assessment were identified: project risks, personnel hazards, failure modes and effects, and environmental concerns. Each one of these areas was then broken down further into more specific categories of interest and analyzed in the same manner. That is, a potential hazard, its cause, and its effect were identified within each category. The hazard was then given an alphanumeric risk score, as defined above, based off the severity and probability posed by the risk before the implementation of any mitigation (including those that would normally be assumed for assigning the actual risk score of the hazard). Mitigations and a method of verification, including for mitigations not yet implemented, were then identified, and the hazard was assigned a post-mitigation score that according to the criteria defined above. The results of this analysis were then recorded in tables that will be expanded and used by the Safety Committee to identify, track, and improve on its response to safety hazards.

4.2.1 Project Risk Analysis

A table outlining all the risks to the the project timeline and the mitigations being implemented to ensure that these risks are accounted for and reduced can be found in Appendix A.1

4.2.2 Personnel Hazard Analysis

4.2.2.1 Construction

A table identifying all hazards, causes, effects, and mitigations to personnel during construction can be found in Appendix A.2.1

4.2.2.2 Testing

A table identifying all hazards, causes, effects, and mitigations to personnel during testing can be found in Appendix A.2.2

4.2.2.3 Launch

A table identifying all hazards, causes, effects, and mitigations to personnel during launch can be found in Appendix A.2.3

4.2.2.4 Recovery

A table identifying all hazards, causes, effects, and mitigations to personnel from the Recovery system can be found in Appendix A.2.4

4.2.2.5 Unmanned Aerial Vehicle

A table identifying all hazards, causes, effects, and mitigations to personnel from the Unmanned Aerial Vehicle system can be found in Appendix A.2.5

4.2.3 Failure Modes and Effects Analysis

4.2.3.1 Vehicles

A table identifying all hazards, causes, effects, and mitigations to the success of the Vehicles system can be found in Appendix A.3.1

4.2.3.2 Recovery

A table identifying all hazards, causes, effects, and mitigations to the success of the Recovery system can be found in Appendix A.3.2

4.2.3.3 Air Braking System

A table identifying all hazards, causes, effects, and mitigations to the success of the Air Breaking System can be found in Appendix A.3.3

4.2.3.4 Unmanned Aerial Vehicle

A table identifying all hazards, causes, effects, and mitigations to the success of the Unmanned Aerial Vehicle system can be found in Appendix A.3.4

4.2.3.4.1 Launch Operations

A table identifying all hazards, causes, effects, and mitigations to the success of launch operations can be found in Appendix A.3.5

4.2.3.5 Launch Support Equipment

A table identifying all hazards, causes, effects, and mitigations to the success of launch support equipment can be found in Appendix A.3.6

4.2.3.6 Payload Integration

A table identifying all hazards, causes, effects, and mitigations to the success of payload integration can be found in Appendix A.3.7

4.2.4 Environmental Hazards

4.2.4.1 Environmental Hazard to Rocket

A table identifying all hazards, causes, effects, and mitigations to the environment's effect on the rocket can be found in Appendix A.4.1

4.2.4.2 Rocket Hazard to Environment

A table identifying all hazards, causes, effects, and mitigations to the rocket's effect on the environment can be found in Appendix A.4.2

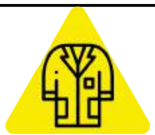
4.3 Launch Safety Checklists

Safety procedures are important to ensure the safe execution of a launch. All safety procedures will be created according to the process described in Section 4.6 and will be used to help ensure smooth operation on launch day. When steps in the launch procedures require the use of certain PPE, the required PPE will shown with team-standard visual indicators, which are outlined in Table 16.

Table 16: List of PPE and corresponding Visual Indicators

Visual Indicator	Required PPE
	Antistatic Gloves
	Cut Resistant Gloves
	Heat Resistant Gloves
	Leather Gloves
	Nitrile Gloves
	Safety Glasses
	Safety Goggles
	Dust Mask

Table 16: List of PPE and corresponding Visual Indicators

Visual Indicator	Required PPE
	Lab Coat

Whenever a PPE visual indicator is shown there will be corresponding, bolded directions with the visual indicators to say say either that the PPE will be used only for the following step, or until instructed to take it off. In this case, another bolded step will instruct when to remove the PPE. In some cases, steps in the procedure must be followed in a particular order, or are required to be performed by a particular person (such as the overseeing technical lead or the team mentor). In these cases, a bolded step in the procedure will appear to explain what special instructions must be followed, and a warning indicator, as seen in Figure 53, will appear with the step.

Figure 53: Warning visual indicator to indicate when special instructions or care must be followed with proceeding steps

Be sure to follow these directions closely - potential hazards or failures that may occur as a result of failing to heed these important instructions will also be listed in the procedure with the instructions. As with PPE, when the steps that are pertinent to the special instructions are complete, another bolded instruction step will indicate that the instructions are no longer in effect.

4.3.1 Launch Operation Procedures

The launch procedure checklists can be found in Appendix A.7, where there is a detailed breakdown of launch operations. Specific instructions regarding the following topics are listed below

- Recovery preparations (A.7.3.3, A.7.3.4, A.7.3.5, A.7.3.6)
- Motor preparations (A.7.2.6)
- Setup on launch pad (A.7.2.7, A.7.3.7)
- Igniter installation (A.7.2.8)
- Launch procedure (A.7.1.3)
- Troubleshooting (A.7.6)
- Post-flight inspection (A.7.1.4, A.7.2.9, A.7.3.8, A.7.4.4, A.7.5.8)

Note that the procedures themselves are far more extensive, and cover **all** aspects of launch day operations. Checklists are in chronological order, divided squad-by-squad for ease of use on launch day.

4.4 Safety Manual

The Safety Officer and Safety Committee has produced, published, and maintained a Team Safety Manual. The Safety Manual has been released to the team via, and published on this website. The Safety Manual contains up to date guidelines pertaining to

- Machine and Tool Use
- Personal Protective Equipment Use
- Construction
- Testing
- Launch
- Local, State, and Federal Law Compliance
- NAR/TAR Safety Code Compliance
- MSDS Purpose and Use

And has been updated as needed, with the team being notified of each update. Members of the team are required to understand and agree to the contents of the safety manual, and to maintain a current knowledge of the contents of any updates made to it, which have be enforced through a signed agreement that all members must sign. A physical copy of the Safety Manual has be kept in the team's workshop, and and has been updated to the most current version within 3 days of the release of any updates.

4.4.1 Safety Manual Contents

The Safety Manual contains a number of sections relating to the safety of rocket construction, testing and launch. Among the included sections are a section on Personal Protective Equipment, which details the situations in which PPE is needed and how to use PPE such as gloves, safety glasses and goggles, respirators and dust masks, and earplugs. All SDS sheets for any potentially hazardous materials used in the rocket are included. A separate section is included on construction safety, specifically tool use and machine shop certification. A section on testing safety details testing procedures and safety hazards related to testing. Launch safety details a number of possible hazards that can occur during a launch, as well as procedures for launch. Educational Outreach safety is included. All safety requirements from local, state, and federal law, as well as the NAR safety code, is included. A specific section on energetics is included as well.

4.4.2 Machine Shop Certification

In order to participate in construction, all members of the team must receive at least Level 1 certification from the Notre Dame Aerospace and Mechanical Engineering Student Fabrication

Lab, or AME SFL. The SFL Level 1 certification process involves passing a quiz on basic machine shop safety, passing a quiz on the use of basic hand and power tools, and participating in a safety walk-through of the AME SFL. Upon completion of these steps, the team member receives a signed card reflecting their certification status. In order to use more advanced tools, such as the drill press or belt sander, further tool-specific certification is required. The process for tool specific certification involves passing a quiz on tool safety and passing a competency test given by AME SFL staff. All certification levels of all team members are kept in a spreadsheet by the Safety Officer, which is referenced during construction to ensure compliance with construction safety rules.

4.4.3 Safety Agreement

All active team members have signed a form asserting that they understand and will comply with the contents of the Manual.

4.5 Material Safety Data Sheets

Material Safety Data Sheets (MSDS) have been acquired from suppliers upon purchase of any materials. An up-to-date compilation of all MSDS shall be kept in a dedicated document as well as in the Safety Manual. A physical copy of the MSDS document is kept in the team's workshop, and added to as more materials are acquired. The Safety Manual also includes a section with guidelines on the organization of MSDS sheets and the relevant safety precautions when dealing with each specific material.

4.6 Procedure Development

Prior to an operation, the Safety Committee and team leadership have developed procedures for the construction, testing, and launch of all vehicles, subsystems, and payloads. The technical design leads most closely related to the subject matter of each procedure have had primary input to ensure that procedures will yield the intended results. The safety officer has then reviewed all procedures to ensure that they outline an operation that poses an acceptable and approved risk. If this is not the case, and any risks cannot be approved, the safety officer will recommend changes to the procedure, and it will not be released until changes are agreed upon. Once a procedure is released, the Safety Officer has published it in the Safety Manual and notified the team. The procedure will then be considered active and the operation will be able to proceed. Members of the team wishing to participate in an operation must thoroughly read and understand the procedure for that operation. If a procedure is violated, it has been documented in order to better understand the causes and effects, and to make whatever changes are necessary for the future in order to ensure that this does not happen in the future.

4.6.1 Competency Quizzes

In order to ensure that for a given operation, participating team members understand the operation's procedure to a point where the operation can be safely and competently carried out, the Safety Officer may require a competency quiz. Competency quizzes will test knowledge and understanding of the contents of the operation procedure, as well as any relevant knowledge pertaining to the tasks that must be performed for the given operation. Each quiz will have a minimum passing grade that team members must achieve in order to assist with the operation in question. Competency Quizzes have been implemented for all launches and prior to any major phase of construction. Any member of the team who has not received a 90% or greater on one of these quizzes has not been allowed to participate in launch or construction.

4.6.2 Operation Readiness Reviews

For especially important operations, the Safety officer or technical lead in charge has required an Operation Readiness Review (ORR) to be conducted prior to the operation. This consists of a presentation to brief participating members about what will occur during the operation, knowledge relevant to the operation, goals and outcomes of the operation, and contingency plans. Following an ORR, a competency quiz has been administered. Operations requiring ORRs include launches and construction phases.

4.7 NAR Safety Code Compliance

The Notre Dame Rocketry Team has taken several steps to ensure compliance with the National Association of Rocketry High Power Rocket Safety Code that has been effective as of August 2012. Appendix A.5 outlines each of the items in the safety code, and how the team and its mentors have been compliant with it.

4.8 Vehicle Demonstration Test Flight Critical Path Forward

The completion of the Vehicle Demonstration Test Flight on March 2, 2019 was successful. The flight did, however, demonstrate some important points of failure that had not been considered by the team. The team will be making mitigations for each newly identified hazard, which can be found in Table A.6. The flight gave the team several important takeaways, which will be immediately implemented going forward into the operational stage of the project at further test flights. Importantly, this test flight's purpose was merely to demonstrate the operation of the vehicle and recovery system, and did not include active use of payload systems. Failures and hazards identified as a result of the vehicle demonstration flight are listed below.

- Partial failure of the nosecone retention system was identified to be caused by insufficient surface area between the two conjoining surfaces of lead screw hex nut and nosecone

bulkhead. Further detail can be found in Section 5.3.2.3 as well as the demonstration test flight safety table.
- Failure of the UAV platform retention flanges was determined to be caused by mechanical failure of the material and structure under load, which was not initially considered in their design. Material selection changes will be implemented to properly account for loads that will be experienced during flight and recovery. Details of the mitigating design change can be found in Section 5.3.2.1 as well as the demonstration flight safety table.
- Failure of one of the zip ties holding the ABS batteries in place was identified, and will be mitigated by printing a custom retention system for the batteries, which will be epoxied into the system. The details of this can be found in Section 6.1.3.5 and the vehicle demonstration flight safety table.
- Though ABS was inactive during flight, it was gathering data and simulating state changes in its software. Failure of the ABS software and sensors to properly identify burnout, and thus to switch states was identified, and will be mitigated as described in Section 6.1.3.5 as well as the demonstration flight safety table.
- Deployment of the main parachute at apogee was visually confirmed. A path forward to ensure that this does not occur has been identified and is being implemented. This path is described in Section 3.3.8 and the demonstration flight safety table.
- The kinetic energy of the rocket coming down was measured to be greater than acceptable margins, which also means a failure of recovery to properly account for kinetic energy with the parachute used. A larger parachute has been selected and ordered, as described in Section 3.3.8 and the demonstration flight safety table.
- Significant overage on the apogee will be fixed via significant ballast of the vehicle, which in turn will require a larger parachute size (noted in Section 3.3.8). The mitigation of this failure is described in the demonstration flight safety table.

With these failures identified, the safety officer and design leads have already identified critical design changes needed to mitigate these failures. The results of all changes made as a result of the initial vehicle demonstration test flight will be reflected in the subsequent test flight and the test flight addendum that will be submitted following the vehicle test flight.

5 Unmanned Aerial Vehicle Payload Technical Design

5.1 Payload Overview

The unmanned aerial vehicle (UAV) with simulated navigational beacon delivery is the Notre Dame Rocketry Team's experimental payload for the 2019 NASA Student Launch Competition. A custom Orientation Correction System and Linear Transport Mechanism will ensure the successful takeoff of the UAV. These systems will be remotely triggered after safe landing under the supervision of a Remote Deployment Officer. After deployment from the launch vehicle, the UAV will fly autonomously to a Future Excursion Area (FEA) via an the Autonomous Flight Subsystem, which sorts through and finds the nearest set of inputted GPS coordinates. The Future Excursion Area Detection Subsystem will detect the yellow FEA and will drop a simulated navigational beacon. The final design of the payload in its fully stowed and fully deployed configurations, may be seen in Figure 54.

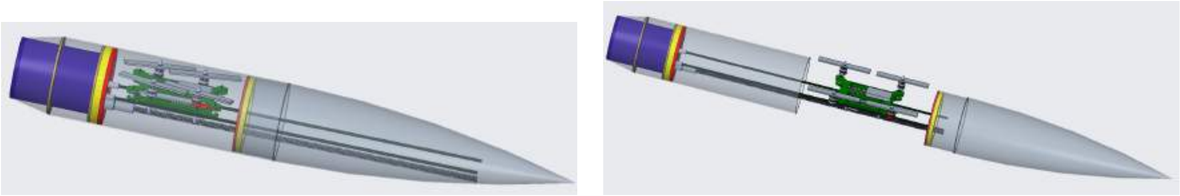


Figure 54: Fully stowed and fully deployed configurations.

5.1.1 Mission Success Criteria

The following items have been deemed qualifications for a successful mission at the 2019 NASA Student Launch Competition.

1. The payload shall be powered off until the rocket has safely landed and has been approved for remote-activation by the Remote Deployment Officer.
2. The payload shall remain retained inside the vehicle utilizing a fail-safe active retention system.
3. The payload shall deploy from inside the launch vehicle from a position on the ground.
4. The payload shall fly to a NASA specified Future Excursion Area.
5. The payload shall drop a simulated navigational beacon on the Future Excursion Area and then shall move a safe distance away from the Future Excursion Area.

5.1.2 Changes Made Since the Critical Design Review

There have been a few changes to the payload experiment since the submission of the Critical Design Review. Each change is pivotal to the overall success of the mission. They are discussed in Table 17.

Table 17: Alternatives and design selections since PDR.

Feature	***Design Selection***	Rationale
Frame Design Selection: Iteration II Versus Iteration III	Iteration III	The advantages of frame design Iteration III over Iteration II was its modified location of the Beacon Deployment System as well as the arm stopper locations. The placement of the servo motor for the beacon deployment system was moved from the center of the bottom piece of the UAV to the back of the UAV. This was done so that both the Beacon Deployment System as well as the Raspberry Pi would be able to fit on the bottom of the UAV. This is critical to mission success as the Raspberry Pi will hold the camera used for target detection of the FEA and the Beacon Deployment System must be on the bottom for it to function as designed. Additionally, the arm stoppers on the top piece of the UAV were modified to stop the arms when they were perpendicular to the UAV in order for the UAV to have clearance for take off.
Arm Extension Mechanism Selection: Belt and Pulley Versus Spring Extension	Spring Extension	Using an independent spring extension mechanism on each arm allows the arms to rotate in opposite directions transitioning from its folded position to its unfolded position. This allows all four arms to fold toward the middle of the UAV and reduces the maximum length of the UAV during its transition from 13.6 inches to 8 inches. This reduction in length makes the UAV deployment system much simpler and lighter, and the belt and pulley system is no longer necessary due to the following design changes. The UAV's arms are now held in place by the rocket's body tube rather than by the aft bulkhead and the belt and pulley system, and each spring moves the attached arm to its unfolded position. Therefore, the belt and pulley system is no longer necessary to hold the UAV in its folded position or for the UAV to transition to its unfolded orientation.

Feature	***Design Selection***	Rationale
Linear Transport Mechanism Motor Selection: Stepper Motor Versus Gear Motor	Gear Motor	The linear transport motor was changed due to weight and design considerations. Implementing the gear motor requires less circuit components; it can run directly off of the battery. The gear motor is also lighter than the stepper motor.
Video Stream Frequency Selection: 915 MHz Versus 5.8 GHz	5.8 GHz	The 915 MHz frequency would have caused latency because it was not meant for video streaming.

5.2 System Level Design and Integration

The payload has been divided into the following subsystems to ensure that the payload can perform all NASA requirements and to evenly divide that the work between engineers of multiple disciplines. The following, Figure 55, shows the system level design for the 2019 Notre Dame Rocketry Team scoring payload.

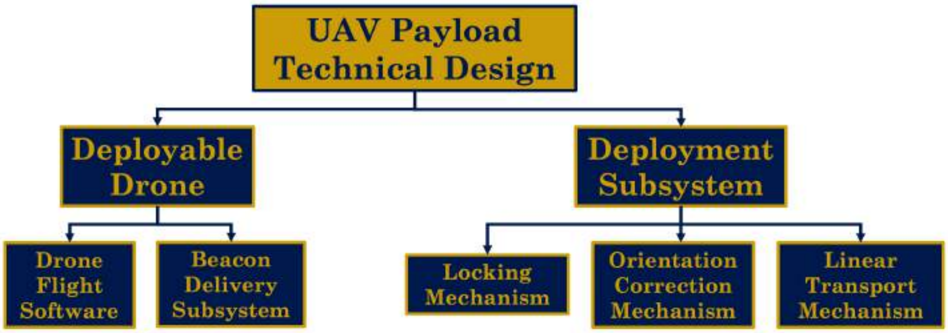


Figure 55: UAV Payload breakdown.

5.2.1 Deployable Drone

During the flight of the rocket, the UAV is secured into place by inserting R-clips through both the aluminum landing struts of the UAV and its platform. This prevents any motion in the x, y, or z directions. These pins attach to the aft bulkhead using braided fishing line and gradually pull out as the UAV is deployed from the rocket. The UAV is placed in the rocket in the folded position, shown in Figure 56.

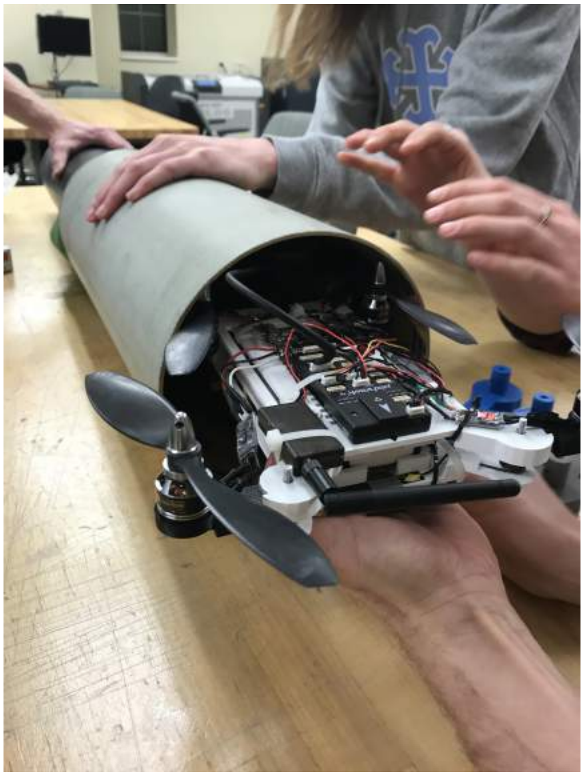
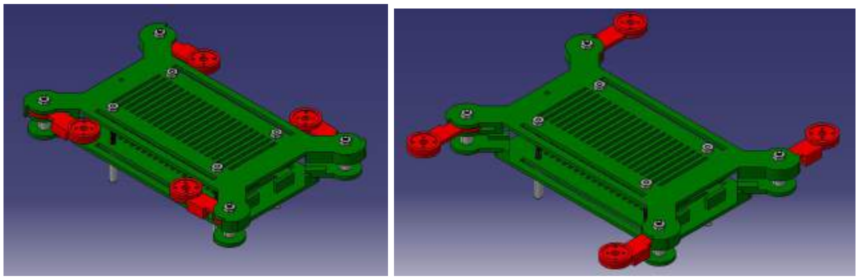


Figure 56: UAV being placed inside the rocket.

The arms are rotated 90 degrees from the flying position so that the UAV is in a rectangular shape and its dimensions are minimized. When the UAV is in the folded position, the torsion springs on each arm are rotated and generate the torque required to deploy the arms to the flying position. The change from a belt and pulley system to independent springs on each arm was made due to the limited payload bay size. In order for the UAV to fit inside the body tube and have enough clearance for lift off, the arms need to rotate from the sides of the body. This change prevents the arms from hitting the fore bulkhead when deploying. As the UAV is deployed from the rocket, the arms rub along the inside of the body tube, which compresses the torsion springs. The arms spring into flight position when the UAV exits the body tube. The two main configurations can be seen in Figure 57



(a) Folded configuration (b) Unfolded configuration

Figure 57: Two main configurations of the drone.

The measurements of the Deployable Drone may be found in Table 18.

Table 18: Measurement assessment of the Deployable Drone.

Dimension	Value
Length (Folded)	8 in
Length (Deployed)	8 in
Width (Folded)	5 in
Width (Deployed)	8.6 in
Height	2.83 in
Weight (With All Electronics)	35.2 oz

Figure 58 shows a CAD drawing of the final UAV frame in the flight orientation. The drawing shows all important dimensions of the UAV in inches. The center section of the UAV is 1.12 inches tall and 2.30 inches wide which enables the battery to fit securely during flight. The length of the landing struts is 1.26 inches which is longer than the minimum of 1 inch to fit the beacon deployment system.

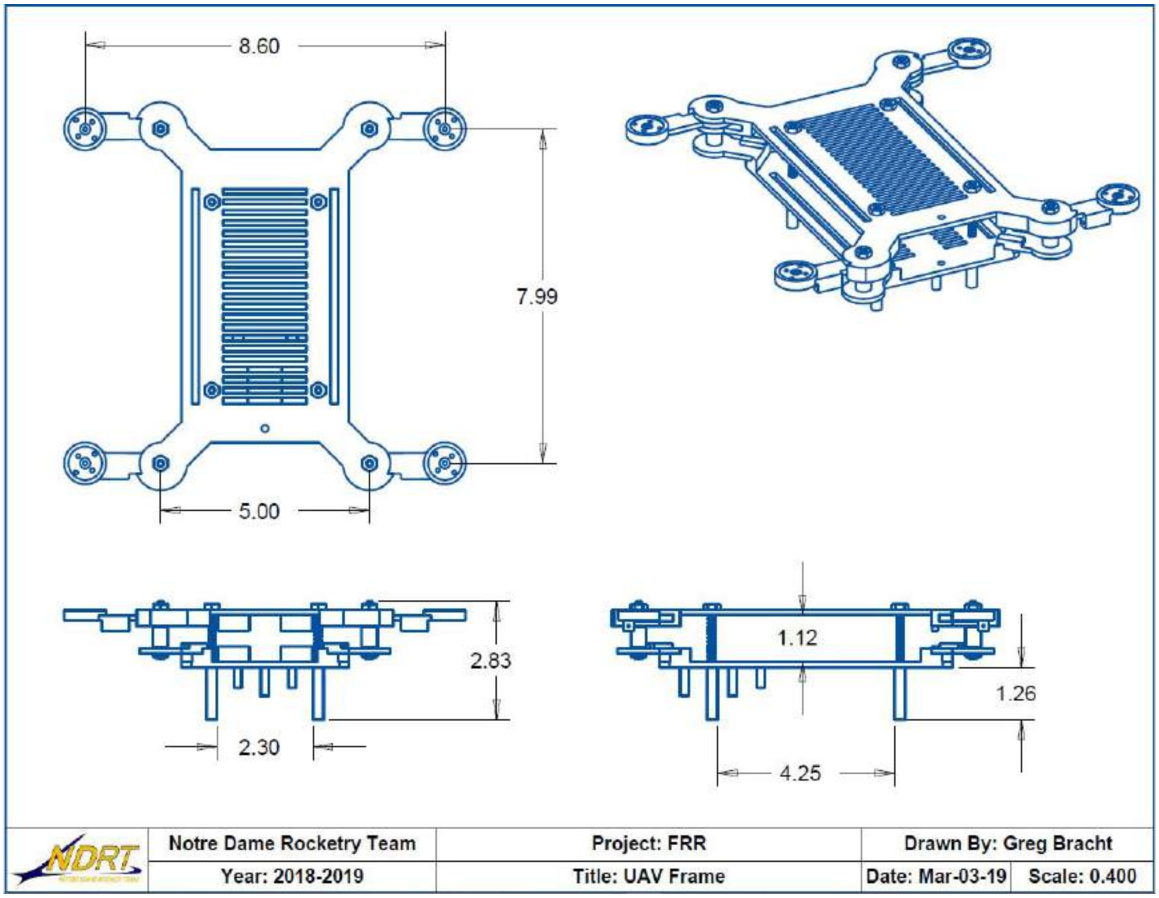


Figure 58: Drawing of the UAV with dimensions.

The following, Table 19, gives an overview of the different parts of the drone with mention of the materials used for each corresponding part.

Table 19: Drone part overview.

Item(s)	Material	Justification of Material
Arms and Frames	ASA	ASA is a durable and weather-resistant polymer frequently used in 3D printing. It is fairly impact-resistant and lightweight, with a density of about 0.62 oz/in^3. The UAV must be strong enough to withstand the forces to which it is exposed in the rocket, such as the approximately 200 m/s^2 acceleration when the main chute is deployed, while also remaining light enough to fly for an extended period of time. Furthermore, 3D printing is a process well-suited to the UAV's production because it allows for several iterations of the frame at low cost and in a short amount of time.

Item(s)	Material	Justification of Material
Supports and Struts	Aluminum	Aluminum is a metal used in many aerospace applications due to its low density. It is strong and lightweight similar to carbon fiber; however, while carbon fiber is a brittle composite prone to fracturing, aluminum is able to yield. This quality is desired for the supports and struts of the UAV as they will be subjected to strong impulses upon landing. Additionally, the UAV will undergo many test flights which will result in many landings and repetitive impulses. Therefore, the reduction of strut failure is achieved by using aluminum that may yield slightly rather than generate cracks that will propagate over time.
Torsion Springs	Steel Wire	The torsion springs used in the deployment of the arms of the UAV are required to be resistant to deformation due to repetitive torsion and lock the arms in the flying position. Therefore, a steel wire torsion spring with a rotation potential of 225 degrees and a spring constant of 0.011 inch-pounds per degree was selected. The spring will be rotated 90 degrees in the flying position and will apply a torque of 1 inch-pound to the arms holding them in the flight position. The steel wire will ensure that the springs will not deform due to repetitive use during test flights and are also inexpensive to have backups if deformation does occur.

5.2.2 Deployment Subsystem

The Deployment Subsystem is the largest component of the UAV payload. This subsystem is broken down into three different stages, identified by their mechanisms:

- Locking Mechanism
  - Properly constrains the UAV during the flight and recovery of the launch vehicle
- Orientation Correction Mechanism
  - Ensures that the UAV will be facing upright after the recovery of the launch vehicle for successful takeoff
- Linear Transport Mechanism
  - Moves the UAV out of the launch vehicle and gives it the clearance needed to takeoff

Additional details about three different mechanisms may be found in the Payload Mechanical Design and Payload Electrical Design sections of the report. The following, Figure 59, shows two CAD top views of the entire subsystem and an as-built top view of the subsystem when deployed.

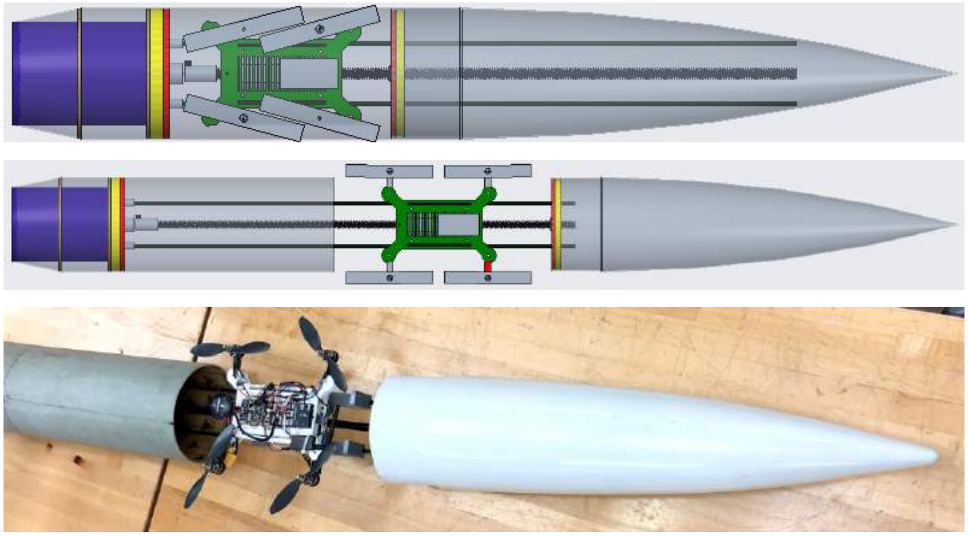


Figure 59: Top views of the UAV Deployment Subsystem.

The following, Table 20, gives an overview of the different parts of the Deployment Subsystem.

Table 20: Deployment Subsystem part overview.

Item	Material	Justification of Material
Leadscrew	5/8"-11 Thread Nylon 6/6	Nylon is strong, stiff, smooth, and has exceptional bearing and wear properties, which is why it can often be used in place of metal. Other benefits to using nylon in place of metal include a reduction in part weight and decreased wear on mating parts like the hex screw epoxied in the fore bulkhead. Using nylon will also help fulfill NASA Vehicle Requirement 2.24.10. (Excessive and/or dense metal will not be utilized in the construction of the vehicle. Use of lightweight metal will be permitted but limited to the amount necessary to ensure structural integrity of the airframe under the expected operating stresses).

Item	Material	Justification of Material
Rotating Bulkhead and Track System (The fore set is connected to the nose cone and also translates linearly along the leadscrew. The aft set is connected to the inside of the UAV payload bay but does not translate linearly.)	MDS-Filled Cast Nylon	The MDS-filled cast nylon offers the impact resistance and toughness of unfilled nylon, but the addition of molybdenum disulphide acts as a lubricant. This addition allows for the material's repeated use with negligible wear. This material is low-friction, self-lubricating, and offers sufficient impact resistance.
Dowel tubes (2)	Carbon Fiber Tube 0.25" ID, 0.32" OD Carbon Fiber	Carbon fiber is one of the strongest plastic composites available. It is incredibly strong, comparable to aluminum 6061, but also lightweight. Another material considered was aluminum alloy 7075. However, this material, though strong, is far too heavy for the system. The properties of carbon fiber will be very important in the prevention of twisting. In other words, the Orientation Correction System requires the simultaneous rotation of both bulkheads. The two high-strength carbon fiber rods will ensure that the fore and aft bulkheads rotate together, as opposed to asynchronous rotation.

5.3 Payload Mechanical Design

5.3.1 Deployable Drone

The UAV frame is designed to maximize the structural strength of the UAV while minimizing weight. The frame is composed of two identical plates made of ASA that are the top and bottom of the UAV. The Pixhawk 4 flight controller and power distribution board are attached to the top plate of the UAV, the battery is secured between the two plates, and the Beacon Deployment System and Raspberry Pi attach to the bottom plate under the UAV. The plates are secured using aluminum rods that extend from the the top plate to 1.2 inches past the bottom plate to provide adequate space for the Beacon Deployment System. These struts are secured using aluminum lock nuts. The arms are also made of ASA and are locked into place using an aluminum rod. The rod extends from the top plate to the bottom plate so that the torsion springs used to unfold the arms are adequately supported. These rods are also secured using aluminum lock nuts.

The team has completed three 3D prints of the UAV frame. The first iteration was printed in PLA and consisted of the body, the arms, and pins to hold the arms. While this design was viable, it was bulky and many areas of the design could be improved to reduce weight and size. The second iteration of the UAV body was printed in ASA because it is a stronger and more flexible material. The body is now composed of multiple parts and the thickness of the arms and body plates have been reduced. The third and final design of the UAV is printed in ASA, shown in Figure 60.

Figure 60: Iteration III.

ASA is different than the proposed carbon fiber material because it is cheaper and easily replaceable. There are few changes between Iteration II and III. The main differences are that the arms stop at 90 degrees instead of 135 degrees, and there are added rods on the bottom of the UAV for securing the beacon servo. The added rods may be seen in Figure 61.

Figure 61: Bottom of the UAV.

The arms have also been shortened so that the UAV is in X formation for flight and so that the UAV has enough clearance for takeoff once it has deployed from the rocket.

Since CDR, the UAV frame has been flown two times to validate the design with deployment and the electronics. The first flight was conducted with the arms fixed in the flight position and the frame was printed in PLA, shown in Figure 62.

Figure 62: Phases of UAV manual flight.

This flight was conducted to test the stability of the UAV during flight and the maneuverability; however, this also served to validate the stress strain analysis conducted in Abaqus. Due to a cross breeze, the UAV hit the ground hard and one of the arms broke. Since the first flight verified the arm orientation and the strength of the body design, the second flight was conducted with a frame printed with ASA and the arms were held using the mechanical deployment system. This flight served to validate the strength of the torsion springs to hold the arms in the flight position. The flight was successful and the arms remained in the flight position during many sharp maneuvers that will not occur during normal flight. This test validated the mechanical spring system used to deploy the arms and lock them in the flight position.

The arm deployment mechanism can be seen in an exploded view below in Figure 63 (torsion spring not pictured).

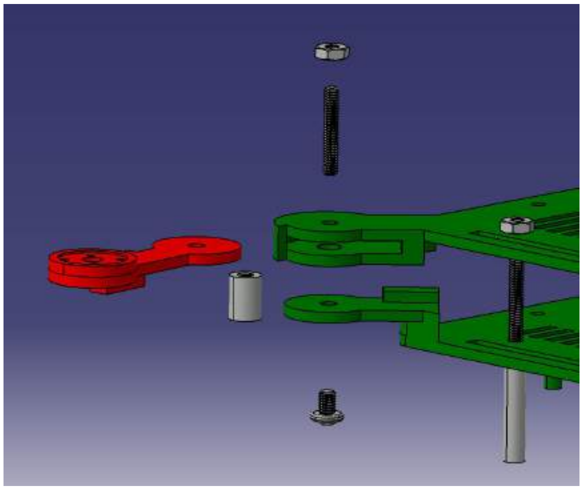


Figure 63: Exploded view of the UAV arm.

The system is composed of the arm, the top UAV plate, an aluminum rod, an aluminum support, and an aluminum screw. The mechanism works by linking one end of the 225 degree steel torsion spring to the UAV bottom plate and the other end to the arm. In the flight position, the spring will apply a constant force to the arm and lock it in place. To put the arms into the folded position, all four arms are held in their folded position until the body tube of the rocket holds them in place. The following, Figure 64, shows a test the team ran to check the ability of the arms to fold.

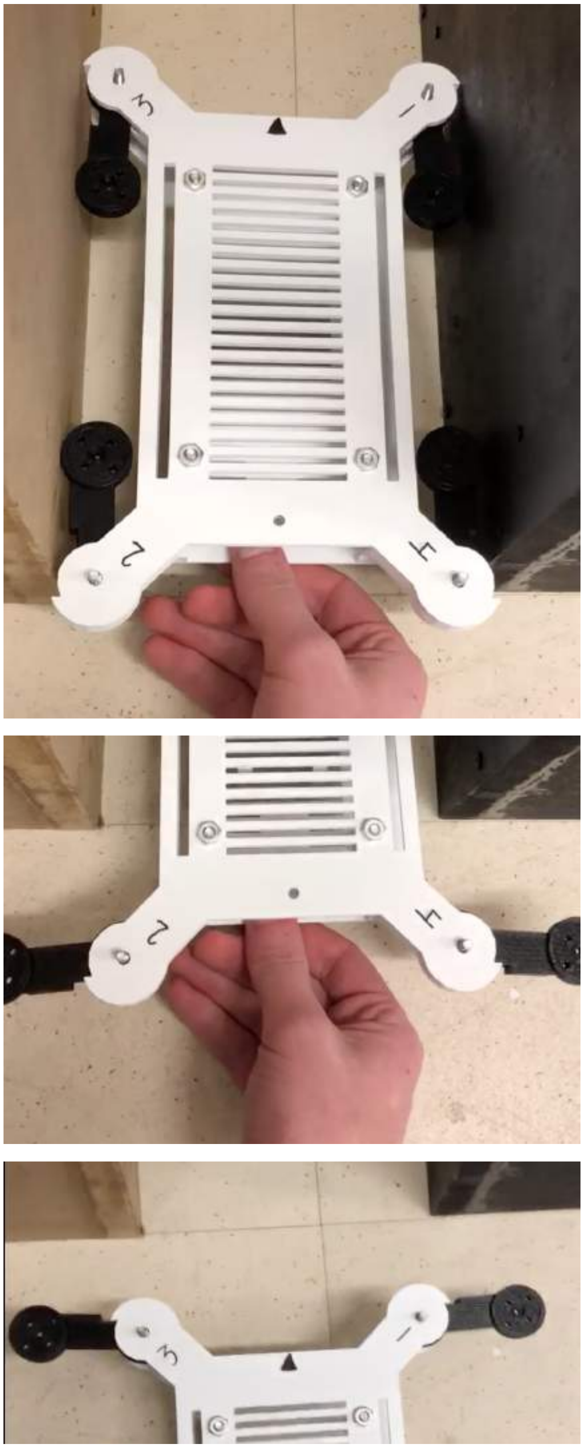


Figure 64: Arm Mechanism test.

Each arm folds toward the interior of the UAV to rest between the UAV's frame and the body tube. Each arm rotates independently of each other.

5.3.2 Deployment Subsystem

5.3.2.1 Locking Mechanism

The UAV must be fully constrained during flight to ensure that it does not disturb the motion of vehicle flight. The primary components of the locking mechanism are the platform and R-clips. The platform was 3D printed at the University of Notre Dame. The design incorporated a slot for a nylon hex nut of 5/8"-11 thread fitted inside the platform for connection with the leadscrew. The design also accommodated for size constraints within the payload bay. The flanges in which the UAV struts are secured are circular with one flat edge. The flat edge allows for an easier release of the R-clips upon deployment. Due to a recent test, with results shown in Figure 65, the platform design has been slightly modified to include stronger flanges, which will be machined out of aluminum at the University of Notre Dame.

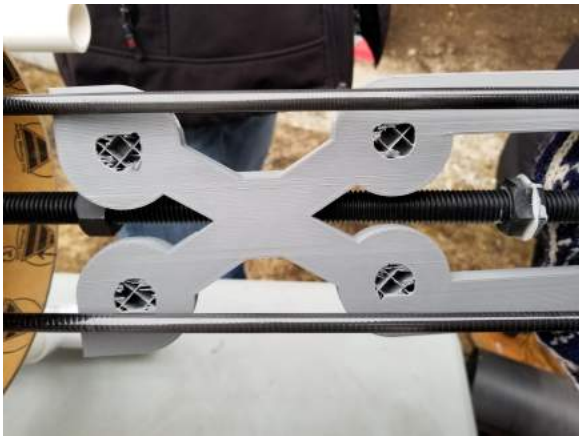


Figure 65: Platform with broken 3D printed flanges.

The acceleration due to parachute deployment was enough to rip the 3D printed flanges off of the UAV platform during recovery, and it was enough to pull the hex nut out of the platform, shown in Figure 66

Figure 66: Platform inside the payload bay with broken 3D printed flanges.

These stronger metal flanges will then be epoxied to the 3D acrylic-styrene-acrylonitrile (ASA) printed platform opposed to the previous acrylonitrile butadiene styrene (ABS). This design change ensures that the flanges will be sufficiently strong. This is particularly important when the main parachute is deployed and the platform experiences maximum loading forces. Table A.6 describes the safety precautions to address these failures.

The R-clips are inserted into the aluminum flanges in order to constrain the UAV in all directions during flight. The R-clips are tied to braided fishing line that attaches to small eye bolts epoxied into the aft bulkhead. When the platform translates linearly along the leadscrew, the fishing lines tighten and the R-clips eventually release, allowing the UAV to take off in the vertical direction.

5.3.2.2 Orientation Correction Mechanism

The Orientation Correction System utilizes an Adafruit 9-Degrees-of-Freedom Absolute Orientation IMU Fusion Breakout BNO055, with a built-in accelerometer and gyroscope, and a servo motor. After remote activation via a Ximimark 433MHz ASK Transmitter/Receiver Module Kit, the sequence will begin. An Arduino MKR Zero will receive a signal from the sensor (including both accelerometer and gyroscope data) that will induce the rotation of the payload for proper orientation.

All machined parts for the orientation correction mechanism were 3D modeled in Creo Parametric 4.0. An exploded view of the aft bulkhead assembly is show in Figure 67.

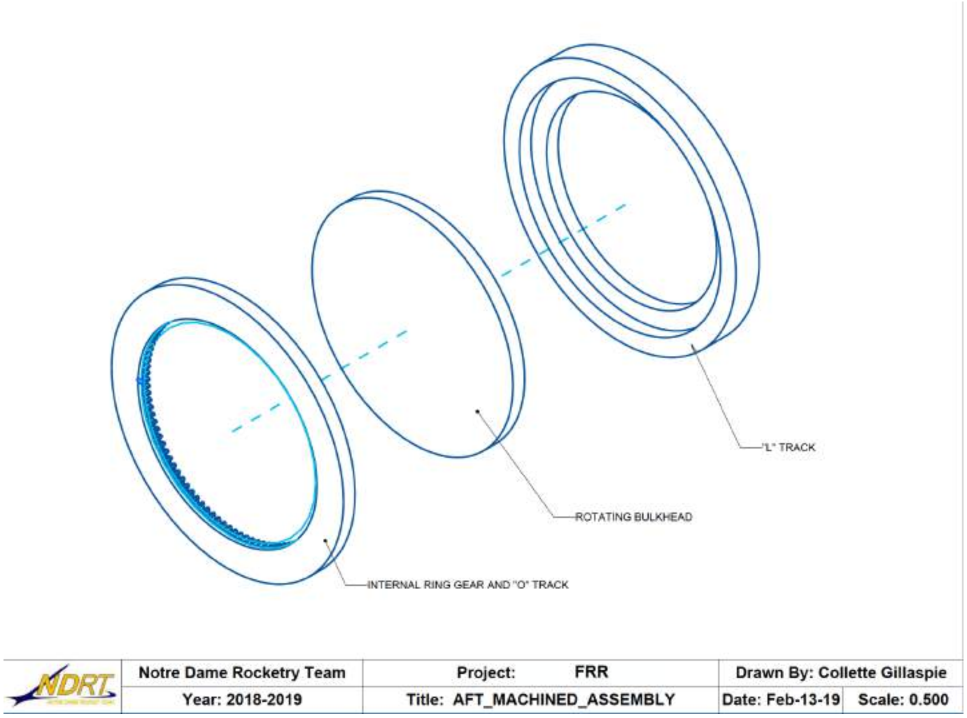


Figure 67: Exploded view of the aft bulkhead assembly

All bulkheads and tracks were machined out of MDS-filled nylon. The O-ring, rotating bulkhead, and L-channel of the aft bulkhead are 3/8" thick, 3/8" thick, and 3/4" thick, respectively. The O-ring, rotating bulkhead, and L-channel of the fore bulkhead are 1/4" thick, 1/4" thick, and 1/2" thick, respectively. The reasoning for a thinner fore bulkhead assembly compared to the aft bulkhead assembly is because the aft bulkhead assembly is holding the entire weight of the system. The thicker aft L-channel is screwed radially into the UAV payload bay from the outside of the launch vehicle. Once modeled, the stationary aft tracks and the aft bulkhead were machined using a techno router. The front 3/8" thick O-ring of the aft bulkhead was machined to have an internal ring gear. A small planetary gear was also created to interface with the ring gear, shown in Figure 70. Eight holes were then drilled concentrically around the outside of the tracks, using a drill press, shown in Figure 68.

Figure 68: Drill press for manufacturing the aft bulkhead assembly.

The two tracks were fitted together and taped to ensure they were aligned, shown in Figure 69.

Figure 69: Track drilling step.

This process occurred for both the fore and aft assemblies. Eight holes were added about the circumference of the track for screwing into the body tube. This is essential for securing the deployment system within the rocket body. The small planetary gear was then epoxied onto the servo motor.

The Orientation Correction Mechanism is designed to spin via the meshing of an internal ring gear and an FS106R servo motor with epoxied pinion, shown in Figure 70, once the rocket has landed, in order to properly align the UAV for flight.

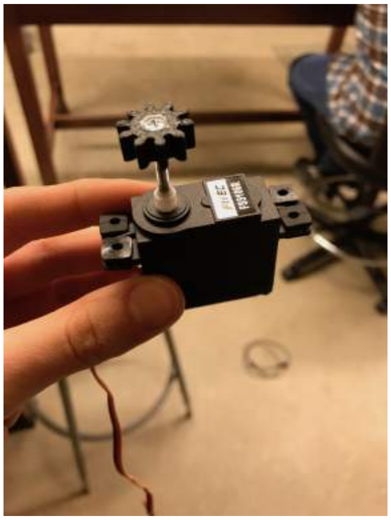


Figure 70: FS106R servo motor with epoxied pinion

While this rotation is essential to mission success, any motion during flight will have a detrimental effect. While powered off, the servo motor will lock the motion of the gear. This will impede any motion of the Orientation Correction System during the flight of the rocket. This system was shown to be successful in preventing any rotation during the full scale test flight on March 2nd. The following, Figure 71, shows the UAV post-deployment and properly oriented.

Figure 71: Properly oriented UAV.

5.3.2.3 Linear Transport Mechanism

The deployment drive system utilizes a nylon lead screw and gear motor system to serve as the Linear Transport Mechanism for the UAV payload. The Linear Transport Mechanism connects the stationary aft bulkhead to the translatable fore bulkhead via the nylon lead screw. This system separates the nose cone from the rest of the UAV payload body tube deploys the payload from the body tube of the rocket. Furthermore, the separation of the nose cone gives ample clearance to allow for the unobstructed takeoff of the UAV. Nylon was chosen for the lead screw, tracks, and bulkheads because of its low coefficient of friction, density, and low deflection under the point loading of the UAV and platform.

The lead screw and the Actobotic gear motor are fixed onto the aft bulkhead to allow rotation with the Orientation Correction System. Two aluminum flanges were machined in order to provide stability and support for the carbon fiber rods. The aluminum flanges were then secured to the bulkhead using epoxy. A motor mount was also machined out of aluminum to connect the gear motor to the the rotating aft bulkhead. Another mount was machined out of aluminum to connect the gear motor shaft to the leadscrew via interior threading on the mount and a set screw to tighten onto the motor shaft. Figure 72 shows the CAD for the mounting system and the manufactured mounting system.

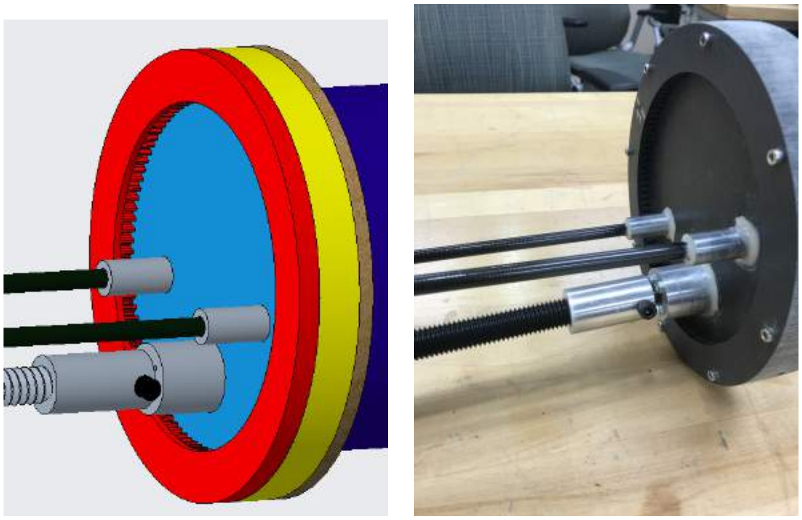


Figure 72: Linear Transport Mechanism mounting system.

The leadscrew is threaded through the fore bulkhead via a small hex nut, which is attached via epoxy. Holes were machined in the fore bulkhead for the carbon fiber rods to run through. The remaining length of the leadscrew and the carbon fiber rods are housed inside of the nose cone. As the gear motor runs, the platform is driven forward, which pushes the fore bulkhead and nose cone. Carbon fiber dowel tubes are inserted into through holes in the platform and fore bulkhead. This ensures that the items attached to the lead screw will translate linearly, and not rotate with the lead screw. The tubes are epoxied to the back bulkhead via machined aluminum flanges. Figure 73 shows how the epoxy was set to cure.

Figure 73: Mounting system machining.

Like the Orientation Correction System, the Actobotic gear motor in the linear transport mechanism can be used to keep the platform and nose cone stationary during flight. When powered off, the gear motor is in a locked configuration because it is very difficult to back drive. This will prevent any turning of the lead screw. If the lead screw is unable to turn, the platform and fore bulkhead will also remain stationary. The 1/2" thick L-channel of the fore bulkhead assembly is epoxied into the nose cone. The 1/4" thick fore rotating bulkhead is free to rotate within the fore bulkhead assembly, and a hex nut of 5/8”-11 thread is epoxied onto this bulkhead for meshing with the leadscrew. A 1/4" thick removable O-ring is bolted onto the L-channel to keep the rotating bulkhead in place during flight. During the rocket’s March 2 flight, the epoxied hex nut was torn off the rotating bulkhead, meaning that friction alone was the only factor keeping the nose cone in place during launch vehicle recovery. Before and after photos may be found in Figure 74.

(a) Before launch (b) After launch (c) After launch

(d) Nose cone slip (e) Nose cone slip

Figure 74: Before and after photos of the Linear Transport Mechanism locking system.

Table A.6 further describes the safety precautions to address this failure.

5.4 Beacon Delivery Subsystem

5.5 Mechanical Beacon Delivery

The Beacon Delivery Subsystem was designed to ensure an accurate, economical, and effective way to deliver the NDRT beacon onto the Future Excursion Area. Additionally, the Beacon Delivery Subsystem was designed to integrate seamlessly with the UAV as a whole. The system itself consists of four parts: the beacons, the holding plate, the rods, and the servo motor which controls the deployment system. Two beacons are fitted onto two rods, which rest upon the holding plate. The plate is controlled by the servo motor, which turns the plate to allow a primary and then secondary deployment of a beacon.

5.5.1 Mechanical Beacon Delivery Layout

The holding plate, which hold the beacons in place until their deployment, was printed out of ASA, which retains enough strength to hold the beacons but also is lightweight enough so as to not impede the flight of the UAV. ASA was chosen over PLA due to its lighter weight. The rods, just as the plate, were printed out of ASA. A rectangular shape was chosen for the rods to ensure that the beacons would not twist during the flight of the UAV. The center of the rods were hollowed to lighten the overall weight of the beacon deployment assembly.

The motor which attaches and rotates the holding plate is the FEETECH FS90R, which is a continuous servo. This continuous servo was chosen over a stepper motor because it provides more stability during disturbances such as liftoff, and provides a continuous torque for a wide range of speed. The FEETECH FS90R was chosen because it gave the necessary torque required to move the plate, but was not overpowered such that it drained energy from the UAV's battery unnecessarily. Additionally, the dimensions of the servo allow it to fit well on the undercarriage of the UAV. Rods were added to the bottom of the UAV, which it can be screwed in to, in order to provide structural support for the servo motor. The servo is attached to these rods via screws. The design of the mechanical assembly for the beacon deployment can be seen in the following Figure 75, which details the different phases of the system.

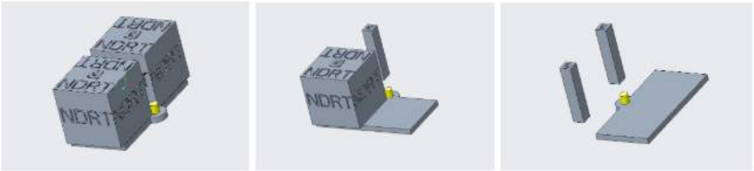


Figure 75: The three phases of the beacon deployment system.

5.5.2 Mechanical Beacon Delivery Integration

The actual assembly of the beacon onto the UAV can be seen in Figure 76. The main difference between the design and the actual assembly is the addition of the platform which was received as one of the servo parts. It was determined that this plate, which was fitted to the servo by the manufacturer, would be a more reliable attachment than the holding platform designed by the team. The holding platform will then be glued to the manufacturer's attachment.

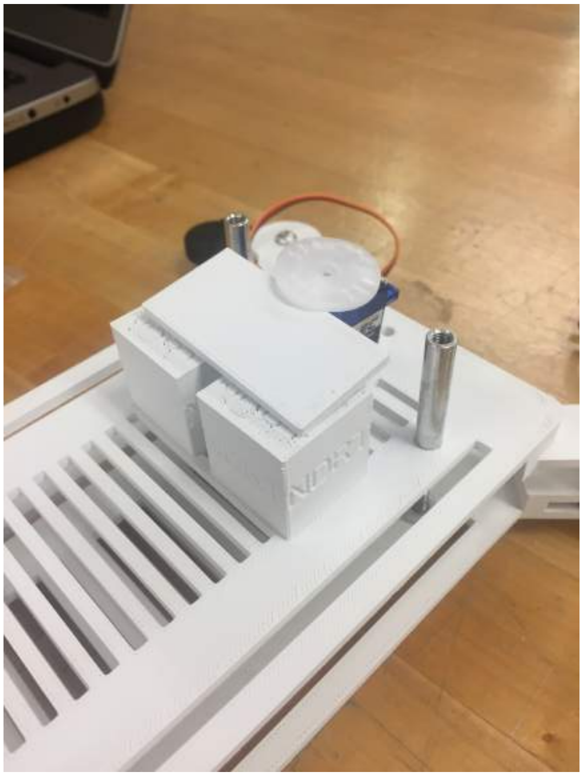


Figure 76: Picture of the beacon deployment system, as it is integrated into the bottom of the UAV.

As can be seen, the Beacon Delivery Subsystem attaches to the undercarriage of the UAV. The system is shorter than the legs of the UAV so that it does not interfere with landing. The battery used to power beacon deployment is the battery used for the entire UAV system. Therefore, the servo motor chosen will not largely affect the battery life of the UAV.

5.5.3 Beacon Design

Figure 77 shows the beacon used on the UAV beacon deployment assembly.

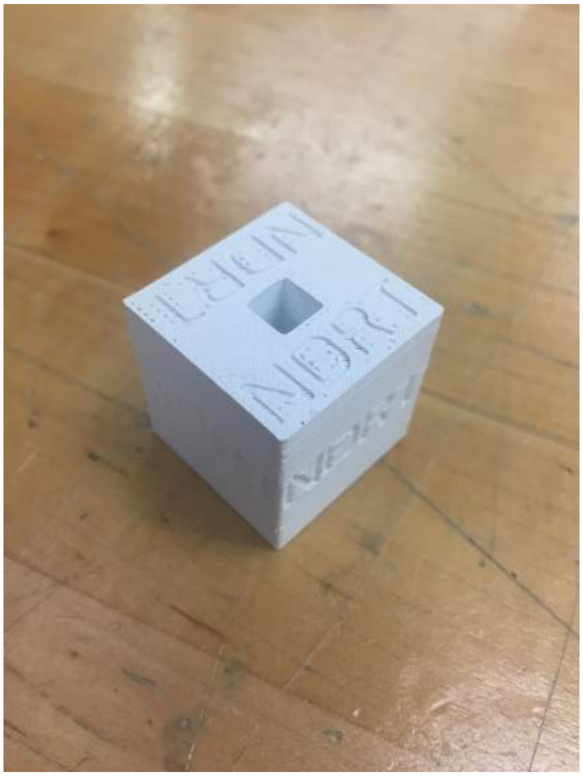


Figure 77: Picture of the beacon.

This design was printed out of ASA, which makes it lightweight and simple to fabricate. Additionally, the hollowed out center of the beacon decreases the weight further.

5.6 Payload Electrical Design

5.6.1 Deployable Drone

The transmitter for the first person view system on the drone has been updated to the Eachine VTX03 Super Mini 5.8GHz 72CH FPV Transmitter. The reason for the update is that the previous 915MHz telemetry set would have resulted in a video stream with extremely high latency. The Eachine transmitter has three output power settings: 25mW, 50mW, and 200mW which makes it ideal for testing. A low power setting can be used for close range testing, and the high power setting, i.e. 200mW, can be used for actual flight during competition. The ground receiver, which has also been updated, is an RC832 5.8G AV Receiver. The Eachine transmitter and the AV Receiver can be seen in Figure 78 and Figure 79 respectively.

Figure 78: Eachine VTX03 Super Mini 5.8GHz 72CH FPV Transmitter

Figure 79: RC832 5.8G AV Receiver

This receiver can be directly connected to a laptop via a USB adapter. Both the transmitter and the receiver have multiple selectable channels in the 5.8GHz band. The current channel that has been chosen is B7, or 5.847GHz. The complete first person view system has been successfully tested indoors using a low power setting.

The UAV is powered by a Turnigy 3S 4500 mAh battery. The battery supplies power to all the electronics onboard the UAV. The battery life, which has been estimated at around 9 minutes at full throttle. This will be verified and addressed in the addendum.

The onboard CPU streams the visual data from the onboard camera via a FPV transmitter to a FPV receiver connected to a laptop on the ground. The ground station laptop displays the data for first person view. This has been tested and performs as expected. There is an established link between the CPU and the flight controller. This allows for test programs to run from the CPU to the flight controller. There is also a telemetry link between the flight controller and the ground station, a laptop. This provides real time spatial coordinates of the UAV visible on Google Maps and performs as expected. Lastly, there is a handheld controller for use in the case where manual takeover is deemed necessary. Flight has been established via the handheld controller. The Figure 80 below shows the as built schematic for the communication system architecture.

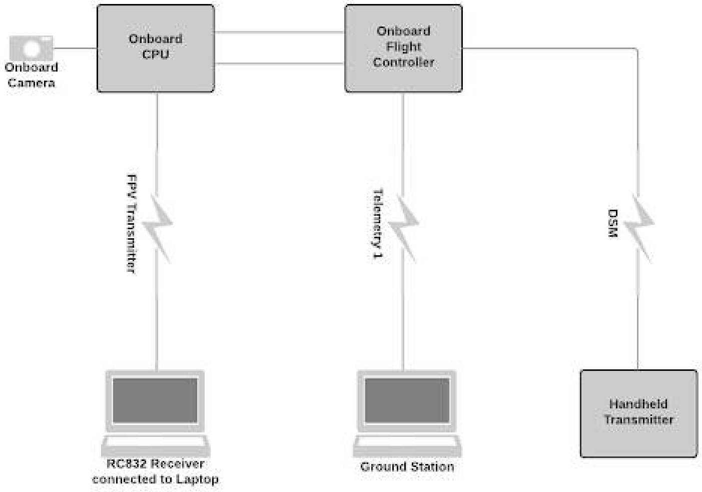


Figure 80: A schematic for the communication system architecture.

The motors in use are the T-Motor MN1806 KV1400. The UAV has successfully obtained stable flight, so the motors are providing the expected thrust. During one test flight, the UAV experienced a rather hard landing and broke an arm. This damaged one of the motors, which we had to replace. Once the motor was replaced the UAV was able to fly again.

The team has implemented the Raspberry Pi 3B as the deployable drone onboard CPU. The Raspberry Pi is integrated with our camera and FPV transmitter/receiver set and has successfully streamed video to the ground station.

The Pixhawk 4 flight controller has performed as expected. Stable controlled takeoff, flight, and landing of the UAV have all been achieved.

Although we have not used the FrSky Taranis X9D for sustained flight, we have proven its functionality. Our team was able to bind this transmitter with the corresponding receiver and send signals to the Pixhawk flight controller. These commands spun the motors and provided lift, although full flight was not achieved.

Thinking that this communication link could be what was preventing flight at the time, we replaced it with a previous transmitter/receiver pair that the team had used. The team noticed the same drone behavior following this change. After further testing, we found that the true error was a motor was spinning in the wrong direction. Our team corrected this issue, and once resolved the drone successfully achieved sustained flight.

Since both transmitter/receiver pairs yielded the same behavior in the drone during testing, we assume that the FrSky Taranis X9D will also facilitate sustained flight as seen in Figure 81.

Figure 81: FrSky Taranis X9D Transmitter

The UAV is equipped with a Raspberry Pi Camera Module V2. The camera has been integrated with the Raspberry Pi and FPV transmitter/receiver set. It transmits video from the UAV to the ground station as expected.

Initially the team intended on using a pushbutton on the drone's arm to begin the power on sequence. It would have been a normally closed button that would have been depressed while the drone was in the rocket housing. This functionality would have removed the battery power from the UAV. Once deployed, the arms would have unfolded, thus releasing the button and allowing power to flow from to battery to the drone.

After changes were made to the UAV's frame, this power on sequence was no longer viable. Thus the team has decided to use a toggle switch to control the power on sequence. It too will control current flow from the battery to the rest of the drone.

The switch will be in the "off" position when it is inserted into the rocket. A cord fixed to the bulkhead will then be attached to the lever of the toggle switch. As the drone is deployed from the rocket, this switch will be activated and pulled into the "on" position. The cord will then disconnect from the lever, leaving the drone ready for takeoff. The toggle switch can be seen in Figure 82 below.

Figure 82: Toggle switch for power on sequence

The electronic system has been secured onto the drone as seen in Figure 83. All of the necessary components have been obtained for this system, but it has not yet been tested.

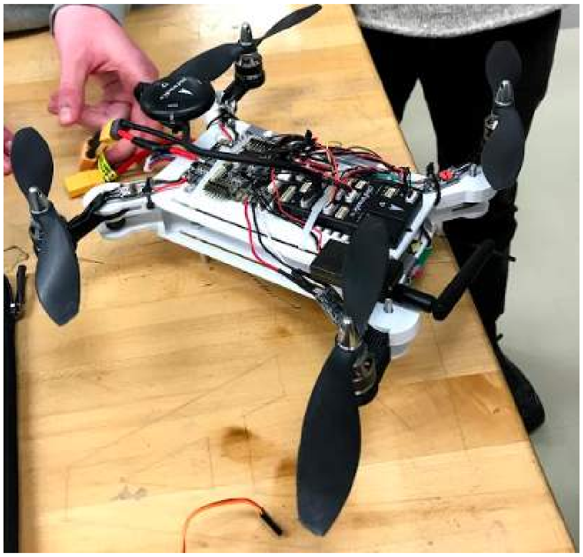


Figure 83: The drone with electronic components secured

5.6.2 Deployment Subsystem

A pin-out schematic of the system is shown in Figure 84. The system will remain powered before flight and will remain idle until the Ximimark receiver shown in Figure 85, receives an initiation signal from its respective transmitter. Once the signal is processed, the microcontroller engages the rotational servo motor, reading in data from the Adafruit 9-DOF BNO055 shown in Figure 86 to determine if the UAV is upright. If the UAV is upright and stationary, the microcontroller will engage the gear motor to drive the leadscrew.

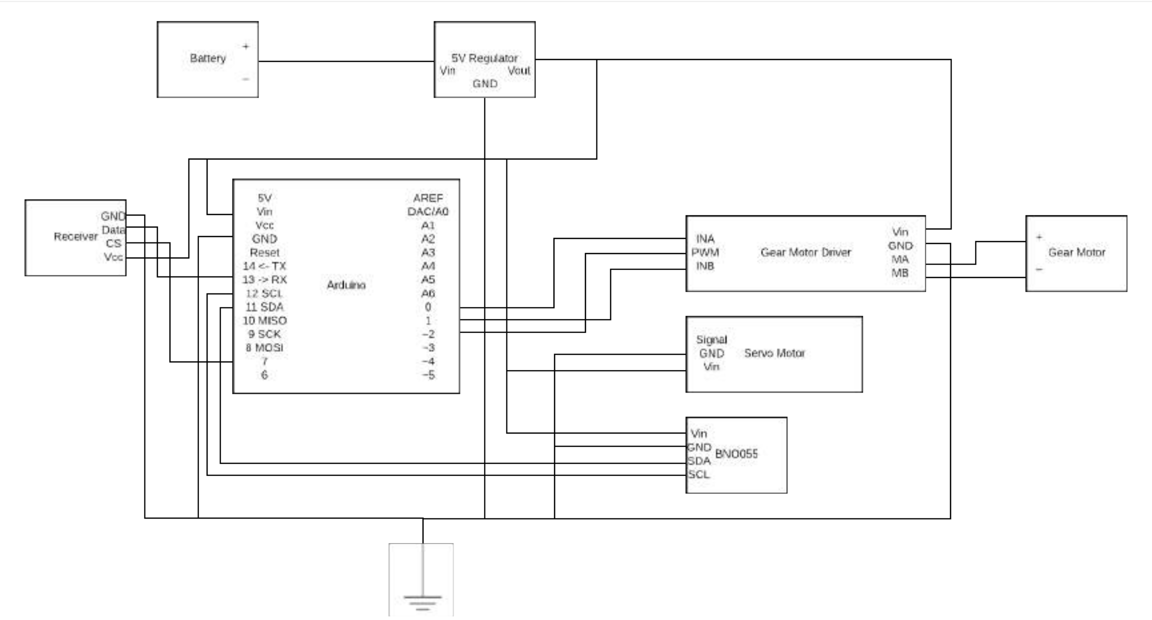


Figure 84: Pin-out schematic of the deployment electronic system

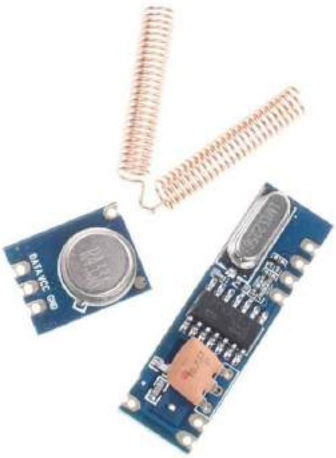


Figure 85: Ximimark receiver

Figure 86: Adafruit 9-DOF BNO055

The system is powered by an E-flite 800mAh 11.1V Lipo battery shown in Figure 87, sufficient for the needs of the system. A Recom R-78E5.0-1.0 5V regulator steps down the battery's voltage so that the microcontroller and the servo motor function properly.

Figure 87: E-flite 800mAh 11.1V Lipo battery

The chosen transmitter and receiver was successfully tested at a maximum range of about 65.6 linear feet (20 linear meters) with a clear line of sight. The range is more limited than the team desired, but determined to be sufficient. This range was tested on the 28th of February of 2019.

The most critical component of the deployment subsystem is the orientation correction mechanism sensor, the Adafruit 9-DOF BNO055, selected due to NDRT's previous successful usage of it. The sensor provides crucial data regarding orientation and the system's position respective to ground. The board contains a MEMS accelerometer, magnetometer, and gyroscope all in one. The accelerometer is rated to a maximum of 16G, the gyroscope has a range of 2000 degrees per second, and the magnetometer has a range of $\pm 1300\mu$T on the x- and y-axis and of $\pm 2500\mu$T on the z-axis.

The deployment subsystem microcontroller was changed to the Arduino MKR Zero shown in Figure 88, principally for space considerations. It still provides the pins needed by the system, but on a much smaller board.

The Arduino processes the signals from the receiver, to initiate the deployment sequence, and from the orientation correction sensor, to determine how much the servo must rotate to reorient the system. Additionally, it outputs the respective signals to the DC gear and rotational servo motors.

Outside of the rocket, another microprocessor, the Elegoo UNO R3 board shown in Figure 89, is responsible for actuating the transmitter, which sends the initiation signal to the receiver.

Figure 88: Arduino MKR Zero

Figure 89: Elegoo UNO R3

The orientation correction motor, the FS5106R shown in Figure 90, has not been changed from previous design. Its principal function is to rotate the UAV platform. This motor's drive board is localized within its package, so it does not need an additional component to control its movement. A small pinion gear is attached to the top of the motor so it may rotate the aft bulkhead. The pinion on the top of servo meshes with an internal ring gear to do so shown in Figure 91. The motor's proper functioning was most recently tested on the 1st of March of 2019.

Figure 90: FS5106R servo motor

Figure 91: Servo interfacing with ring gear

The linear transport motor was changed from the Nema 14 stepper motor to the 116 RPM Planetary Gearmotor with Encoder (a DC gear motor, Figure 92) due to weight and design considerations. Implementing the gear motor requires less circuit components; the stepper motor would require a voltage regulator to bring down the battery voltage to its operating level, whereas the gear motor can run directly off of the battery. The gear motor is also lighter than the stepper motor. It is connected to a PWM motor controller, at the heart of which is a VNH3SP30 driver, which processes the signals transmitted by the microcontroller. Furthermore, to accomplish its purpose, the gear motor is connected via aluminum coupler epoxied to the aft nylon rotating bulkhead shown in figure 93. The motor is screwed into this aluminum coupler. Set screw on another aluminum coupler connected to the shaft of the motor. The other side of this second coupler is threaded 5/8-11 to connect to the leadscrew. The motor's proper functioning was most recently tested on the 1st of March of 2019.

Figure 92: 116 RPM Planetary Gearmotor

Figure 93: Gear motor with coupler.

5.7 Payload Software Design

5.7.1 Autonomous Flight Subsystem

The UAV will first deploy from the rocket and establish a connection with the UAV operator. The drone will record its own position and compare it with the previously defined GPS coordinates of each FEA. The UAV will set a waypoint to the nearest FEA. The UAV will then take off and fly to the FEA. After arriving at the FEA, the UAV will search for the exact position of the FEA using image recognition. If found, it will center itself over the FEA and deploy the beacon. If not found, the UAV will increase its altitude and search again. A flowchart of the logic used is shown in Figure 94.

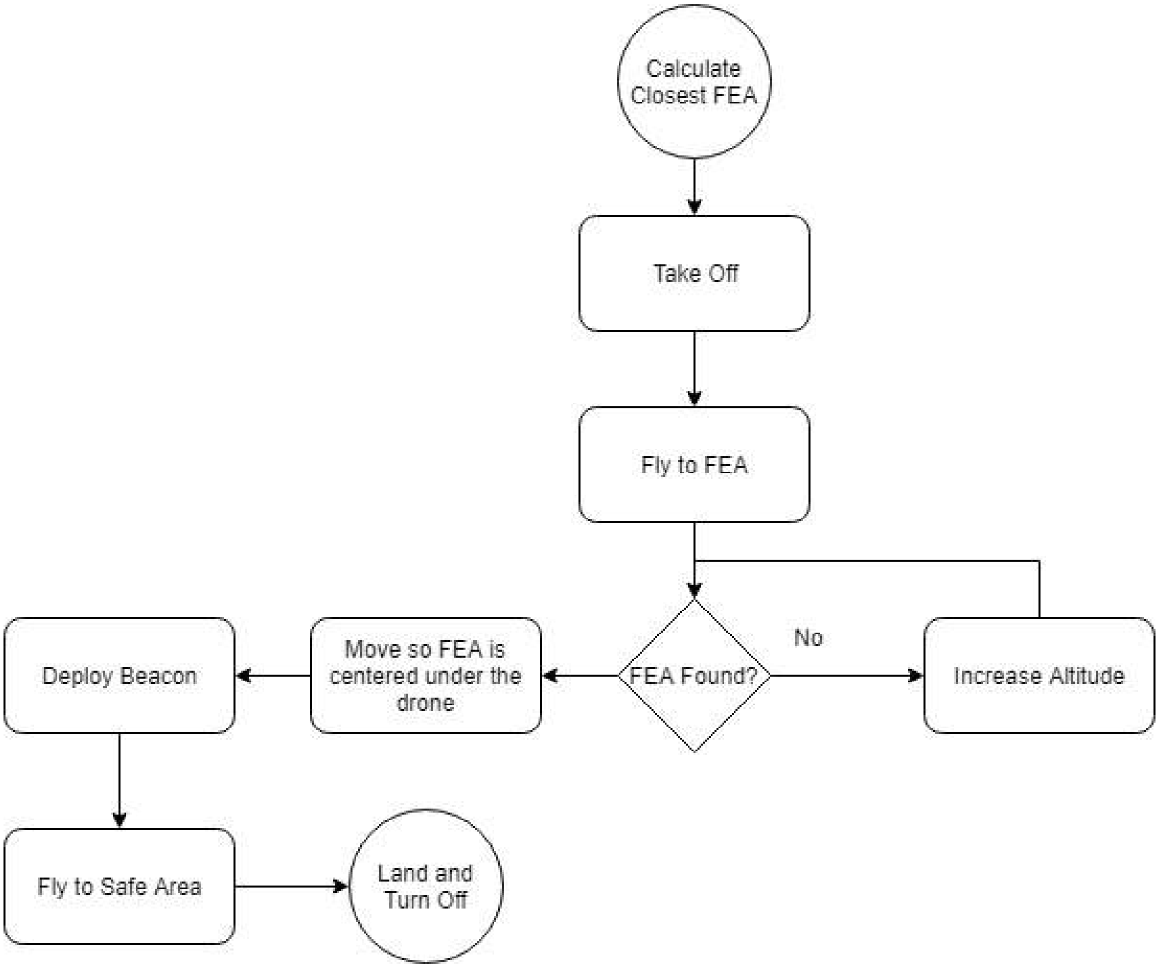


Figure 94: Flowchart of target detection process

In order to select which FEA the team wants to pursue, the team has written a program to determine the closest FEA by comparing the GPS coordinates of the drone with the GPS coordinates of the FEAs. The shortest distance to be flown will be chosen.

In order to maintain a safe environment, the team has an option to switch to manual control to prevent hazards. The team made sure to maintain safety by ensuring that all nearby people were aware of testing and out of range of the drone.

Due to the weather conditions not being suitable for flight, the team has not been able to execute the autonomous flight subsystem testing outdoors. Once the weather reaches a warm enough temperature, the team will perform a simple test flight in an outdoor field that has been approved for UAV operation. In order to test the connection between the raspberry pi that the autonomous flight program runs on, and the pixhawk flight controller, the team will perform a take off and landing flight. A simple program involving a takeoff, ascent of 3 meters, and land in place will be uploaded to the raspberry pi. The pi's desktop will be streamed to an eternal laptop using the FPV transmitter to use as a monitor. The program will then be run from this configuration.

5.7.1.1 Future Excursion Area Detection Subsystem

The team has incorporated several features into the FEA detection subsystem. The system works by taking in an input image, converting it to an ideal color space, creating a binary mask based on color thresholds, running morphological transformations on the binary mask, extracting geometric features from the transformed binary mask, and then running these features through a Support Vector Machine. Several steps were taken to create the optimal binary mask of the image. The team first created a dataset by manually annotating object masks (representing the location of the FEA in the image) over target images. These manual masks were then compared against any computer-generated masks using an objective function called Intersect over Union, shown in equation 4:

$$E = \frac{A \cap I}{A \cup I} \tag{4}$$

where A is the manually annotated mask and I is the mask as annotated by the computer. Computer-generated masks were then created using the same dataset which had been annotated earlier. When creating these masks, the team considered 12 separate color spaces and 7 separate morphological operations. The team examined each sequence of two morphologies and each sequence of three morphologies. The results of the Intersection over Union for each combination of color space and morphological transformation were placed in a spreadsheet. After analyzing this data, it was determined that the HLS color spectrum, combined with the dilation, closing, and erosion morphological operations, gave the best result on the objective function. This gave an average score of .894 on the objective function. The average values for each colorspace for the dilation, closing, and erosion operations can be seen in Table 21, an excerpt from a larger 393 row table.

Table 21: The average values for each colorspace for the dilation, closing, and erosion operations

Colorspaces	Dilation, Closing, Erosion
BGR	0.889
GRAY	0.837
BGRA	0.889
BGR565	0.888
BGR555	0.888
XYZ	0.863
CrCb	0.883
HSV	0.887
Lab	0.884
Luv	0.873
HLS	0.894
YUV	0.881

The final algorithm works by reading in an RGB image, converting it to the HLS color spectrum, and checking if each pixel falls within 95% of the values in the training set. Every pixel which falls within the range is set to 1, while the rest are set to 0 in the mask. After that, the dilation, closing, and erosion transformations are done in sequence, with the resulting image being our object mask.

Once that mask is created, several geometric features are extracted from it. These features include aspect ratio (the width divided by height of the bounding rectangle), extent (area divided by bounding rectangle area), solidity (area divided by float area), compactness (perimeter squared divided by area), eccentricity (major axis divided by minor axis), and the logarithm of the Hu Moments, a set of features which are transformation-invariant. After these features are extracted, they are sent into a support-vector machine trained on images taken from a UAV of the FEA. The logic for this system is shown in Figure 22.

1. Select FEA

2. Fly to FEA

3. Check if on top of FEA with target detection software

3a. If the drone is on top of FEA, jump to step 5

3b. If the drone is not on top of FEA, go to step 4

4. Use target detection software to figure out which direction to move and move there. Return to step 3

5. Descend to near the ground.

6. Check if on top of FEA with target detection software

6a. If the drone is still on top of FEA, go to step 7

6b. If the drone is not on top of the FEA, return to the previous altitude and return to step 3.

7. Deploy Beacon

8. Fly to safe distance from FEA and land

Table 22: Logic flow for FEA detection

This is the current plan from flying the drone to the target area and deploying the beacon. The process is broken down into several steps with redundancies to ensure proper deployment

Step 4 of the flight plan involves applying the target detection algorithm to the UAV's flight control in order to direct it towards the center of the target. The process outlined in Section 1.1.2.1 above is followed. The image is converted to an object mask, which then has geometric features extracted from it. These features are passed to a Support Vector Machine, which determines whether the image contains the FEA. Once the existence of the FEA has been determined, the center pixel values of the object mask are found. These pixel values can then be used to provide course correction to the UAV. The images below show the thought process of the FEA detection algorithm. It reads in the input image as seen on the left, then creates the object mask as seen in the middle, then locates the center of the object mass, as shown by the black dot on the right in Figure 95.

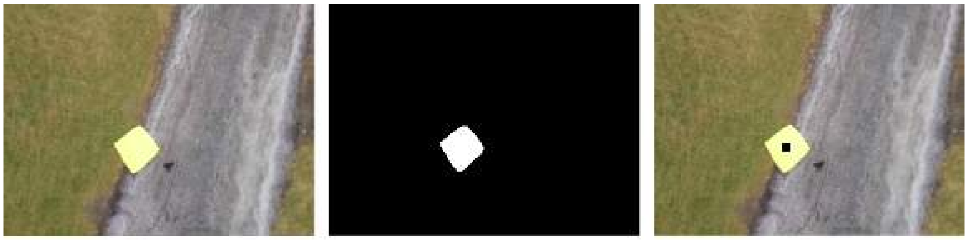


Figure 95: FEA detection

The servo motor used to release the beacon will be integrated with the Pi, and the program will be able to interface with it through the GPIO pins onboard the Pi. By controlling the PWM connection, the program will be able to release the beacon once UAV has navigated to the right spot above the FEA. Additionally, in the event of a manual override, the remote controller will also be able to interface with the servo, rotating it to deploy one or both beacons as necessary.

To test the UAV's ability to identify the FEA, the team performed a series of tests using the raspberry pi's camera. A simple program to read in video from the Pi's onboard camera and print out the results of the target detection algorithm was implemented.

The program was then run on the pi , and the pi's desktop was streamed to a remote laptop using the FPV transmitter to allowed the team to see the video feed from the raspberry pi camera.

The team then set up an indoor testing environment inside an atrium pictured below, where a proxy FEA matching the color and size of the expected FEA at competition was placed on the floor as shown in Figure 96.

Figure 96: FEA indoor testing

The team members then held the camera above the FEA on the upper floor and walked to several different positions in order to allow the pi's video feed to receive a variety of different views of the FEA. After doing this, the Pi was able to accurately identify the location of the mock FEA in most configurations. It found the center of mass, and the Support Vector Machine was able to tell if the FEA was currently in the frame.

Due to the winter weather conditions, the team has not been able to test the target detection algorithm outdoors. Once the weather conditions are suitable for flight, the team will perform further testing of the target detection subsystem's ability to control the flight path of the UAV. These tests will involve placing the proxy FEA at a known GPS location, programming the UAV to fly to that location, and then using the refined target detection algorithm to accurately have the UAV fly to the proxy FEA, drop the beacon, and safely land.

6 Project Plan

6.1 Testing

6.1.1 Vehicle Testing

Table 23: Launch Vehicle Test Plan

Test Name	Test ID	Description	Requirements Tested	Status
C_G Verification Test	LV1	Locate CG with fully configured payloads and with simulated payloads.	LV2.17-1	In Progress.
Simulated Payload Mass	LV2	Assess the viability of vehicle without payload integration.	LV2.20.1.3.2-4	Complete.

6.1.1.1 LV1: C_G Verification Test

Objective: The Launch Vehicle will be tested with the objective of verifying the stability of the rocket. The minimum stability requirement to launch is 2.0 calipers.

Tested Items:

- Fully Assembled Vehicle.

Motivations:

- Ensure proper launch stability.

Table 24: LV1 Success Criteria

Description	Criteria	Result
Rocket C_G will be measured to within 2 inches of predicted C_G	Pass/Fail	Complete, Pass
C_G will be within 2.2 - 2.8 calipers of C_P	Pass/Fail	Complete, Pass

Equipment:

- Vehicle Stand.

Procedure: The C_P and predicted C_G will be measured and marked on the full scale vehicle. The rocket will be loaded onto one vehicle test stand at the predicted C_G marker and adjusted until it can balance on the 1/4" wood piece.

Results: The predicted C_G was 0.1" aft of the measured C_G, resulting in a stability margin of 2.37.

6.1.1.2 LV2: Simulated Payload Mass

Objective: The Launch Vehicle will be tested with simulated masses representing payloads.

Tested Items:

- Launch Vehicle Integrity

Motivations:

- Ensure Launch Vehicle viability without relying on payload masses.

Table 25: LV2 Success Criteria

Description	Criteria	Result
Vehicle flight will not be compromised by ballasted mass	Pass/Fail	Complete, Pass
Ballasted masses will be within 1" of simulated mass	Pass/Fail	Complete, Pass

Equipment:

- Ballast.
- Plastic Bag.
- Tape.

Procedure: Using a bag and a scale, enough sand will be poured to match the weight of the payload. the bag will then be securely sealed, and mounted inside the vehicle using bulkheads within an inch of the simulated mass.

Results: The measured payloads were correctly matched with mass and placed at the C_G position of the payload originally.

6.1.2 Recovery Testing

Table 26: Recovery Test Plan

Test	Description	Requirement to be Verified	Success Criterion	Scheduled Completion Date
Simulated Flight Test	Tests Raven 3 altimeters' ability to take trigger deployment event at apogee	3.5	Raven allows current flow at apogee during a simulate flight	March 1
Electronic Match Testing	Tests Raven 3 altimeters' ability to ignite e-matches under flight conditions	3.6	Altimeters are able to ignite e-matches at apogee during a simulated flight	March 1
Black powder testing	Tests effectiveness of black powder ejection system for parachute deployment	3.2	Black powder charge initiates a successful separation event	March 2
Deployment System Shake Test	Tests the connections within the system and ensures that the system can undergo the stresses during flight.	3.1	System does not prematurely deploy, and remains active during shake and drop tests	March 2
Jolly Logic Chute Release tests	Tests to ensure that the chute releases allow the main parachute to unfurl at the correct altitude	3.1.1	Jolly Logic Chute Releases correctly release the main parachute at 500ft AGL during a simulated flight test	March 2

6.1.2.1 Simulated Flight Tests

Objective

The objective of this test is to ensure that all altimeters can reliably initiate a deployment event at apogee.

Tested Items

The Raven 3 Altimeters were tested.

Motivation

A successful deployment at apogee is essential for the flight of the launch vehicle.

Set-Up

The altimeters undergo a simulated test flight using the Featherweight interface program to generate a generic flight profile and demonstrates the deployment trigger using an LED.

Success Criteria

The Simulated Flight test will be considered a success only if all three altimeters are able to consistently trigger a deployment event at apogee during a simulate flight.

Procedure

The altimeter is connected to a laptop and interfaces with the Featherweight software. An LED is connected to the apogee channel of the altimeter and observed to light at apogee.

Results

The Simulated flight test was performed 6 times, twice per altimeter, and was successful every time. This satisfied the success criteria in proving that the Raven 3 altimeters were reliable for triggering deployment at apogee.

6.1.2.2 Electronic Match Testing

Objective

The objective of this test was to demonstrate that the e-matches could be ignited by the altimeters

Tested Items

- The Raven 3 Altimeters
- The electronic matches

Motivation

The electronic matches are an integral part of the deployment system, and are necessary for a successful deployment.

Set-Up

The altimeters are run through a simulated flight with a e-match connected to the apogee channel.

Safety

Ensure that all participants are wearing protective eye-wear, and are standing at a safe distance from the e-matches when they ignite. Perform the test away from flammable objects.

Success Criteria

The test will be considered successful if the electronic matches ignite at apogee during the simulated flight.

Procedure

1) Clear area of nonessential persons

2) Attach e-match to apogee channel of altimeter

3) Run simulated flight

4) Ensure e-match ignition

Results

This test was performed 6 times, twice per altimeter, and was successful every time. This validated the reliability of the Raven 3 and brand of e-matches chosen to trigger deployment.

6.1.2.3 Black Powder Testing

Objective

The objective of this test was to demonstrate that the black powder charges are sufficient to causes separation and parachute ejection.

Tested Items

- The CRAM system
- The black powder charges

Motivation

The black powder charges are an integral part of the deployment system, and are necessary for a successful deployment.

Set-Up

Black powder charges are placed inside of the recovery system and the launch vehicle is assembled.

Safety

Ensure that all participants are wearing protective eye-wear, and are standing at a safe distance from the black powder charges when they ignite. Perform the test away from flammable objects.

Success Criteria

The test will be considered successful if the black powder charge is separate the launch vehicle and ejects either the drogue or packed main parachute.

Procedure

1) Clear area of nonessential persons

2) Attach wires to black powder charges

3) Ensure that everyone is standing at a safe distance

4) Ignite the black powder charges

Results

This test was performed with 4g of black powder and was unsuccessful. A pressure chamber was not created in the body tube due to the air-holes required for access to the CRAM. This was solved by creating a seal around the ejection charge side of the CRAM using non-hardening duct seal. The test was performed again with 5g of black powder and was successful in generating the pressure necessary to separate the airframe and ejected the parachutes.

6.1.3 ABS Testing

Table 27: Air Braking System Test Plan

Test Name	Test ID	Description	Requirements Tested	Status
Subscale Testing	AT1	Verify stable flight with a 3D printed subscale drag tab coupler attached to subscale vehicle; Verify successful avionics datalogging.	AB-2, AB-7, AB-9, AB-13	Complete.
Electronics Ground Testing	AT2	Verify electronic component functionality and secure integration into printed circuit board.	AB-5, AB-6, AB-12	Complete.
Mechanical Hardware Ground Testing	AT3	Verify successful operation and robustness of ABS mechanical components and system.	AB2.24.1-1, AB-3, AB-10, AB-15, AB-17	Complete.
Software Ground Testing	AT4	Test to verify ABS control code properly responds to previous flight data and controls the assembled mechanism.	AB-3, AB-7, AB-11, AB-13	In Progress.
Flight Testing	AT5	Verify braking power of ABS and test success of control algorithm in flight.	AB2.20.2-1, AB-1, AB-2, AB-4, AB-8, AB-9, AB-14, AB-15	Incomplete.

6.1.3.1 AT1: Subscale Testing

Objective:

The Air Braking System will conduct a test with two objectives during the Notre Dame Rocket Team sub-scale launch in preparation for Critical Design Review. The first objective is to verify that the flight trajectory is stable and apogee is reduced compared to a control flight when a coupler with drag tabs extended is attached to the rocket. For the full scale rocket, ABS must reduce the apogee by approximately 200 ft., so for the 40% sub-scale the tabs must reduce the apogee by approximately 80 ft. The second objective will be to verify successful data collection on a prototype of the avionics for the full scale Air Braking System. Additionally, data collected by an on board Inertial Measurement Unit (IMU) and gyroscope sensors will be used to assist the UAV payload team in selecting an orientation correction sensor.

Tested Items:

- Stable flight with sub-scale drag tab coupler attached.
- Impact of sub-scale drag tabs on flight apogee.
- Prototype avionics data acquisition.

Motivations:

- Validate feasibility of stable flight and apogee attenuation with drag tabs.
- Validate preliminary avionics prototype and gather data for algorithm and Kalman filter development.

Table 28: AT1 Success Criteria

Description	Criteria	Result
Rocket apogee shall be reduced by 80 ft. from the control apogee with the drag tab coupler as measured by on-board altimeters	Pass/Fail	Complete, Pass
Sensors shall successfully log data to SD card in computer-readable format	Pass/Fail	Complete, Pass
Recorded data shall be statistically similar to Recovery Subsystem measurements	Pass/Fail	Fail. Measured altitude follows similar trajectory but with a significant gap in measured apogees. Calibration needed to ensure equal altimeter readings for ABS and Recovery altimeters.
Adequate raw data shall be gathered to assist in constructing Kalman data filter parameters	Pass/Fail	Complete, Pass

Equipment:

- Subscale Rocket
- Removable 3D printed drag tab coupler
- Avionics System
    - Arduino MKR Zero
    - Bosch BNO055 Accelerometer
    - Freescale MPL3115A2
    - 3.3 V Li-Po Battery
    - Status LEDs
- Laptop for data verification

Setup:

Refer to the vehicle test plan for full subscale vehicle setup. The ABS subscale electronics bay is constructed from laser cut plywood. The avionics prototype board is constructed with soldered female header pins which allow for easy assembly and disassembly of the Arduino and sensors from the board. This board is attached then screwed to the vertical plywood deck of the electronics bay. On the opposite side of the deck, a 3.3V LiPo Battery is taped and zip tied to the deck and then connected to the Arduino. The aft bulkhead of the ABS subscale payload bay is then epoxied to the forward bulkhead of the recovery data acquisition payload bay for ease of assembly into the body tube.

Safety Notes:

Flight safety procedures shall be followed at launch. Team members shall only interact with the payload bay with permission of the team safety officer and RSO. Li-Po batteries shall be transported in a fire-proof battery case and batteries shall be inspected for swelling, punctures, or leakage before handling.

Procedure:

Follow procedure outlined in the vehicle test plan for launch vehicle procedure. The 3.3 V battery will be plugged into the Arduino and the team shall confirm that the blue and green status LEDs light up to indicate successful data recording and save to the SD card. The ABS electronics bay shall then be loaded for the duration of the flight and then removed after each flight for data transfer from the SD card to a laptop. Prior to the second launch, a 3D printed coupler with a subscale drag tab assembly will be attached to the vehicle body.

Results:

Measured (unfiltered) flight apogees as recorded by the ABS avionics prototype and the recovery system avionics are shown in table 29 below. Pictures of the 3D printed tab coupler and avionics system post-launch are shown in Figures 97 and 98 and below. Note that due to issues with the parachute during the landing of the second flight, one of the drag tabs broke off of the coupler upon landing, as shown in figure 97 below.

Table 29: AT1 Subscale Apogee Results

Flight Number	ABS Recorded Apogee (ft.)	Recovery Recorded Apogee (ft.)
1	1065	1022
2	978	905

Figure 97: Subscale Drag Tab Coupler Upon Landing

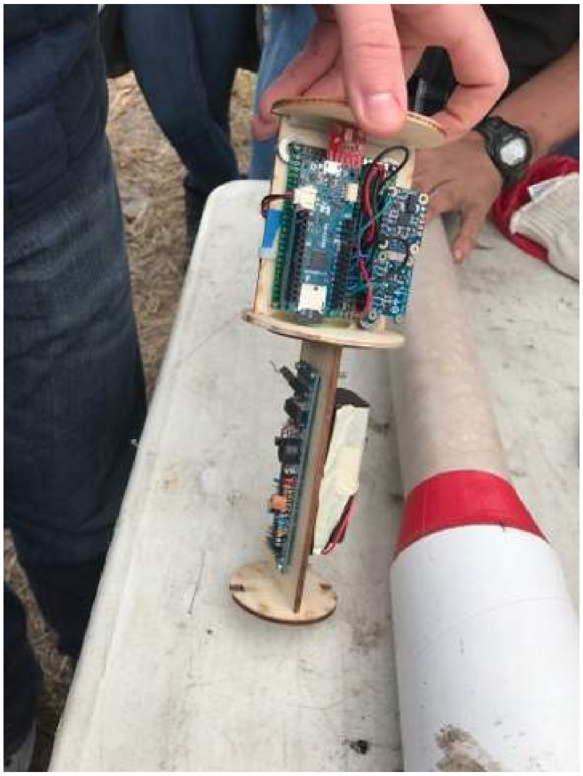


Figure 98: Subscale Avionics Payload Upon Landing

The drag tab coupler for the second subscale flight met the success criteria by experiencing a stable flight and reducing the apogee by 87 ft. according to the ABS avionics data, or by 117 ft. according to the recovery avionics data. The flight demonstrated an apogee reduction greater than the 80 ft. requirement suggesting the tabs still operated successfully. The success criteria was met to collect data for use in Kalman filter configuration.

The ABS flight data did not meet the success criteria of showing the data to be statistically close to the recovery data. The data for ABS and Recovery show a similar flight trajectory, but the first flight had a 43 ft. difference in the recorded apogees of the ABS and recovery altimeters, while the second flight had a difference of 73 ft. Based on the data and inspection of the vehicle, it was determined that the difference in the altimeter data resulted from not properly calibrating the altimeters to ensure matching readings. Additionally, the difference occurred partially due to an issue with the pressure-sealing bulkhead which may have led to an unpredicted pressure event during flight. To counter this problem in the full scale flight, calibration procedures will be prepared for the ABS sensors and the pressure sealing of the bulkheads will be inspected during construction.

There are two main takeaways from the subscale launch flight data for control code development. First, the subscale data is being used to devise more accurate flags to represent transitions into different flight stages. Our launch code correctly transitioned through all stages between ARMED and LANDED during flight, however the data we recovered suggests that we can make some adjustments to ensure further accuracy of the transitions, such as relying more heavily on Kalman-filtered altitude data to set transition flags.

Comparing altitude graphs in Figures 99 and 101 to acceleration graphs in Figures 100 and 102 makes it apparent that, even with the application of our Kalman filter, the former is subjected to far fewer data spikes and sensor noise. Further, adjustments will be made to ensure more accurate Kalman data filtering, as the graphs indicate a tendency to overshoot the actual measurement as indicated by the figures below and comparisons with the data gathered by the recovery avionics.

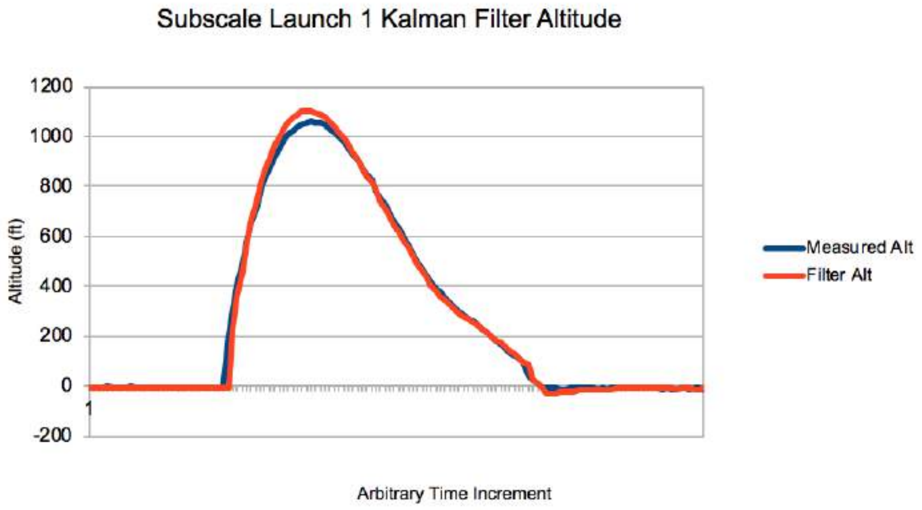


Figure 99: ABS Subscale 1 Altitude Data

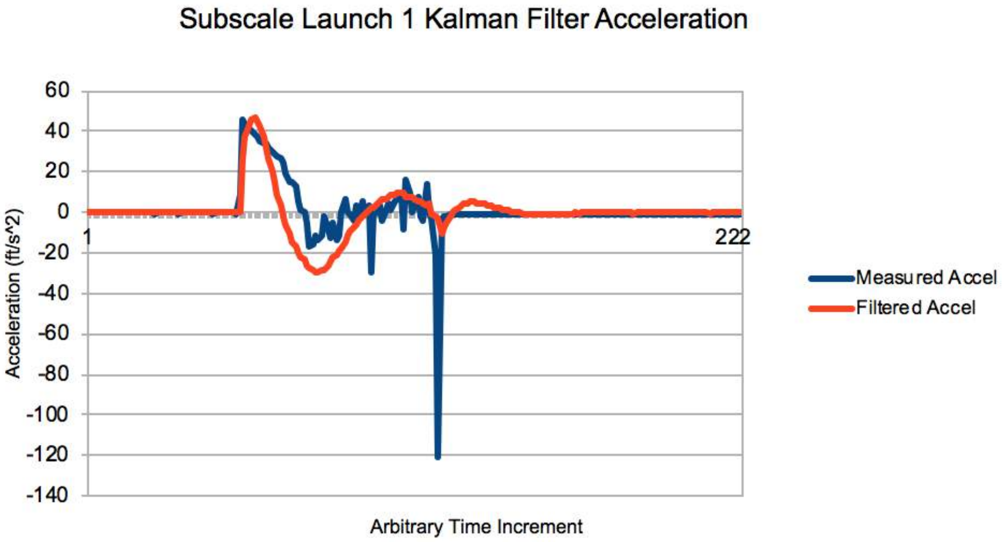


Figure 100: ABS Subscale 1 Acceleration Data

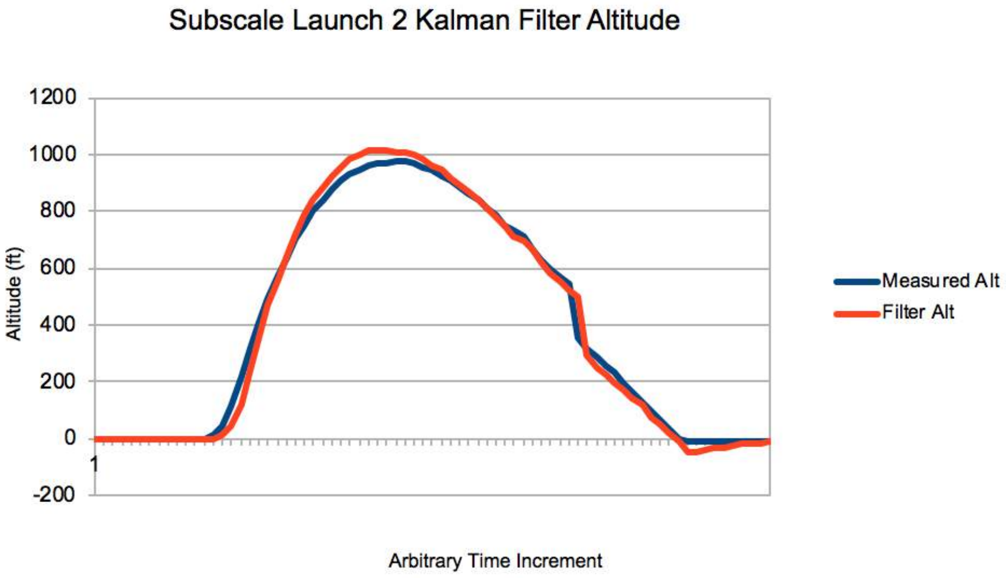


Figure 101: ABS Subscale 2 Altitude Data

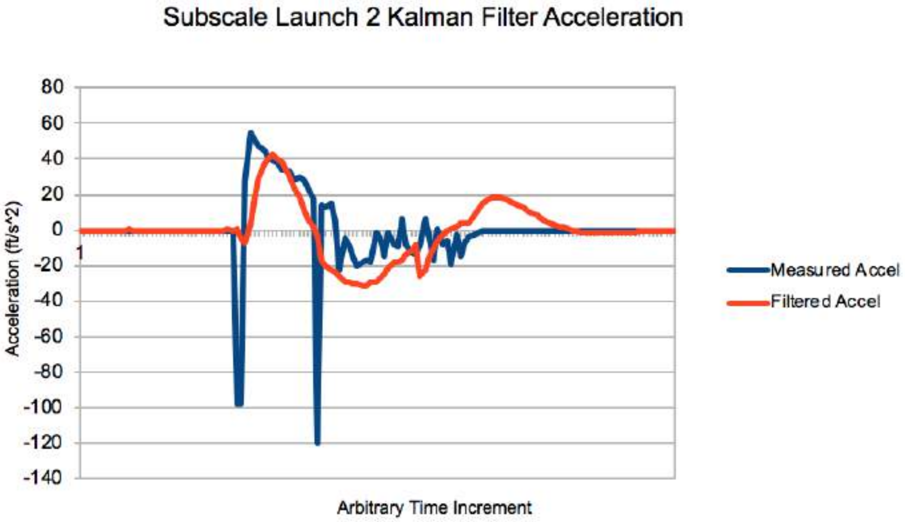


Figure 102: ABS Subscale 2 Acceleration Data

6.1.3.2 AT2: Electronics Ground Test

Objective:

Low-level performance tests shall be performed with the printed circuit board (PCB) and ancillary equipment before it is fully integrated into the rocket body. This test shall determine the proper connectivity of the board with attached components and base electronics performance characterization.

Tested Items:

- Verify electronic components function properly
- Test PCB connection security and continuity
- Verify battery run-time on idle

Motivations:

- Ensure avionics hardware performance
- Ensure avionics assembly integrity

Table 30: AT2 Success Criteria

Description	Criteria	Result
Printed circuit board shall provide solid electrical connection to all components	Pass/Fail	Complete, Pass
LED user interface shall illuminate under proper input when wired through printed circuit board	Pass/Fail	Complete, Pass
Motor shall operate as expected when wired through printed circuit board	Pass/Fail	Complete, Pass
Sensors shall log data as expected when wired through printed circuit board	Pass/Fail	Complete, Pass
Assembled ABS shall successfully remain powered in an idle state for a minimum of 3 hours	Pass/Fail	Complete, Pass

Equipment:

- Multimeter
- Soldering iron and solder
- Soldering smoke absorber
- Hitec D980TW Servo Motor
- Assembled Avionics PCB with associated components

Setup:

Solder all required components to PCB as illustrated in the board diagram. Attach motor and battery to appropriate Molex connectors on PCB. Fully assemble all avionics components. Ensure valid test code is loaded on microcontroller.

Safety Notes:

Safety precautions should be followed when handling the battery. The battery should be inspected for defects and placed in a fire proof case when not in use. Team personnel should exercise caution when operating the soldering iron and use the smoke absorbing fan to reduce the hazard of inhalation. Caution should be exerting when handling the servo motor when power is connected to avoid risk of pinching from unexpected rotation.

Procedure: Verify electrical continuity between PCB contacts with multimeter for all connections defined in board diagram file. Power on and arm system by toggling mechanical switches. Verify all status LEDs illuminated as expected under test code logic. Verify motor turns when induced by test code. Assemble the system with the motor connected and power turned on and leave the system running on idle. Verify that the system does not power off for a minimum of 3 hours.

Results:

The original design of the ABS printed circuit board was placed under testing on January 17th. This first iteration failed AT2 success criteria due to errors made during the design phase. Pin layouts for the Arduino and sensors were flipped relative to their reference orientation. At that time, components were placed in the PCB with the orientation flipped to accomodate this error, which allowed for identification of additional errors. The decoupling capacitors on the voltage regulator were found to be wired in series with the input power supply and output load, rather than parallel and connected to ground. This resulted in incorrect voltage regulator operation and damage to one capacitor with no injury to team personnel. This issue also lead to a PCB trace burning out as verified by a voltmeter continuity test.

A second revision of the PCB was designed and ordered with the necessary changes. This circuit was tested with a voltmeter to verify continuity of necessary connections. Code uploaded to the Arduino allowed for verification of status LED and motor operation. The sensors were successfull in recording data with the given PCB connections, and the battery was shown to last sufficiently long in an idle state.

6.1.3.3 AT3: Mechanical Ground Test

Objective:

The objective of this test is to assess the successful operation and robustness of the Air Braking System mechanical system.

Tested Items:

- Successful control of servo motor actuation with fully assembled mechanical system using avionics control connections
- Verify ABS mechanical system actuation and associated metrics

Motivations:

- To ensure a safe and stable flight by ensuring symmetrical tab extension and proper actuation
- To Verify ABS mechanism capabilities and address possible improvements

Table 31: AT3 Success Criteria

Description	Criteria	Result
ABS drag tabs must deploy symmetrically from the enclosure	Pass/Fail	Complete, Pass
Mechanism shall be capable of continuous full extension and retraction without jamming or damage to the mechanism	Pass/Fail	Complete, Pass
Drag tabs shall be capable of full extension in under 0.5 seconds	Pass/Fail	Complete, Pass. Tabs successfully extend in 0.3 seconds
Shaft Potentiometer successfully transmits positional data	Pass/Fail	Complete, Pass

Equipment:

- Assembled ABS Mechanical System and Mounting
- Hitec D980TW Servo Motor
- Arduino MKR Zero
- Assembled Avionics for full test
- 7.4 V Battery
- Laptop

Setup:

Fully assemble the ABS mechanical system and connect the servo motor to the associated pins of the Arduino. Connect the 7.4 V battery to the servo motor and connect power to the Arduino through a 5V regulator from the 7.4 V battery.

Safety Notes:

Team members shall inspect batteries for defects before handling and store batteries in a fireproof bag when not in use. Team members shall take care to not put fingers near the mechanism when power is connected to avoid potential injury of pinching if the mechanism were to actuate.

Procedure:

Verify the servo motor is properly calibrated and drag tabs successfully deploy symmetrically upon command from the Arduino programmed via the laptop. Test that the tabs successfully deploy in under 0.5 seconds. Upload a program to the Arduino to run the servo motor through ten consecutive cycles to check for jamming. Verify that shaft potentiometer properly transmits positional data.

Results: The assembled Air Braking System mechanism was shown to be capable of actuating as designed and expected. The drag tabs successfully deploy symmetrically per the success criteria. Further, the mechanism successfully meets all other criteria. The system was set to run a looped program to fully extend and retract the tabs continuously. The system was allowed to run continuously for five minutes and performed nominally with no apparent damage or loose components as a result. The tabs were found to deploy in approximately 0.3 seconds which fulfills the 0.5 second success criteria. It also should be noted that the system may be capable of faster speed, but the speed used in the test was deemed acceptable and higher speeds were not tested to avoid increased current draw that might lead to a burnout of the motor circuitry over time. The shaft potentiometer successfully submits data to the analog pin of the Arduino MKR Zero.

6.1.3.4 AT4: Software Ground Test

Objective:

These tests shall be used to validate that the ABS control code responds correctly to simulated flight data in terms of filtering the data and setting control outputs appropriately. A test will be done to run a simulated flight with the mechanical system connected to verify proper tab actuation and certify sufficient functionality to be considered mission ready.

Tested Items:

- Code robustness and functionality
- Kalman filter performance and trust matrix
- Drag tab extension values (PID Controller)

Motivations:

- Validate successful ABS control code design and operation for mission success
- Evaluate possible improvements, specifically in the Kalman filter trust matrix

Table 32: AT4 Success Criteria

Description	Criteria	Result
Kalman filter must be effective in smoothing out data spikes from previous flight data.	Altitude vs time and acceleration vs time graphs will be plotted with raw data and Kalman filter data to visually confirm that the filter is effective.	Complete
Kalman trust matrix must be optimized to best filter data.	The final values for the trust matrix must most accurately represent the perceived real-world state values given sensor data.	In Progress
PID controller must output correct values for drag tab extension when testing with data from a previous flight and recording extensions to the SD card for later analysis.	Tab extensions produced by the simulation must match values for tab extensions produced by human computation at a sufficient number of test points in the range of data.	Complete
With an assembled mechanical system, actuation under a simulated flight must match expected performance. A simulated detected jam must result in tab retraction.	Pass/Fail	Complete, Pass

Equipment:

- Arduino MKR Zero
- USB 2.0 cable
- SD card
- Laptop
- Assembled mechanical system
- 7.4 V Battery

Setup:

Ensure a proper connection between the Arduino and the test computer through the USB cable, as well as a proper connection between the Arduino and the SD card. Assemble ABS mechanical system when running the physical simulation flight.

Safety Notes:

Follow safety procedures for handling batteries and avoiding contact with the mechanical system while power is connected to avoid pinching.

Procedure:

Utilize the Kalman Filter simulation (in Excel) to produce relevant acceleration and altitude graphs from last year's full scale launch data. Repeat process with the data from both subscale test launches. Next utilize a modified version of the control code that takes previous flight data from the SD card as sensor data input. Upload this code to the Arduino and run it with each of the three previously mentioned data sets. Independently calculate the drag tab extensions at random test points during the flight interval and compare these to the control code (and PID controller) determined extension values which were outputted to the SD card.

Connect the ABS mechanical system. Run a simulated flight test with previous flight data and observe mechanical system actuation. Note any issues and verify operation under specific scenarios such as a detected jam.

Results:

The Kalman filter was shown to be capable of effectively smoothing out data spikes. The Kalman filter was plotted alongside sensor data, and any noise in sensors was shown to be largely ignored by the filter.

The values of the Trust Matrix for the Kalman filter have not been finalized. This is due to the fact that when simulated data is input to the Kalman, the filter currently is not sufficiently precise in time or altitude to finalize the Trust Matrix values. The data from the March 2nd test flight is being used to improve the Kalman trust matrix coefficients. Tab extensions produced by the simulation matched values for tab extension produced by human computation. These results were satisfactory due to their sufficient number of test points in the range of data.

A simulation of tab extension was ran using data provided from Open Rocket and the tab actuation of a fully assembled ABS matched expectations as the tabs deployed fully at burnout and retracted at apogee. Similar results were achieved with a full actuation test which demonstrated the ability of the tabs to a actuate based on sensor readings. As a result, the primary factor in providing a successful transition is providing proper conditionals for transitioning between states. Data provided by Open Rocket and Rocksim will be used to set those altitude and acceleration conditions, and full scale control flights will be used to verify these conditions prior to tab actuation.

6.1.3.5 AT5: Flight Tests

Objective:

This test shall be used to validate successful ABS integration and payload design performance to verify mission readiness.

Tested Items:

- Data acquisition
- Flight state and control algorithm operation success
- Mechanical system actuation and impact on mission performance (full braking power and apogee control precision)

Motivations:

- Validate successful ABS design and operation for mission success
- To assess practical system limitations and evaluate possible improvements

Table 33: AT5 Success Criteria

Description	Criteria	Result
The ABS electronics deck must be sealed from the lower sections of the design to prevent unpredictable pressure changes for the altimeter data.	Pass/Fail	Complete, Pass
ABS electronics must remain powered on, collecting data, and properly armed or disarmed depending on the flight number when installed in the vehicle.	Pre-flight checklists will be prepared and followed at the launch. Status LEDs will indicate proper data collection and arming of the software. Pass/Fail	Complete, Pass
The ABS drag tabs do not extend until motor burnout.	Ground Inspection shows no extension on launch pad. Data confirms no tab extension until motor burnout. Pass/Fail	Incomplete. Tabs were not active during March 2 test flight.
All ABS components are shown to be capable of withstanding flight and landing forces in order to be used in future flights.	Pass/Fail	Complete, Pass
The ABS is able to log raw sensor data and flight state algorithm data for post-mission analysis.	Pass/Fail	Failed to fully meet description due to accelerometer issues, Incomplete
The ABS must reduce the apogee of the rocket by at least 200 ft. during the second flight which shall test the full braking power of the ABS.	Pass/Fail	Incomplete
The ABS must slow the vehicle to a final apogee within 25 ft. of the 4,700 ft. target during the third test flight.	Pass/Fail	Incomplete.

Equipment:

Assembled Vehicle and associated payloads including ABS.

Setup: Refer to vehicle test plans for vehicle assembly.

- Observe all components are connected to PCB and battery is charged
- Inspect all sections of the Air Braking System for damage and defects that would impact mission performance
- Ensure the proper control code is uploaded to the Arduino MKR Zero. **Ensure that SD card is inserted in Arduino prior to powering on**
- Flip control switches to power the system. Flip the arming switch for the appropriate flight number (off for control flight 1, on for actuation flights 2 and 3).
- Verify status LEDs report system is ready for launch
- Follow vehicle safety procedures to load Air Braking System into vehicle fin can. Sign off procedure checklists with ABS, Vehicles, and Safety leads.
- Verify drag tabs do not extend prematurely on launch pad

Safety Notes:

All flight test safety procedures shall be followed at the direction of the Safety officer and RSO. Care shall be taken when handling batteries and powered electronics. Team personnel shall only handle the vehicle with authorization from the Safety officer and RSO.

Procedure:

Vehicle test flight procedures shall be followed for launch. The first flight shall serve as a control flight, with an inactive ABS mechanical system that is collecting data. The second flight shall serve as a test of the full braking power of the ABS by fully extending the tabs at motor burnout and retracting at apogee. The third flight shall serve as a test of the precision of the control algorithm in achieving the target apogee of 4,700 ft. The ABS data will be analyzed post launch to assess mission performance and necessary changes or further flight testing. Data will be used to verify flight models and coefficient of drag with the tabs actuating.

- Follow post-launch procedures to safely recover rocket after landing with safety officer approval
- Extract system from rocket body
- Inspect the mechanical system and full payload bay for damage
- Verify electrical system connections are not damaged and could be reused in another flight
- Remove the SD card and insert SD card into computer to read flight data
- Verify valid flight data from all sensors is stored on SD card
- Record maximum altitude recorded by altimeter sensor
- Verify altimeter data confirms the rocket reached apogee near target

Results:

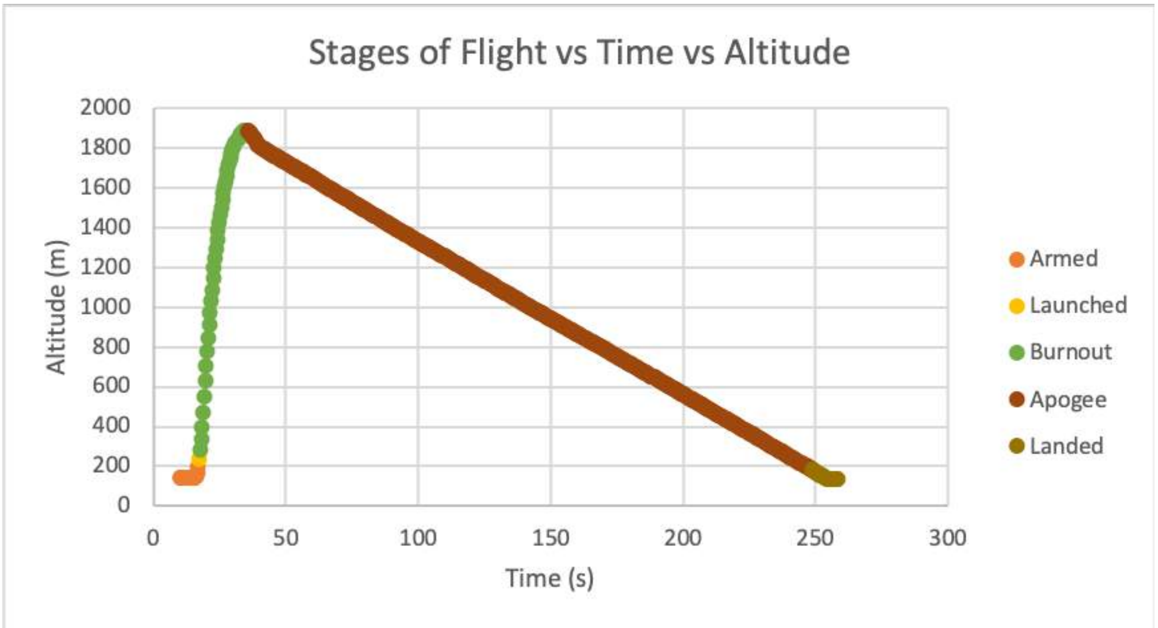


Figure 103: Full Scale Test Flight with Stages

A control test flight was conducted on March 2nd.This flight allowed for verification of some of the success criteria for AT5. The ABS electronics deck was successfully sealed from the lower sections of the vehicle using Clay to seal holes cut for running wires, and the data collected was smooth to indicate there was no pressure disturbances.

ABS electronics were successful in remaining powered until removal from the fin can after recovery. The ABS collected data and properly held the tabs retracted during flight.

The ABS only suffered two minor damages as a result of flight. One of the two zip ties securing the battery was sheared during landing, while the other zip tie continued to secure the battery. This will be mitigated in future flights by using a custom battery container which was not used in this flight as a result of damage to the battery case during handling prior to the flight. Additionally, one of the nylon #6-32 screws fell out of its nylon standoff securing the bearing plate. However all other components of the ABS appeared unaffected and other screws remained tight, as well as the drag tabs maintaining alignment with their slots in the fin can. This damaged screw has been replaced and an additional step to further check screw tightness will be added to future flight procedures. Overall, this flight verified the success criteria that the system is capable of withstanding flight.

The team's first flight confirmed that ABS data was logging correctly. Not only was the data the sensors collected largely free of noise, the recorded ABS apogee of 5745 feet was only 30 feet away from the recorded Recovery apogee of 5715 feet and closely matched the flight trajectory recorded by the recovery altimeters. Both sensors continued to record accurate data after a very fast impact with the ground, showing that the sensors are robust enough to stand up to landing forces. The one failure was that the accelerometer recorded a max acceleration of 29.91 m/s^2 during liftoff, significantly lower than either was predicted by simulations or was confirmed by Recovery altimeters. Given this failure of the accelerometer, the test is deemed only a partial success.

The data was also sampled slower than desired. Post launch assessment identified that the sampling rate of the sensors was being reduced due to the delay of writing to the SD card. In order to increase the sampling rate, a buffer array will be used to locally store sets of at least one hundred data points which can then be stored on the SD card at a later time, reducing the time lost on writing to the card.

Due to weather delays in previous weeks, only the one flight conducted on March 2nd has been completed. As a result, data about the performance of the ABS in flight has not yet been acquired. Test results for an active ABS flight will be submitted by the payload demonstration deadline.

6.1.4 UAV Testing

Table 34: UAV Test Plan

Test	Description	Requirement to be Verified	Success Criterion
Manual Flight Test	Tests UAV's ability to take off, fly, and land under manual control and verifies flight position of the body frame	4.4.5-1	UAV successfully takes off from the ground, ascends to a height of 10 feet, travels 10 feet, and lands
Orientation Correction Roll Test	Tests servo's ability to make UAV platform turn upright	4.4.1	UAV platform successfully rotates and stays in upright position
Deployment Drive Test	Tests the motor's ability to move the UAV platform out of the body tube	4.4.1	UAV platform successfully clears the body tube
Deployment System Shake Test	Tests the connections between the system and the nose cone and the system and the body tube	4.4.1	System remains connected within the body tube and to the nose cone
Autonomous Deployment and Unfolding Test	Tests DDS's ability to deploy the UAV	4.4.1	DDS successfully removes UAV from payload bay, DDS successfully removes R-clips from UAV landing struts, UAV successfully unfolds into flight orientation

Test	Description	Requirement to be Verified	Success Criterion
Manual Takeoff Test	Tests UAV's ability to take off from the rocket's payload bay	4.4.5-1	UAV successfully takes off from DDS platform and flies under manual control for 10 feet before landing.
Autonomous Deployment and Unfolding Test	Tests DDS's ability to deploy the UAV	4.4.1	DDS successfully removes UAV from payload bay, DDS successfully removes R-clips from UAV landing struts, UAV successfully unfolds into flight orientation
Manual Takeoff Test	Tests UAV's ability to take off from the rocket's payload bay	4.4.5-1	UAV successfully takes off from DDS platform and flies under manual control for 10 feet before landing.
Autonomous Takeoff Test	Tests UAV's ability to deploy autonomously	4.4.5-1	UAV successfully takes off autonomously and ascends to a height of 3 meters before landing in place
FEA Detection Test	Tests UAV's ability to identify and fly to FEA	4.4.5-2	UAV successfully flies to and lands on FEA autonomously
Beacon Deployment Test	Tests UAV's ability to deliver beacon to FEA	4.4.8	UAV successfully delivers beacon to FEA autonomously

6.1.4.1 Manual Flight Test

Objective

The objective of the manual flight test is to verify the stability of the UAV during takeoff, flight and landing while also verifying the integrity of the frame design under flight loads.

Tested Items

- The stability of the UAV during flight
- The strength of the frame

Motivation

The test is to ensure that the drone is capable of stable and controlled flight. The test also affirms the structural integrity of the UAV. These are both essential to successful completion of the payload mission.

Set-Up

The drone must be fully deployed and in its flight configuration. All electronics must be checked for defects.

Safety

Check all screws and nuts on the UAV. Check all velcro and straps securing UAV electronics. Check arms are secured in the flight position.

Success Criteria

The test will be successful if the UAV successfully takes off from the ground, ascends to a height of 10 feet, travels 10 feet, and lands. During this flight, the UAV must remain stable and not oscillate. Furthermore, there must not be any cracks or fractures anywhere on the UAV frame once the flight has been completed.

Procedure

1) Power on UAV electronics

2) Slowly increase the power on the throttle and monitor the UAV for stablity

Results

The UAV has successfully completed the Manual Flight Test. It was able to achieve a stable hover and was able to be maneuvered to a landing site.

6.1.4.2 Deployment Drive Test (DDS)

Objective

The objective of the test is to confirm the capability of the Linear Transport System in pushing the nose cone forward to provide adequate takeoff space for the UAV. There will be three iterations of the test. First, it will be tested without the weight of the UAV and on a smooth surface. The second test will be with the UAV weight and on a smooth surface. The third test will be with the UAV weight and on a rough surface with small obstacles. By performing multiple iterations of the test, any failure of the system will be more easily identified. This test will fulfill the requirement 4.4.1.

Tested Items

The components of the Deployment Drive System that will be assessed in the test are as follows:

- Integrity of the lead screw
- Force provided by the stepper motor
- Integrity of the fore and aft bulkheads

Motivation

The Linear Deployment System is a crucial aspect of the Deployment System. The UAV needs an adequate opening for takeoff, and the Linear Deployment System creates the necessary opening. Failure of the Linear Deployment System would result in a failure of the payload mission.

Set-Up

The Linear Deployment System will be fully integrated with the Orientation Correction System and be fully integrated into the payload section of the rocket.

Safety

All persons not involved with the test will be notified and cleared from the area to avoid any accidental collisions. A minimum safety distance of three feet will be maintained from the rocket throughout the test. All moving parts will be examined prior and during the test to ensure they are free from debris and in working order. All electronics will be monitored in order to prevent electrical surges.

Success Criteria

The Deployment Drive Test will be considered a success if and only if the Linear Transport System creates the adequate takeoff distance for each iteration after receiving the command to do so. This test does not involve the success of the Orientation Correction System or the success of the UAV.

Procedure

The rocket will be placed horizontally on a flat, smooth surface. The area will be cleared of all nonessential persons. The Deployment Drive System will be checked for any debris that may inhibit the motion of the system. The electronics will be powered on. The Linear Transport System will receive a signal to begin. As the system is running, it will be continuously monitored by the team members. Upon completion or failure of the system the electronics will be powered off. This process will be repeated for the remaining two iterations: one with the weight of the UAV and another with the weight of the UAV and on a rough surface with small impediments.

Results

This test has not been conducted yet but shall be completed prior to the payload demonstration flight.

6.1.4.3 Orientation Correction System Test (OCS)

Objective

The objective of the Orientation Correction System Roll Test is to confirm the ability of the system to properly orient the UAV and its platform when placed in any random orientation. The successful completion of this test fulfills requirement PL 4.4.1-1.

Tested Items

- The accuracy of the orientation of the platform
- The consistency of the system's performance

Motivation

This test is to ensure that the UAV can take off in an upright position upon safe landing. This system is critical to completing the payload mission. The system will be tested in various conditions to ensure reliability on launch day.

Set-Up

The orientation correction system will be placed on a designated surface where the team can see the performance of the system.

Safety

Always check the battery and electronics prior to conducting tests for any faults or defects. The system will be closely monitored during the test.

Success Criteria

The test will be considered successful if the platform is able to orient perpendicular to the gravity vector. The team will compare data from the Arduino to make sure that the physical results and computational results are consistent. If the trial is unsuccessful, then the team will identify the problem and perform the experiment again. If the trial is successful, the team will conduct the experiment multiple times to confirm its consistency.

Procedure

1) Clear area of nonessential persons

2) Assemble the OCS by connecting the two rotating bulkheads by the leadscrew and guide rods

3) Check electronics for defects and if no issues are present, proceed to power on

4) Place system in a designated surface and in any random orientation

5) Send signal to begin orientation correction

6) When the servo motor stops, confirm the platform is in its upright orientation

7) Compare to Arduino data to ensure platform is perpendicular to gravity vector

8) Power down electronics

9) Repeat procedure until multiple trials are conducted

Results

The test has not been conducted yet but shall be completed prior to the payload demonstration flight.

6.1.4.4 Deployment System Shake Test

Objective

The objective of the Deployment System Shake Test is to ensure that the deployment system and the nose cone connection are secure during flight. This test fulfills requirement 4.1.1.

Tested Items

- Durability and robustness of lead screw connection to inner bulkhead of nose cone
- Durability and robustness of screw connection between the deployment housing and the body of the rocket

Motivation

This test is to ensure that the lead screw connection to the inner bulkhead is secure enough to withstand the forces of flight so that the nose cone is not removed. This test also ensures that the entire deployment system remains screwed into the body during flight.

Set-Up

The deployment system will be successfully integrated into the rocket for this test.

Safety

Check the system to make sure that no components are loose or unattached. Check all screw connections to make sure they are tightly fastened.

Success Criteria

The test will be considered successful if the nose cone and deployment system remain securely fastened in their proper positions when shaken. The nose cone connection to the bulkhead via a hex nut must not move nor tear any threads. The inner housing connection to the outer body tube must not shear the screws or tear through the nylon.

Procedure

1) Clear area of nonessential persons

2) Assemble the deployment system by connecting the two rotating bulkheads by the leadscrew and guide rods

3) Insert the screws around the body tube in the marked locations. Ensure that the screws are tightly fastened.

4) Shake the system for 15 seconds

5) Check the connections between the housing and the body tube for failure

6) Check the connections between the hex nut on the inner bulkhead and the leadscrew for failure

7) Check all other components for failure or fracture

8) Detach the nose cone

9) Repeat procedure until multiple trials are conducted

Results

The results of this test proved that the system would hold a significant amount of force. The Deployment System Shake Test was conducted three times in order to ensure consistency. Each time, the screws remained connected to the housing and the hex nut connection remained secure. The test was then designated as a success due to the absence of failure in any of the components. However when tested in flight, the hex nut disconnected from the inner bulkhead of the nose cone and the flanges securing the UAV on the platform sheared. The flanges will be reconstructed out of aluminum for better strength and resistance to shear. The direction of the bulkhead and housing will be flipped so that the backing for the hex nut counteracts the force on the bulkhead. After these changes, the system will be tested again to confirm reliability.

6.1.4.5 Beacon Deployment Test

Objective

The objective of the Beacon Deployment Test is to confirm that the airborne drone can repeatedly and successfully drop a beacon onto a 10ft by 10ft tarp.

Tested Items

- The height of the UAV from the tarp
- The horizontal speed of the UAV in respect to the tarp
- Angle of UAV at time of release

Motivation

The motivation for this test is to ensure that the variables of height, speed, and angle are understood well enough so that the UAV can reliably release the beacon onto the tarp every time.

Set-Up

Load the beacon onto the drone and lay out the tarp in a large open area.

Safety

Ensure all members remains alert and aware of the situation during UAV flight to minimize injuries. Check all screws and nuts on the UAV. Check all velcro and straps securing UAV electronics. Check arms are secured in the flight position.

Success Criteria

The test will be deemed a success if the UAV can drop the beacon successfully on the tarp 9 out of 10 times given a height of 10 ft, an angle of 10 degrees off of horizontal, or a speed of 10 feet per second.

Procedure

1) Clear area of nonessential persons

2) Construct, inspect, arm, and launch UAV
3) Fly UAV over tarp
4) Adjust flight variables as necessary
5) Fly tests until 9 successful flights in a row are recorded

Results

The test has not been conducted yet but shall be completed prior to the payload demonstration flight.

6.2 Requirements and Verifications

6.2.1 NASA Requirements

At this point in the project, nearly all NASA requirements and Team Derived requirements have been verified. All in progress verification methods are due to a requirement not being met in the initial vehicle demonstration flight or waiting to be tested in the payload demonstration flight. The NASA project timeline allowing for additional time to fully test the payloads by the demonstration flight has resulted in these requirements not being met. The team understands the deadline and shall have all requirements verified and submitted with the Re-Flight Addendum documentation.

6.2.1.1 NASA General Requirements

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
1.1	Students on the team will do 100% of the project, including design, construction, written reports, presentations, and flight preparation with the exception of assembling the motors and handling black powder or any variant of ejection charges, or preparing and installing electric matches (to be done by the team's mentor).		X			The team shall conduct periodic internal assessments to ensure all work is being done solely by team members and that faculty advisors and mentors are involved in an advising capacity, with the exception of energetics handling.	X		

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
1.2	The team will provide and maintain a project plan to include, but not limited to the following items: project milestones, budget and community support, checklists, personnel assignments, STEM engagement events, and risks and mitigations.		X			The NDRT shall hold weekly meetings to address project milestones and assign tasks. The team shall include all project milestones, budget and community support, checklists, personnel assignments, STEM engagement events, and risks and mitigations in the milestone review reports.	X		
1.3	Foreign National (FN) team members must be identified by the Preliminary Design Review (PDR) and may or may not have access to certain activities during launch week due to security restrictions. In addition, FN's may be separated from their team during certain activities.		X			The Notre Dame Rocketry Team shall survey team members regarding foreign citizenship and pass along contact information to the SL Management Team.	X		
1.4	The team must identify all team members attending launch week activities by the Critical Design Review (CDR). Team members will include:		X			The team shall submit all members attending launch week to the NASA SL Management Team no later than January 2nd, 2019.	X		

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
	1.4.1. Students actively engaged in the project throughout the entire year.								
	1.4.2. One mentor (see requirement 1.13).								
	1.4.3. No more than two adult educators.								
1.5	The team will engage a minimum of 200 participants in educational, hands-on science, technology, engineering, and mathematics (STEM) activities, as defined in the STEM Engagement Activity Report, by FRR. To satisfy this requirement, all events must occur between project acceptance and the FRR due date and the STEM Engagement Activity Report must be submitted via email within two weeks of the completion of the event. A sample of the STEM Engagement Activity Report can be found on page 33 of the handbook.		X			The team shall conduct STEM engagement activities between Oct. 5th, 2018 through Mar. 3rd, 2019 and submit the STEM Engagement Activity Report to the NASA SL Management Team within 10 days of the event. The team shall track the number of students engaged in activities and team members in participation.	X		

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
1.6	The team will establish a social media presence to inform the public about team activities.		X			The team shall create a Facebook page, Instagram, and Twitter account to promote team activities at the University and in the South Bend community.	X		
1.7	Teams will email all deliverables to the NASA project management team by the deadline specified in the handbook for each milestone. In the event that a deliverable is too large to attach to an email, inclusion of a link to download the file will be sufficient.		X			All upcoming deliverable deadlines shall be addressed at weekly meetings. Team officers shall review the document size of each deliverable and verify they are less than 10 mb.	X		
1.8	All deliverables must be in PDF format.		X			Team shall export all documents to a PDF format before officer submits them to the SL Management Team.	X		
1.9	In every report, teams will provide a table of contents including major sections and their respective sub-sections.		X			The team shall create an outline of the sections of each report prior to writing the main text. This outline shall be built into a table of contents.	X		
1.1	In every report, the team will include the page number at the bottom of the page.		X			The team shall write reports in a LaTeX format that automatically updates the page number.	X		

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
1.11	The team will provide any computer equipment necessary to perform a video teleconference with the review panel. This includes, but is not limited to, a computer system, video camera, speaker telephone, and a sufficient Internet connection. Cellular phones should be used for speakerphone capability only as a last resort.		X			The team shall rent a webcam and teleconference phone from the College of Engineering Dean's office 1 week prior to all teleconferences with NASA. This equipment shall be tested with an officer's laptop to be in working order prior to the day of the call.	X		
1.12	All teams will be required to use the launch pads provided by Student Launch's launch services provider. No custom pads will be permitted on the launch field. Eight foot 1010 rails and 12 foot 1515 rails will be provided. The launch rails will be canted 5 to 10 degrees away from the crowd on launch day. The exact cant will depend on launch day wind conditions.		X			The team shall use either eight foot 1010 rails and 12 foot 1515 rails during all full scale test launches.	X		

General Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
1.13	Each team must identify a “mentor.” A mentor is defined as an adult who will be supporting the team throughout the project year. The mentor must maintain a current certification, and be in good standing, through the National Association of Rocketry (NAR) or Tripoli Rocketry Association (TRA) for the motor impulse of the launch vehicle and must have flown and successfully recovered (using electronic, staged recovery) a minimum of 2 flights in this or a higher impulse class, prior to PDR. The mentor is designated as the individual owner of the rocket for liability purposes and must travel with the team to launch week.		X			The team shall identify the "mentor" in Section 1.1 (Team Summary) of the PDR report. This section shall include the NAR/TAR section the mentor belongs to as well as the mentor’s contact information.	X		

6.2.1.2 NASA Vehicle Requirements

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.1	The vehicle will deliver the payload to an apogee altitude between 4,000 and 5,500 feet above ground level (AGL). Teams flying below 3,500 feet or above 6,000 feet on Launch Day will be disqualified and receive zero altitude points towards their overall project score.				X	The launch vehicle shall reach an altitude between 4,500 and 5,000 feet as recorded by recovery altimeters without the assistance of an Air Braking System. This shall be verified during the Vehicle Demonstration Flight.		X	
2.2	Teams shall identify their target altitude goal at the PDR milestone. The declared target altitude will be used to determine the team's altitude score during Launch Week.		X			The vehicle shall be designed to reach a target altitude of 4,700 ft. This altitude shall be identified in the PDR report.	x		
2.3	The vehicle will carry one commercially available, barometric altimeter for recording the official altitude used in determining the Altitude Award winner. The Altitude Award will be given to the team with the smallest difference between their measured apogee and their official target altitude on launch day		X			The altimeter used in the recovery subsystem shall be a Raven 3 purchased from a commercial vendor and used for recording apogee.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.4	Each altimeter will be armed by a dedicated mechanical arming switch that is accessible from the exterior of the rocket airframe when the rocket is in the launch configuration on the launch pad.		X			The altimeters shall be integrated into the vehicle and a hole shall be made in the vehicle body such that the altimeter switches are accessible.	X		
2.5	Each altimeter will have a dedicated power supply.		X			Each altimeter shall be wired to a single battery and each battery shall be wired to a single altimeter.	X		
2.6	Each arming switch will be capable of being locked in the ON position for launch (i.e. cannot be disarmed due to flight forces).			X		The team shall simulate flight forces on the full scale avionics assembly through a shake test with the arming switches in the ON position. Integrity of the design shall be verified if the arming switches remain ON through 5 consecutive shake tests.	X		
2.7	The launch vehicle will be designed to be recoverable and reusable. Reusable is defined as being able to launch again on the same day without repairs or modifications.			X		The launch vehicle shall be recovered during the Vehicle Demonstration Flight and re-assembled within 2 hours to verify that it can be flown again on the same day.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.8	The launch vehicle will have a maximum of four (4) independent sections. An independent section is defined as a section that is either tethered to the main vehicle or is recovered separately from the main vehicle using its own parachute.		X			The vehicle shall have two (2) independent sections.	X		
2.8.1	Coupler/airframe shoulders which are located at in-flight separation points will be at least 1 body diameter in length.		X			The vehicle shall have a single separation point with a 6 inch shoulder on the airframe, resulting in a 1 body tube diameter length.	X		
2.8.2	Nosecone shoulders which are located at in-flight separation points will be at least ½ body diameter in length.		X			The launch vehicle shall have no in-flight separation points at the nosecone.	X		
2.9	The launch vehicle will be limited to a single stage		X			The vehicle shall use a single stage L-Class motor.	X		
2.1	The launch vehicle will be capable of being prepared for flight at the launch site within 2 hours of the time the Federal Aviation Administration flight waiver opens.			X		Vehicle preparation shall be rehearsed and timed at test launches.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.11	The launch vehicle will be capable of remaining in launch-ready configuration on the pad for a minimum of 2 hours without losing the functionality of any critical on-board components.	X		X		Electrical power components shall be analyzed and sized to power all systems for a designated time. Each subsystem shall be powered on for a minimum of 2 hours prior to conducting flight tests.	X		
2.12	The launch vehicle will be capable of being launched by a standard 12-volt direct current firing system. The firing system will be provided by the NASA-designated launch services provider.				X	The vehicle shall utilize an ignition system designed for a 12V DC launch system.	X		
2.13	The launch vehicle will require no external circuitry or special ground support equipment to initiate launch (other than what is provided by the launch services provider).		X			The launch vehicle shall be designed to use standard launch services equipment provided by the team mentor.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.14	The launch vehicle will use a commercially available solid motor propulsion system using ammonium perchlorate composite propellant (APCP) which is approved and certified by the National Association of Rocketry (NAR), Tripoli Rocketry Association (TRA), and/or the Canadian Association of Rocketry (CAR).		X			The motor shall be ordered from a verified vendor and utilize ammonium perchlorate composite propellant.	X		
2.14.1	Final motor choices will be declared by the Critical Design Review (CDR) milestone.		X			The final motor choice shall be listed in the Technical Design of the Launch Vehicle in the CDR milestone report.	X		
2.14.2	Any motor change after CDR must be approved by the NASA Range Safety Officer (RSO) and will only be approved if the change is for the sole purpose of increasing the safety margin. A penalty against the team's overall score will be incurred when a motor change is made after the CDR milestone, regardless of the reason.		X			The team shall use the motor choice given at the CDR milestone for all test flights and at competition	X		
2.15	Pressure vessels on the vehicle will be approved by the RSO and will meet the following criteria:		X			The vehicle shall contain no pressure vessels.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.15.1	The minimum factor of safety (Burst or Ultimate pressure versus Max Expected Operating Pressure) will be 4:1 with supporting design documentation included in all milestone reviews.		X			The vehicle shall contain no pressure vessels.	X		
2.15.2	Each pressure vessel will include a pressure relief valve that sees the full pressure of the tank and is capable of withstanding the maximum pressure and flow rate of the tank.		X			The vehicle shall contain no pressure vessels.	X		
2.15.3	Full pedigree of the tank will be described, including the application for which the tank was designed, and the history of the tank, including the number of pressure cycles put on the tank, by whom, and when.		X			The vehicle shall contain no pressure vessels.	X		
2.16	The total impulse provided by a College or University launch vehicle will not exceed 5,120 Newton-seconds (L-class).		X			All motors shall be L-Class or below.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.17	The launch vehicle will have a minimum static stability margin of 2.0 at the point of rail exit. Rail exit is defined at the point where the forward rail button loses contact with the rail.	X				OpenRocket simulations shall be used to compute the stability margin throughout flight. This analysis shall verify the rocket achieves a margin of 2 at the point the first rail button clears the rail.	X		
2.18	The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit	X				OpenRocket simulations of the vehicle's flight shall determine that the vehicle's off-rail velocity is at least 52 fps.	X		
2.19	All teams will successfully launch and recover a subscale model of their rocket prior to CDR. Subscales are not required to be high power rockets.		X			The subscale flight shall be completed by the second week of December on one of two potential launch days partnering with Michiana Rocketry.	X		
2.19.1	The subscale model should resemble and perform as similarly as possible to the full-scale model, however, the full-scale will not be used as the subscale model.	X			X	OpenRocket simulations of the subscale shall confirm that it performs as similarly as possible to the full-scale vehicle. Data from the subscale flight shall be compared to simulations to evaluate accuracy of simulations.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.19.2	The subscale model will carry an altimeter capable of recording the model's apogee altitude.		X			An altimeter capable of recording the model's apogee altitude shall be selected for use in the subscale vehicle.	X		
2.19.3	The subscale rocket must be a newly constructed rocket, designed and built specifically for this year's project.		X			The team shall source all new components for the subscale. The rocket shall be a scale model of the competition vehicle.	X		
2.19.4	Proof of a successful flight shall be supplied in the CDR report. Altimeter data output may be used to meet this requirement.		X			The subscale vehicle shall record data with a single altimeter of the same make and model to be used in the competition vehicle.	X		
2.2	All teams will complete demonstration flights as outlined below.		X			Requirements 2.20.1 and 2.20.2 shall be verified.		X	
2.20.1	Vehicle Demonstration Flight - All teams will successfully launch and recover their full-scale rocket prior to FRR in its final flight configuration. The rocket flown must be the same rocket to be flown on launch day. The following criteria must be met during the full-scale demonstration flight:		X			Requirements 2.20.1.1 through 2.20.1.9 shall be verified.		X	

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.20.1.1	The vehicle and recovery system will have functioned as designed.		X			The vehicle shall reach at targeted altitude to within 100 feet and the recovery system shall operate as a single separation event at apogee, with the main chute fully deploying at 500 feet.		X	
2.20.1.2	The full-scale rocket must be a newly constructed rocket, designed and built specifically for this year's project.		X			The full-scale rocket shall be fully designed and built for this year's project.	X		
2.20.1.3	The payload does not have to be flown during the full-scale Vehicle Demonstration Flight. The following requirements still apply:		X			Requirements 2.20.1.3.1 and 2.20.1.3.2 shall be verified.		X	
2.20.1.3.1	If the payload is not flown, mass simulators will be used to simulate the payload mass.		X			Ballast masses of the UAV payload shall be brought to launch day and secured in the body to simulate the payload.	X		
2.20.1.3.2	The mass simulators will be located in the same approximate location on the rocket as the missing payload mass.		X			The payload CG and location in the rocket shall be used to locate the CG of the ballast.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.20.1.4	If the payload changes the external surfaces of the rocket (such as with camera housings or external probes) or manages the total energy of the vehicle, those systems will be active during the full-scale Vehicle Demonstration Flight.		X			The camera mounts and Air Braking drag tabs shall be present and active on all demonstration flights.		X	
2.20.1.5	Teams shall fly the launch day motor for the Vehicle Demonstration Flight. The RSO may approve use of an alternative motor if the home launch field cannot support the full impulse of the launch day motor or in other extenuating circumstances.		X			The motor selected for use in the demonstration/test flight will be the same motor used on the competition launch day.	X		
2.20.1.6	The vehicle must be flown in its fully ballasted configuration during the full-scale test flight. Fully ballasted refers to the same amount of ballast that will be flown during the launch day flight. Additional ballast may not be added without a re-flight of the fullscale launch vehicle.		X			Any ballast intended for use at launch day shall be included in the demonstration flight.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.20.1.7	After successfully completing the full-scale demonstration flight, the launch vehicle or any of its components will not be modified without the concurrence of the NASA Range Safety Officer (RSO).		X			The final full-scale demonstration flight shall be prior to the FRR milestone. Any additional changes deemed necessary shall be identified and communicated to the NASA RSO for confirmation.		X	
2.20.1.8	Proof of a successful flight shall be supplied in the FRR report. Altimeter data output is required to meet this requirement.		X			Altimeter data shall be included in the FRR report.	X		
2.20.1.9	Vehicle Demonstration flights must be completed by the FRR submission deadline. If the Student Launch office determines that a Vehicle Demonstration Re-flight is necessary, then an extension may be granted. Teams completing a required re-flight must submit an FRR Addendum by the FRR Addendum deadline.		X			A demonstration flight will be performed before March 4th. Should a re-flight be needed, an addendum will be submitted by the date given by the Student Launch office.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.20.2	Payload Demonstration Flight - All teams will successfully launch and recover their full-scale rocket containing the completed payload prior to the Payload Demonstration Flight deadline. The following criteria must be met during the Payload Demonstration Flight:		X			Requirements 2.20.2.1 through 2.20.2.4 shall be verified.		X	
2.20.2.1	The payload must be fully retained throughout the entirety of the flight, all retention mechanisms must function as designed, and the retention mechanism must not sustain damage requiring repair			X		The active retention system shall contain the nose cone and all internal components of the UAV payload. Post launch assessment shall be performed to verify that there is no damage to the retention system that would induce additional risks in subsequent launches.	X		
2.20.2.2	The payload flown must be the final, active version.		X			The UAV shall be fully constructed and been through all ground testing prior to the first demonstration flight.		X	

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.20.2.3	If the above criteria is met during the original Vehicle Demonstration Flight, occurring prior to the FRR deadline and the information is included in the FRR package, the additional flight and FRR Addendum are not required.		X			No addendum will be written if all above criteria are met.		X	
2.20.2.4	Payload Demonstration Flights must be completed by the FRR Addendum deadline. No extensions will be granted.		X			All payload demonstration flights shall be completed prior to March 25th, 2019.		X	
2.21	An FRR Addendum will be required for any team completing a Payload Demonstration Flight or NASA required Vehicle Demonstration Re-flight after the submission of the FRR Report.		X			The FRR addendum shall be submitted in the event that the demonstration flight scheduled in Feb. warrants additional testing past the FRR milestone.		X	
2.21.1	2.21.1. Teams required to complete a Vehicle Demonstration Re-Flight and failing to submit the FRR Addendum by the deadline will not be permitted to fly the vehicle at launch week.		X			All documents shall be submitted prior to the milestone deadline.		X	

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.21.2	Teams who successfully complete a Vehicle Demonstration Flight but fail to qualify the payload by satisfactorily completing the Payload Demonstration Flight requirement will not be permitted to fly the payload at launch week		X			The team shall meet all requirements for Payload Demonstration Flight. Payload qualification shall be identified through ground testing and full scale flight.		X	
2.21.3	Teams who complete a Payload Demonstration Flight which is not fully successful may petition the NASA RSO for permission to fly the payload at launch week. Permission will not be granted if the RSO or the Review Panel have any safety concerns.		X			A post launch assessment shall determine if the payload demonstration flight met all mission success criteria. If a not fully successful mission is identified, the petition shall be submitted.		X	
2.22	Any structural protuberance on the rocket will be located aft of the burnout center of gravity.	X				The Air Braking System shall be the only active protuberance on rocket and shall be located aft of the burnout center of gravity.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.23	The team's name and launch day contact information shall be in or on the rocket airframe as well as in or on any section of the vehicle that separates during flight and is not tethered to the main airframe. This information shall be included in a manner that allows the information to be retrieved without the need to open or separate the vehicle.		X			The team shall paint the team name and contact information on the launch vehicle.		X	
2.24	Vehicle Prohibitions		X			Requirements 2.24.1 through 2.24.10 shall be verified.	X		
2.24.1	The launch vehicle will not utilize forward canards. Camera housings will be exempted, provided the team can show that the housing(s) causes minimal aerodynamic effect on the rocket's stability.		X	X		The vehicle design shall include no control surfaces and only fixed fins on the aft section of the vehicle. Camera housing shall be shown in the demonstration flight to have no adverse effects on flight stability	X		
2.24.2	The launch vehicle will not utilize forward firing motors.		X			The vehicle shall utilize a single aft firing motor to generate thrust.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.24.3	The launch vehicle will not utilize motors that expel titanium sponges (Sparky, Skidmark, MetalStorm, etc.)		X			The motors under consideration shall be free of metal expelling sponges.	X		
2.24.4	The launch vehicle will not utilize hybrid motors.		X			The launch vehicle motor shall be a commercially available solid rocket motor.	x		
2.24.5	The launch vehicle will not utilize a cluster of motors.		X			The launch vehicle shall use a single motor.	X		
2.24.6	The launch vehicle will not utilize friction fitting for motors.		X			The launch vehicle shall use a commercially available active motor retention system.	X		
2.24.7	The launch vehicle will not exceed Mach 1 at any point during flight.	X				OpenRocket and RockSim models shall verify that the launch vehicle does not exceed Mach 1 at any point during flight.	X		
2.24.8	Vehicle ballast will not exceed 10% of the total un-ballasted weight of the rocket as it would sit on the pad (i.e. a rocket with and un-ballasted weight of 40 lbs. on the pad may contain a maximum of 4 lbs. of ballast).	X	X			OpenRocket and CAD models shall verify the total un-ballasted weight of the launch vehicle. Ballasted flight shall consist of total ballast weight no more than 10 of the calculated weight.	X		

Vehicle Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
2.24.9	Transmissions from onboard transmitters will not exceed 250 mW of power	X				On board transmitters for GPS location tracking shall be chosen with a power rating <250 mW.	X		
2.24.10	Excessive and/or dense metal will not be utilized in the construction of the vehicle. Use of lightweight metal will be permitted but limited to the amount necessary to ensure structural integrity of the airframe under the expected operating stresses.	X				The launch vehicle shall utilize light weight metal solely where composite materials are unable to support stresses during flight.	X		

6.2.1.3 NASA Recovery Requirements

Recovery Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
3.1	The launch vehicle will stage the deployment of its recovery devices, where a drogue parachute is deployed at apogee and a main parachute is deployed at a lower altitude. Tumble or streamer recovery from apogee to main parachute deployment is also permissible, provided that kinetic energy during drogue-stage descent is reasonable, as deemed by the RSO.			x		The recovery shall be staged to descend under a drogue and a main held together by a chute release. The main chute shall be deployed at 500 ft AGL and the terminal velocity during drogue descent shall be no greater than 100 ft/s.	X		

Recovery Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
3.1.1	The main parachute shall be deployed no lower than 500 feet.		X		x	Vehicle Demonstration launch shall record the acceleration from main deployment begins at an altitude no lower than 500 ft.	X		
3.1.2	The apogee event may contain a delay of no more than 2 seconds		X		X	The recovery system altimeters shall have staggered redundant delays with the first at apogee and the others programmed for 1 and 1.5 seconds after apogee is detected. Altimeter data shall record flight events to further validate the delays.	X		
3.2	Each team must perform a successful ground ejection test for both the drogue and main parachutes. This must be done prior to the initial subscale and full-scale launches.			x		Ground testing of black powder charges shall be conducted with the flight parachutes. Test shall be successful if a single black powder charge separates the airframe and ejects the chutes. This shall be done multiple times prior to launch to determine the necessary amount of black powder.	X		

Recovery Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
3.3	At landing, each independent section of the launch vehicle will have a maximum kinetic energy of 75 ft-lbf.	x				Matlab and Python codes shall be used to model the descent speed of each independent section of the vehicle. These programs shall show that the main parachute is capable of reducing landing kinetic energy to below 75ftlb		x	
3.4	The recovery system electrical circuits will be completely independent of any payload electrical circuits.		x			The recovery system shall be an independent subsystem. All electronics shall be wired independently from payloads and shall share zero connections or signals with payload electronics.	X		
3.5	All recovery electronics will be powered by commercially available batteries.		x			Commercially available 9V batteries shall be used to power recovery components and altimeters.	x		
3.6	The recovery system will contain redundant, commercially available altimeters. The term "altimeters" includes both simple altimeters and more sophisticated flight computers.		x			3 independent Raven3 altimeters shall be used in the recovery subsystem.	x		

Recovery Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
3.7	Motor ejection is not a permissible form of primary or secondary deployment.		x			Primary and secondary deployment shall be attained through black powder detonation to induce launch vehicle separation and a chute release respectively.	x		
3.8	Removable shear pins will be used for both the main parachute compartment and the drogue parachute compartment.		x			Shear pins shall be used to hold the payload and the booster sections together.	X		
3.9	Recovery area will be limited to a 2,500 ft. radius from the launch pads.	x			x	Matlab, OpenRocket, and RockSim shall be used to verify that the drift of the rocket is less than 2500ft for up to 20 mph winds. A test launch shall be performed and GPS location shall show the distance from the launch rail is no greater than 2,500 ft.	x		
3.1	Descent time will be limited to 90 seconds (apogee to touch down).	x			x	Matlab, OpenRocket, and RockSim shall be used to verify that descent time is less than 90s. This will also be verified with altimeter data during a test launch.	x		

Recovery Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
3.11	An electronic tracking device will be installed in the launch vehicle and will transmit the position of the tethered vehicle or any independent section to a ground receiver.		x	x		All parts of the rocket shall be tethered with a nylon shock chord, and a GPS transmitter shall be used to locate the launch vehicle after landing.	X		
3.11.1	Any rocket section or payload component, which lands untethered to the launch vehicle, will contain an active electronic tracking device.		x			The launch vehicle shall consist of two tethered sections which contain all payloads and the tracking device.	X		
3.11.2	The electronic tracking device(s) will be fully functional during the official flight on launch day.			x		Ground testing shall be verified to give the location of the rocket prior to being taken out to the launch pad. Prior to any test flights, the ground testing shall establish the accuracy of the tracking device.	X		

Recovery Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
3.12	The recovery system electronics will not be adversely affected by any other on-board electronic devices during flight (from launch until landing).		x	x		Carbon fiber shield shall be implemented via the carbon fiber body and carbon fiber bulkheads placed around the avionics bay. Demonstration flight and operation of payloads shall verify no signals adversely affect deployment events.	X		
3.12.1	The recovery system altimeters will be physically located in a separate compartment within the vehicle from any other radio frequency transmitting device and/or magnetic wave producing device.		x			Carbon fiber shall be placed around the recovery bay in order to shield it from other on-board electronics.	X		
3.12.2	The recovery system electronics will be shielded from all onboard transmitting devices to avoid inadvertent excitation of the recovery system electronics.		x			Carbon fiber shall be placed around the recovery bay in order to shield it from other on-board electronics.	x		

Recovery Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
3.12.3	The recovery system electronics will be shielded from all onboard devices which may generate magnetic waves (such as generators, solenoid valves, and Tesla coils) to avoid inadvertent excitation of the recovery system.		x			Carbon fiber shall be placed around the recovery bay in order to shield it from other on-board electronics.	x		
3.12.4	The recovery system electronics will be shielded from any other onboard devices which may adversely affect the proper operation of the recovery system electronics.		x			Carbon fiber shall be placed around the recovery bay in order to shield it from other on-board electronics.	x		

6.2.1.4 NASA Payload Requirements

Payload Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
4.4.1.	Teams will design a custom UAV that will deploy from the internal structure of the launch vehicle.		X	X		The team shall perform all analysis and trade studies to construct a unique UAV for the mission. The demonstration flight shall show that the UAV can deploy from the vehicle.	X		

Payload Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
4.4.2	The UAV will be powered off until the rocket has safely landed on the ground and is capable of being powered on remotely after landing.			X		The UAV shall undergo ground testing that demonstrates that deployment mechanism alone is capable of bringing the UAV from a power OFF to a power ON state.	x		
4.4.3.	The UAV will be retained within the vehicle utilizing a fail-safe active retention system. The retention system will be robust enough to retain the UAV if atypical flight forces are experienced.	X		X		Analysis at a maximum predicted load of 30Gs shall be used to size the active retention structural elements. The structural integrity shall be shown in the vehicle demonstration flight by retaining a ballasted UAV payload and all deployment components.	X		
4.4.4.	At landing, and under the supervision of the Remote Deployment Officer, the team will remotely activate a trigger to deploy the UAV from the rocket.		X			The team shall verify that they have permission from the RDO prior to sending any signal to the launch vehicle at the competition and the team mentor at all other launches.	X		

Payload Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
4.4.5.	After deployment and from a position on the ground, the UAV will take off and fly to a NASA specified location, called the Future Excursion Area (FEA). Both autonomous and piloted flight are permissible but all reorientation or unpacking maneuvers must be autonomous.			X		The UAV shall demonstrate autonomous and piloted flight. The deployment shall be triggered soley from a single signal sent by the team.		X	
4.4.6.	The FEA will be approximately 10 ft. x 10 ft. and constructed of a color which stands out against the ground.		X			The team shall verify the size of the FEA on the launch field prior to flight in Alabama at competition.	X		
4.4.7.	One or more FEA's will be located in the recovery area of the launch field. FEA samples will be provided to teams upon acceptance and prior to PDR.		X			The team shall verify that the FEA is delivered to the team.	X		
4.4.8.	Once the UAV has reached the FEA, it will place or drop a simulated navigational beacon on the target area.			X		The UAV shall complete multiple ground test flights carrying the beacon to a predetermined area.		X	

Payload Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
4.4.9.	The simulated navigational beacon will be designed and built by each team and will be a minimum of 1 in W x 1 in H x 1 in D. The school name must be located on the external surface of the beacon.		X			The team shall custom design a 3D printed navigational beacon to be carried by the UAV.	X		
4.4.10.	Teams will ensure the UAV's batteries are sufficiently protected from impact with the ground.		X			The team shall place the battery in the middle of the UAV body to properly shield the battery from any impact.	X		
4.4.11.	The batteries powering the UAV will be brightly colored, clearly marked as a fire hazard, and easily distinguishable from other UAV parts.		X			The team shall verify that all batteries are clearly marked with the appropriate hazard and safety warning.	X		
4.4.12.	The team will abide by all applicable FAA regulations, including the FAA's Special Rule for Model Aircraft (Public Law 112-95 Section 336; see https://www.faa.gov/uas/faqs).		X			The team shall work with the safety committee and mentor to ensure full compliance with FAA regulations. The UAV design team officer shall read the applicable FAA rule.	X		

Payload Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
4.4.13.	Any UAV weighing more than .55 lbs. will be registered with the FAA and the registration number marked on the vehicle.		X			Because the UAV weighs more than 0.55 lbs., the team shall go through the necessary procedures to register the UAV with the FAA as soon as possible.	X		

6.2.1.5 NASA Safety Requirements

Safety Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
5.1	Each team will use a launch and safety checklist. The final checklists will be included in the FRR report and used during the Launch Readiness Review (LRR) and any launch day operations.		X	X		The team shall write and follow launch day checklists for pre-departure, pre-launch, and recovery activities. Launches shall occur only after design leads have signed off on all launch day checklists.	X		
5.2	Each team must identify a student safety officer who will be responsible for all items in section 5.3.		X			The student safety officer shall be listed in the General Information section of the PDR and all stated responsibilities shall be communicated to said officer.	X		

Safety Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
5.3	The role and responsibilities of each safety officer will include, but are not limited to:		X			Responsibilities listed in requirements 5.3.1 through 5.3.4 shall be communicated to the safety officer and all other team officers.	X		
5.3.1	Monitor team activities with an emphasis on Safety during:		X			Responsibility shall be communicated to Safety Officer	X		
5.3.1.1	Design of vehicle and payload		X			"	X		
5.3.1.2	Construction of vehicle and payload		X			"	X		
5.3.1.3	Assembly of vehicle and payload		X			"	X		
5.3.1.4	Ground testing of vehicle and payload		X			"	X		
5.3.1.5	Subscale launch test(s)		X			"	X		
5.3.1.6	Full-scale launch test(s)		X			"	X		
5.3.1.7	Launch day		X			"	X		
5.3.1.8	Recovery activities		X			"	X		
5.3.1.9	STEM Engagement Activities		X			"	X		
5.3.2	Implement procedures developed by the team for construction, assembly, launch, and recovery activities.		X			"	X		
5.3.3	Manage and maintain current revisions of the team's hazard analyses, failure modes analyses, procedures, and MSDS/chemical inventory data.		X			"	X		

Safety Requirements		Verification Method				Verification Plan	Status		
ID#	Description	A	I	D	T		CV	IP	NS
5.3.4	Assist in the writing and development of the team's hazard analyses, failure modes analyses, and procedures.		X			"	X		
5.4	During test flights, teams will abide by the rules and guidance of the local rocketry club's RSO. The allowance of certain vehicle configurations and/or payloads at the NASA Student Launch does not give explicit or implicit authority for teams to fly those vehicle configurations and/or payloads at other club launches. Teams should communicate their intentions to the local club's President or Prefect and RSO before attending any NAR or TRA launch.		X			The team shall work directly with the mentor and Michiana Rocketry club to ensure full compliance with local RSO for launch days. Intentions for launch shall be communicated in advance to the Michiana Club President.	X		
5.5	Teams will abide by all rules set forth by the FAA.		X			The team safety officer shall be aware of all FAA rules for flight at the local launch site. The team shall work with its advisors to further ensure full compliance.	X		

6.2.2 Team Derived Requirements

6.2.2.1 Derived Vehicle Requirements

Derived Vehicle Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
LV2.17-1	Center of Gravity shall be predicted using multiple simulation tools.		X			Models shall be created in CREO, OpenRocket, and RockSim to simulate mass properties.	2.17	Necessary to track mass budget of payload components and verify the stability margin.	x		
LV2.17-2	The Center of Gravity shall be measured prior to launch to within 2 inches of the predicted CG.				x	Prior to any launch, the CG shall be physically measured through balancing the fully loaded rocket on a stand.	2.17	Necessary to ensure that the CG predictions of the launch vehicle are accurate	X		
LV2.19.1-3	Subscale dimensions shall be 40% ± 5% of the projected fullscale dimensions	x				Subscale will be an approximate 40% scale of the fullscale projections. This will be accomplished by sourcing the correct items and designing to this specification	2.19	Necessary to ensure that subscale is an accurate scale and that the drag tabs are capable of creating a measurable effect on apogee.	x		
LV2.20.1.3.2-4	Simulated masses' CG's shall be within 1 inch of the CG of the original mass	x				Payload center of gravity shall be calculated using CREO and shall dictate the location of all payload ballast used during the Vehicle Demonstration Flight.	2.20.1.3.2	Necessary to verify that the simulated mass correctly represents the mass in the vehicle and the test flight provides useful data.	x		
LV2.22-8	The Air Braking System will be located aft of the burnout center of gravity.		X			The aft Center of Gravity shall be calculated using OpenRocket and RockSim and verified to be fore of the Air Braking System.	2.22	Necessary for stability of rocket during flight as the system is also located near the Center of Pressure.	x		

Derived Vehicle Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
LV-1	The transition section shall have a turn angle less than 24 degrees.		X			The length of the transition section shall be determined based off of the turn angle induced on the flow over the airframe.	N/A	Flow separation over a large portion of the circumference of the body induces additional drag and occurs typically at angles greater than 24 degrees.	X		
LV-2	The rail buttons shall be reinforced within the airframe.		X			The buttons shall be screwed into wooden blocks between the motor mount and body tube to add structural integrity.	N/A	The rail button must extend beyond the airframe to accommodate the wider payload bay diameter.	x		

6.2.2.2 Derived Recovery Requirements

Derived Recovery Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
RC3.2-1	The deployment system shall utilize black powder charges no greater than 6 grams each.		X			Ground testing shall be done starting with 3 grams of black powder and progressing in increments of 0.5 grams to identify the optimal amount necessary for parachute ejection.	3.2	Excessive use of black powder induces the risk of structural fatigue and over pressurization of the components.	X		
RC3.3-1.1	The parachute shall be packed in a volume of body tube 6 inches diameter and 30 inches in length.				X	The team shall test multiple packing methods to verify that the chosen parachute can be packed into this volume. This method shall be documented to be used at all launches.	RC-3.3.1	Necessary to standardize parachute packing such that the chute will not get caught during deployment or be too tight for the ejection system to function.	X		

Derived Recovery Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
RC3.4-1	The recovery system shall be a separate assembly from the rest of the launch vehicle		X			The recovery system shall be designed such that it can be removed from the launch vehicle.	3.4	Allows the subsystem to be independence of the launch vehicle to replace components and access altimeter data.	X		
RC3.11-1	A GPS transmitter shall be installed in a section of the rocket containing no EF Opaque materials.		X			The GPS unit shall be placed in the EF transparent nose cone prior to ground testing. The unit shall transmit position to a ground receiver during all test flights.	3.11	This ensures that the position of the launch vehicle is known at very point during flight and assigns responsibility of integrating the GPS unit to the Payload Team.	X		
RC-1	The recovery subsystem, including parachutes and deployment mechanism, shall weigh no more than 190 oz.		X			Component weights shall be approximated in flight simulations until actual mass is measured. Each component shall be weighed during construction to ensure max weight is not exceeded.	N/A	The vehicle design team has allocated maximum mass budgets for each subsystem. This requirement ensures the entire recovery subsystem is within the limits of the launch vehicle.	X		
RC-2	All parachutes and shock chords shall be covered in Nomex cloths prior to being packed in the airframe.		X	X		Nomex cloth shall be placed around the packed chute and sleeves over the shock chords. These shall be assessed for damage after each black powder event to ensure no burn damage is present on recovery components.	N/A	The use of black powder for parachute ejection can cause damage to parachutes and shock chords.	X		

Derived Recovery Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
RC-3	All parachute rigging shall be rated for a factor of safety no less than 2 to ensure sufficient connection between the parachute and airframe.	X				The maximum predicted load on the weakest component of the recovery harness shall be sized to have a factor of safety greater than 2.	N/A	Maximum predicted load is at main chute deployment and presents the highest risk of failure of the system.	X		
RC3.6-1	The main parachute release shall be triggered by a redundant system separate from the flight altimeters.		X			Two independent Jolly-Logic chute releases shall be used in series to fully deploy the main parachute.	3.6	The single point separation dictates that the main chute be tethered together during drogue descent and must separately ensure redundancy in its deployment.	X		

6.2.2.3 Derived Payload Requirements

Derived Payload Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
PL4.4.1-1	The deployment of the UAV shall be divided into Orientation Correction and Linear Translation subsystems.		X	X		The orientation correction shall level the UAV with the ground for multiple landing configurations. The linearly translation system shall separate the nose cone from the airframe and extend the UAV platform such that it clears all external body frames.	4.4.1	The deployment mechanism must be capable of clearing all external components of the rocket so that the UAV can takeoff for any landing conditions.	x		

Derived Payload Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
PL4.4.2.-1	The UAV shall be powered on solely through mechanical translation during the deployment sequence.			X		The linear translation system shall be ground tested to demonstrate that the UAV changes from a power OFF state within the airframe into a power ON state upon fully exiting the airframe.	4.4.2	The UAV must be able to be powered on during deployment.		X	
PL4.4.3.-1	The team shall verify the Locking Mechanism secures the UAV to the deployment platform throughout flight.			X		The team shall simulate flight forces thorugh shake testing to verify the UAV is constrained in all direction in the airframe.	4.4.3	The UAV must be immobile during flight. It is crucial that the Locking Mechanism can properly constrain the UAV to prevent damage.		X	
PL4.4.5-1	The team shall ensure the ability of the UAV to be both remotely piloted and autonomously controlled.			X		The team shall demonstrate stable flight using both FrSky Taranis X9D Plus 2.4 GHz ACCST Radio and DroneKit-Python.	4.4.5	In the event that there is a malfunction with autonomous flight, the UAV must be proven to operate nominally for piloted flight as well.		X	
PL4.4.6.-1	The team shall develop target detection functionality using Python scripts using the OpenCV library.	X		X		The team shall run code on a Raspberry Pi to validate proper target detection. Targets shall be identified using hue, separation value (HSV) color space.	4.4.6	A primary goal of the UAV is to deploy the beacon on the FEA. It is critical that the camera is able to distinguish the FEA and that the script onboard the Raspberry Pi can analyze footage.	X		

Derived Payload Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
PL4.4.7-1	The team shall use DroneKit-Python and the GPS coordinates of the FEA to set target positions to find the closest Future Excursion Area to initially set waypoints for the drone.			X		The team shall generate input data for a simulated FEA location and verify the UAV will create a flight path to that location.	4.4.7	The GPS is not accurate enough to ensure FEA location alone. The UAV must instead go to the general known location of the FEA and create waypoints for autonomous flight while it detects the FEA.	x		
PL-1	The UAV and deployment system shall have a total length not exceeding 14 inches.		x			The UAV airframe and deployment assembly shall be modeled in CREO to verify that the system can be integrated into the Payload Bay body tube.	N/A	The length of the airframe shall not exceed 12 feet and the payload bay must contain 1 caliper of 6 inch body tube.	X		
PL-2	The UAV payload shall be removable from the airframe.		X			The UAV retention system shall be bolted into the airframe to provide access to the electronics and structural components.	N/A	The structural elements must be inspected for fatigue between launches and for integration of all the components. An epoxied component does not allow for the UAV to be accessed in the event of an electrical failure.	x		

6.2.2.4 Derived ABS Requirements

Derived ABS Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
AB2.20.2-1	The Air Braking System shall be the final active version and demonstrate successful activation of the system in flight, meeting mission success criteria.			X		The ABS shall be active in payload demonstration flights. The payload shall demonstrate a reduction in the control flight apogee of the rocket. Recorded apogee and flight data stored on the ABS microSD card shall indicate predicted performance of the system.	2.20.2	The ABS shall qualify as an additional vehicle payload and thus will be subject to payload demonstration requirements.		X	
AB2.24.1-1	The Air Braking System shall increment deployment of all drag tabs simultaneously.			X		The ABS shall demonstrate extending all tabs the same distance beyond the body tube for simulated flight data. The system shall demonstrate predictable response and reliability of the mechanism.	2.24.1	Forward canards are prohibited to prevent attitude control of the rocket. The drag tabs must be verified to all deploy simultaneously to prevent inducing instability through moment imbalances from the additional drag force.	X		
AB-1	The location of the drag tab extensions shall be located within 4 inches of the post burnout center of pressure.	X				The team shall use OpenRocket to locate the post burnout center of pressure and size the body tube to satisfy this constraint.	N/A	Aerodynamic protuberances caused by the drag tabs should be located close to the center of pressure to minimize effects of flight stability.	X		

Derived ABS Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
AB-2	The vehicle shall experience a stable and safe flight with the Drag tabs extended.				X	Subscale flights with a subscale drag tab coupler shall be used to verify preliminary stability. Full scale vehicle tests will verify flight stability.	N/A	The ABS must only impact the trajectory of the vehicle in the vertical direction resulting in a stable flight. Unstable flight presents a safety hazard to the vehicle and team personnel.		X	
AB-3	The ABS shall exhibit autonomous control over the full range of actuation during flight.			X		A single servo motor, once powered on, shall provide continuous control of the mechanism to dictate the actuation of the tabs. The servo shall make decisions autonomously based on data from avionics.	N/A	Continuous and autonomous control is necessary in order to precisely control the induced drag on the vehicle.		X	
AB-4	The ABS shall be integrated into the vehicle as a single removable payload.	X		X		CAD software shall be used to size tolerances for ABS. These dimensions shall be used in construction to demonstrate the final assembly fits within the body tube.	N/A	Designing the ABS as a single removable entity improves the efficiency of the integration strategy and reduces the risk of interfering with integration of other components.	X		

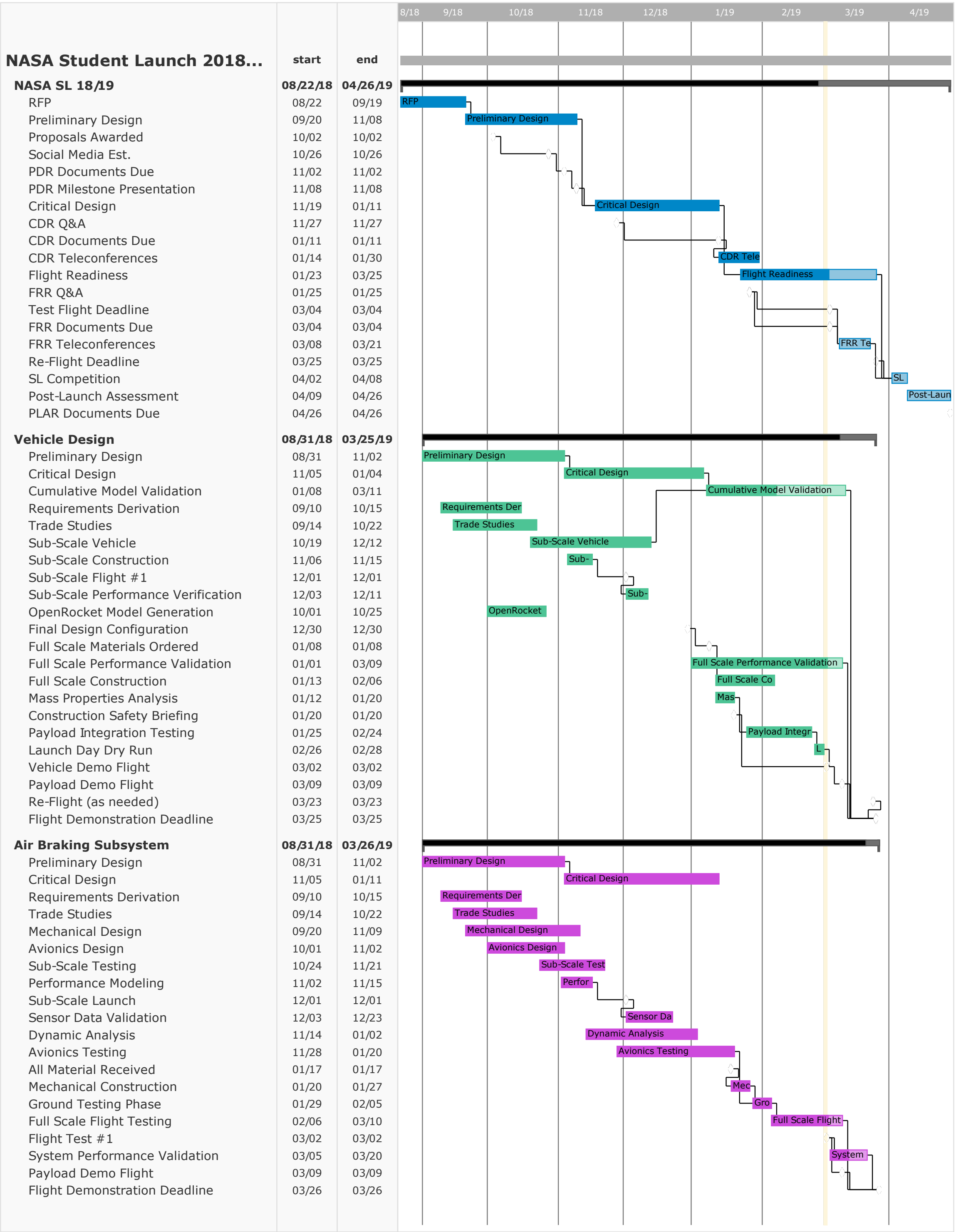
Derived ABS Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
AB-5	The ABS power and arming switches shall be accessible from the external of the vehicle and shall have visible indicators to represent the control state the system is in.		X	X		The designed shall have the power and arming switches available near the barometer pressure hole in the vehicle body. The LED indicators shall be inspected during integration to be both visible and change depending on simulated data being fed to the system.	N/A	The power and arming of all systems in the vehicle must be accessible externally to reduce risk of false triggers. Additionally, the ability to visually confirm the status of the control system through color changing LED's will improve system reliability.	X		
AB-6	ABS Electronics shall be directly soldered to the avionics PCB when possible, and all avionics shall be secured to prevent disconnection during flight.		X			The system shall be inspected before integration to ensure all fasteners and connections are secure. The system shall be subjected to shake tests before flight.	N/A	In order to ensure the continuous control described in Req. AB-2. the avionics system must be secure and reliably connected.	X		
AB-7	The ABS shall be capable of determining the vehicle velocity and altitude within a maximum of ±5.0 m and ±5.0 m/s respectively.				X	The system will record accelerometer and barometer data and pass it through a Kalman filter to reduce noise and calculate altitude and velocity within the given tolerances.	N/A	Accurate measurements are necessary to reliably control the apogee of the vehicle.	X		

Derived ABS Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
AB-8	The ABS shall autonomously actuate its drag tabs and alter the drag of the rocket to achieve an apogee of 4,700 ± 25 ft.				X	The system's actuation shall be ground tested and the successful apogee control shall be demonstrated in vehicle demonstration flights.	N/A	The ABS must operate independent of team personnel on the ground. The ABS must demonstrate successful operation in pursuit of achieving target apogee.		X	
AB-9	The ABS shall be capable of reducing the apogee of the rocket by no less than 200 ft.				X	The vehicle will undergo a control flight with no drag tab extension, and a full braking test with full extension after motor burnout. The difference in apogee between the tests will be used to verify the requirement.	N/A	Considered vehicle motor options project an apogee of approximately 4,900 ft. To achieve the 4,700 ft. target apogee, the ABS must be capable of reducing apogee by 200 ft.		X	
AB-10	The Drag Tabs shall not actuate beyond the mechanical limit of their enclosure.			X		A hollow shaft potentiometer shall be fixed to the shaft to provide positional feedback and ensure the servo motor does not over actuate.	N/A	Damage to the ABS and vehicle may occur if the tabs are over actuated and control of the tabs is lost or the tabs are jammed.	X		

Derived ABS Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
AB-11	The ABS shall contain redundant systems to ensure tabs are retracted in case of system failure.			X		The ABS shall include a hollow shaft potentiometer that will provide positional feedback that will be used to determine if system failure has occurred and the tabs need to be retracted.	N/A	Uncontrolled and unpredictable flight characteristics leading to hazards to the vehicle and personnel are a risk of an ABS system failure if tabs are extended. If possible, the tabs should be set to retract if any form of system failure is detected.	X		
AB-12	ABS electronics shall be capable of being powered on for no less than 3 hours with all systems active.				X	The ABS current draw is derived in the CDR documentation and indicates the system can remain powered for 9 hours with the selected battery. A ground test of the fully assembled ABS shall verify the system can remain powered for 3 hours.	N/A	The ABS must be capable of remaining powered on in the event of an extended waiting period before launch while on the launchpad.	X		
AB-13	The ABS must be capable of logging all raw data and calculated vehicle state data for post-launch review.			X		This requirement will be verified through ground and flight testing.	N/A	Data is necessary to evaluate the successful operation of the ABS as well as perform post-mission analysis to improve the system for future launches.	X		

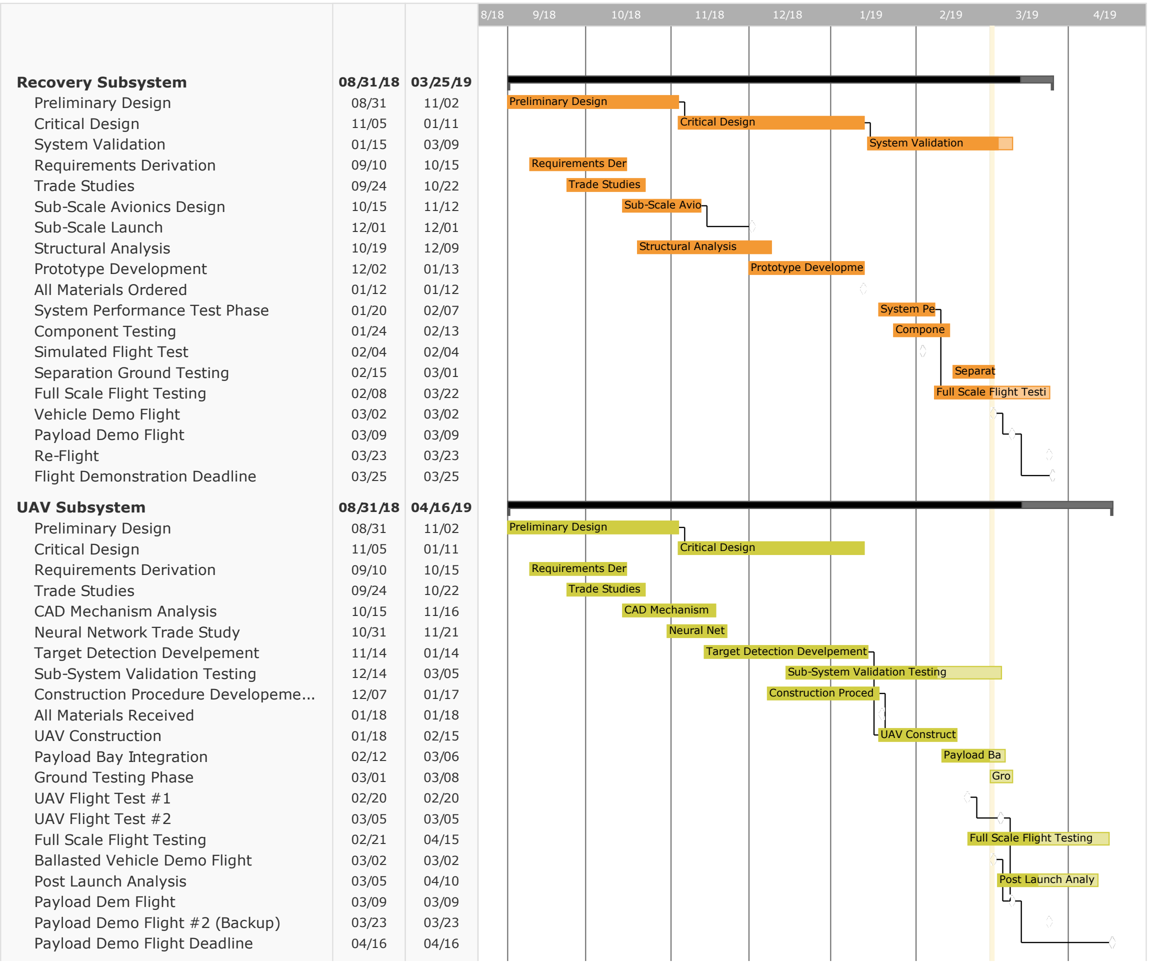
Derived ABS Requirements		Verif. Method				Verification Plan	Parent	Justification	Status		
ID#	Description	A	I	D	T				CV	IP	NS
AB-14	The ABS must be inspected prior to every flight for signs of defects.		X			Pre- and post-flight safety checklists shall be created that require a visual inspection of the system.	N/A	System failure is likely to occur if system defects are not identified. For certain components such as the battery, a defect also poses a hazard to the ABS, vehicle, and team personnel.	X		
AB-15	The ABS components must be capable of surviving flight and landing forces.			X		This requirement will be verified through ground shake testing and flight tests.	N/A	In order to ensure the ABS is reusable the system must be able to withstand flight forces.	X		
AB-16	The ABS avionics module must be sealed section of the airframe.			X		Integration testing of the system shall demonstrate the ABS system is isolated from the slots for the drag tabs.	N/A	To ensure the ABS altimeter does not experience noise spikes, the avionics bay must be pressure sealed with the exception of the vehicle body vent holes.	X		
AB-17	The Drag Tabs must be capable of fully extending in no less than 0.5 seconds.				X	This requirement will be verified through ground testing.	N/A	The ABS must have fast actuation in order to precisely control the drag tabs in the short time frame of the flight.	X		

6.3 Project Timeline



NASA Student Launch 2018...	start	end
NASA SL 18/19	**08/22/18**	**04/26/19**
RFP	08/22	09/19
Preliminary Design	09/20	11/08
Proposals Awarded	10/02	10/02
Social Media Est.	10/26	10/26
PDR Documents Due	11/02	11/02
PDR Milestone Presentation	11/08	11/08
Critical Design	11/19	01/11
CDR Q&A	11/27	11/27
CDR Documents Due	01/11	01/11
CDR Teleconferences	01/14	01/30
Flight Readiness	01/23	03/25
FRR Q&A	01/25	01/25
Test Flight Deadline	03/04	03/04
FRR Documents Due	03/04	03/04
FRR Teleconferences	03/08	03/21
Re-Flight Deadline	03/25	03/25
SL Competition	04/02	04/08
Post-Launch Assessment	04/09	04/26
PLAR Documents Due	04/26	04/26
Vehicle Design	**08/31/18**	**03/25/19**
Preliminary Design	08/31	11/02
Critical Design	11/05	01/04
Cumulative Model Validation	01/08	03/11
Requirements Derivation	09/10	10/15
Trade Studies	09/14	10/22
Sub-Scale Vehicle	10/19	12/12
Sub-Scale Construction	11/06	11/15
Sub-Scale Flight #1	12/01	12/01
Sub-Scale Performance Verification	12/03	12/11
OpenRocket Model Generation	10/01	10/25
Final Design Configuration	12/30	12/30
Full Scale Materials Ordered	01/08	01/08
Full Scale Performance Validation	01/01	03/09
Full Scale Construction	01/13	02/06
Mass Properties Analysis	01/12	01/20
Construction Safety Briefing	01/20	01/20
Payload Integration Testing	01/25	02/24
Launch Day Dry Run	02/26	02/28
Vehicle Demo Flight	03/02	03/02
Payload Demo Flight	03/09	03/09
Re-Flight (as needed)	03/23	03/23
Flight Demonstration Deadline	03/25	03/25
Air Braking Subsystem	**08/31/18**	**03/26/19**
Preliminary Design	08/31	11/02
Critical Design	11/05	01/11
Requirements Derivation	09/10	10/15
Trade Studies	09/14	10/22
Mechanical Design	09/20	11/09
Avionics Design	10/01	11/02
Sub-Scale Testing	10/24	11/21
Performance Modeling	11/02	11/15
Sub-Scale Launch	12/01	12/01
Sensor Data Validation	12/03	12/23
Dynamic Analysis	11/14	01/02
Avionics Testing	11/28	01/20
All Material Received	01/17	01/17
Mechanical Construction	01/20	01/27
Ground Testing Phase	01/29	02/05
Full Scale Flight Testing	02/06	03/10
Flight Test #1	03/02	03/02
System Performance Validation	03/05	03/20
Payload Demo Flight	03/09	03/09
Flight Demonstration Deadline	03/26	03/26

Figure 104: Project Gantt Chart (1 of 2)



Recovery Subsystem	**08/31/18**	**03/25/19**
Preliminary Design	08/31	11/02
Critical Design	11/05	01/11
System Validation	01/15	03/09
Requirements Derivation	09/10	10/15
Trade Studies	09/24	10/22
Sub-Scale Avionics Design	10/15	11/12
Sub-Scale Launch	12/01	12/01
Structural Analysis	10/19	12/09
Prototype Development	12/02	01/13
All Materials Ordered	01/12	01/12
System Performance Test Phase	01/20	02/07
Component Testing	01/24	02/13
Simulated Flight Test	02/04	02/04
Separation Ground Testing	02/15	03/01
Full Scale Flight Testing	02/08	03/22
Vehicle Demo Flight	03/02	03/02
Payload Demo Flight	03/09	03/09
Re-Flight	03/23	03/23
Flight Demonstration Deadline	03/25	03/25
UAV Subsystem	**08/31/18**	**04/16/19**
Preliminary Design	08/31	11/02
Critical Design	11/05	01/11
Requirements Derivation	09/10	10/15
Trade Studies	09/24	10/22
CAD Mechanism Analysis	10/15	11/16
Neural Network Trade Study	10/31	11/21
Target Detection Develepement	11/14	01/14
Sub-System Validation Testing	12/14	03/05
Construction Procedure Developeme...	12/07	01/17
All Materials Received	01/18	01/18
UAV Construction	01/18	02/15
Payload Bay Integration	02/12	03/06
Ground Testing Phase	03/01	03/08
UAV Flight Test #1	02/20	02/20
UAV Flight Test #2	03/05	03/05
Full Scale Flight Testing	02/21	04/15
Ballasted Vehicle Demo Flight	03/02	03/02
Post Launch Analysis	03/05	04/10
Payload Dem Flight	03/09	03/09
Payload Demo Flight #2 (Backup)	03/23	03/23
Payload Demo Flight Deadline	04/16	04/16

Figure 105: Project Gantt Chart (2 of 2)

6.4 Project Budget

The Notre Dame Rocketry Team has budgeted $28,300 for the competition this year. The funding for this project comes from two primary revenue streams. The first is funding directly provided by the University of Notre Dame through club allocation funding for the student chapter of AIAA and departmental funds in the College of Engineering. The primary revenue stream, however, is charitable donations by the NDRT corporate sponsors. This year's sponsors include The Boeing Company, TimkenSteel, and Pratt & Whitney. A breakdown of the funds secured at this point in the competition is given in Table 44.

Table 44: Notre Dame Rocketry Team Funding Sources

Source	Amount
Carryover (2017/18)	$ 2,516.54
The University of Notre Dame	$ 2,500.00
EE Senior Design	$ 500.00
ND Day Fundraising	$ 876.46
The Boeing Company	$ 10,000.00
TimkenSteel	$ 1,000.00
Pratt & Whiney	$ 5,000.00
Northrup Team Stipend	$ 200.00
ND Alumni Donation	$ 2,000.00
ND EE Department	$ 5,000.00
TOTAL	$ **28,593.00**

The current sourced funds total $28,593.00 and are more than sufficient for covering the costs of this year's project. Going forward, the team plans to continue building on its primary revenue stream and increase fundraising to support Research and Development within for the program. The funds raised for the 2018/19 competition have been allocated to each major program area and are given in Table 45. This reflects the allocated amount as well as the funds spent to date towards the vehicle construction and travel accommodations.

Table 45: Budget Allocations

Allocation	Amount	Funds Spent
Vehicle Design	$5,500.00	$4,602.75
Recovery Subsystem	$2,000.00	$1,903.00
UAV Payload	$3,250.00	$2,102.53
Air Braking System	$1,750.00	$1,190.52
Vehicle Subtotal	$**12,500**	**9,798.80**
STEM Engagement	$300.00	$300.00
Competition Travel	$8,000.00	$7,858.00
EE Senior Design Travel	$5,000.00	$5,000.00
Miscellaneous	$500.00	$339.23
Research & Development	$2,000.00	$0.00
TOTAL	$28,300.00	$23,296.03
Total Revenue	$**28,593.00**	$**28,593.00**
Remaining Funds	$**293.00**	$**5,296.97**

The largest expenditures for the team are the overall launch vehicle construction and traveling to competition. This budget allows for an overall project margin of $293.00 with $500 set aside for cost overrun or expedited shipping payments as unseen expenses. This plan also allows for funds to be already secured going into the summer for future development of the program.

The material acquisition plan for the team this year has relied heavily on vendors the team has partnered with in the past, such as Apogee Components. Additional sources for procuring components have been researched to reduce both cost and lead time on materials after being ordered.

A detailed breakdown of the itemized budget organized into allocation categories for the project is shown in Table 46.

Table 46: Itemized Budget

Vehicle Component	Vendor	Description	Qty	Price Per Unit ($)	Total Cost ($)
Subscale Nose Cone	LOC Precision		1	20.74	20.74
Subscale Fore Body Tube	LOC Precision		1	10.44	10.44
Subscale Aft Body Tube	LOC Precision		1	18.26	18.26
Subscale Motor Mount	LOC Precision		1	9.60	9.60
Subscale Motor	Aerotech		1	29.99	29.99
Subscale Tabs	3D Print		1	30.00	30.00
Subscale Fin Plywood	LOC Precision		1	5.00	5.00
Subscale Transition	3D Print		1	20.00	20.00
Subscale Centering Rings (75 - 54mm)	Apogee Rockets		4	7.59	30.36
Subscale Centering Rings (54 - 29mm)	Apogee Rockets		4	10.38	41.52
Subscale Bulkheads (3")	Apogee Rockets		2	3.98	7.96
Subscale Bulkheads (2.16")	Apogee Rockets		2	2.89	5.78
Rail Buttons	Apogee Rockets	1010	1	7.83	7.83
Rail Buttons	Apogee Rockets	1515	1	11.17	11.17
Subscale Coupler ("2.16")	LOC Precision		1	4.35	4.35
RocketPoxy (2 Pint)	Glenmarc		1	43.75	43.75
Rail Button Offsets	3D Prints		2	10.00	20.00
Fiberglass Nose Cone	PML	29" long	1	121.79	121.79
RocketPoxy (2 Pint)	Apogee Components		1	43.75	43.75
Carbon Fiber Body Tube (6")	PML	45", 31", 21"	2	479.95	959.9
Carbon Fiber cutting (60" per tube)	PML	45", 31", 21"	3	6.00	18.00
Phenolic 6" coupler	Apogee	11.75"	1	94.95	94.95
Fin Can Slotting	PML		4	6.00	24.00
Fiberglass Body Tube (7.51")	PML	22"	1	199.99	199.99
Fiberglass Body Tube cutting	PML	48" –> 22"	1	2.50	2.50
Carbon Fiber Sheet (1/8")	RockWest Composites	Fins	1	200.00	200.00
Fin Cutting	Notre DamePhysics Lab		1	60.00	60.00
JBWeld	JBWeld		2	13.79	27.58
ABS Slots	PML		1	50.00	50.00
Fiberglass Motor Centering Rings	Apogee Components	6/3/2019	3	19.95	59.85
Fiberglass Bulkheads	Apogee Components	6"	2	6.89	13.78
Fore Bulkheads	Apogee Components	7.5 - 6	2	13.01	26.02

Motor	Cesaroni / Aerotech		4	290.00	1,160.00
Transition Section	Custom Order		1	200.00	200.00
Screw Pack	Home Depot		1	10.00	10.00
Various Shipping Costs			1	300.00	300.00
RockSim	Apogee		4	20.00	80.00
Motor Mount	PML		1	28.99	28.99
Miscellaneous			1	500.00	500.00
Mobius Action Cam	SpyTec		1	79.95	79.95
Scale	Accuteck		1	24.95	24.95
		TOTAL COST			$ 4,602.75
		Allocation			$ 5,500.00
		Margin			$ 897.25
Recovery System Components	Vendor	Description	Qty	Price per Unit ($)	Total Cost ($)
Parachute	Rocketman Parachutes	Parachute	1	190.00	190.00
Altimeters	Eggtimer	Altimeters	2	35.00	73.00
Garolite Plates	McMaster Carr	Used for Bulkheads	2	44.10	88.20
3D Printing	Notre Dame	ABS Plastic	1	120.00	120.00
PC343-3031-5000-MW-4630-CG-N-IN	McMaster Carr	Spring	8	12.96	133.79
Safety Pins/ Holding rods	McMaster Carr	Aluminum Rods	1	5.48	5.48
Hex nuts, for bulkheads and latch mechanism	McMaster Carr	Hex nuts qty: 100	1	7.58	7.58
Shock Cords	Us Cargo Control	28yd of Shock cords	2	41.52	83.04
Chute Release	Jolly Logic	Chute Release	2	155.94	311.88
Batteries (9V)	Walmart	Batteries	1	18.99	18.99
7.4V 800mAh 30C	GOLDBAT	Altimeter Batteries	2	10.79	21.59
Power HD High Voltage 6.0-7.4V #HD-1235MG	Power HD	Servo Motors	2	42.90	85.80
Eye Bolts	McMaster Carr	Eyebolts for bulkheads	2	6.16	12.31
5/16 In Threaded Link 1760lb Capacity Packaged	Del Cidt	Quick Links	4	3.12	12.48
C-Clamps	Home Depot	C-Clamps	4	16.76	67.06
BACOENG 3 Gallon Vacuum Chamber Kit	BACOENG 3	Vacuum Chamber	1	200.00	200.00
#29128 - 36" Nylon Parachute	Apogee Rockets	Drogue Parachute	1	21.80	21.80
20Ft. Standard Parachute	Rocketman	Main Parachute	1	450.00	450.00
		TOTAL COST			$ 1,903.00
		Budget Allocation			$ 2,000.00
		Margin			$ 97.00
Air Braking System Components	Vendor	Description	Qty	Price Per Unit	Total Cost
Arduino MKR ZERO	Arduino	Microcontroller (Note: 2 extra in excess inventory)	2	21.9	43.8
Adafruit BNO055	Adafruit	Accelerometer & Orientation IMU	1	34.95	34.95
Adafruit LIS3DH	Adafruit	Triple Axis Accelerometer for testing	1	4.95	4.95
Sparkfun MPL3115A2	Sparkfun	Altitude Pressure Breakout Board	1	14.95	14.95
Hollow Shaft Potentiometer (RH32PC R5K L2%)	P3 America, Inc.	Potentiometer for 0.3125" shaft encoding	1	15	15

Hollow Shaft Potentiometer (640ES103A06NAAY)	Online Components	Potetiometer for 0.25" shaft encoding (new)	1	21.5	21.5
Hollow Shaft Potentiometer (640CS103A06NAAY)	Digi-Key	Potentiometer with 180 degree rotation. Replaces "-ES-" model which only gives 90 degrees	1	25.17	25.17
Adafruit LED Sequins Multicolor Pack of 5	Adafruit	LED	2	3.95	7.9
Breakaway 0.1" 2x20pin Strip Dual Male Header	Adafruit	Header Pins for Sensors	3	0.95	2.85
Small PCB Test Points (100 pack)	Adafruit	PCB Test Points	1	9.95	9.95
Small Alligator Clip to Male Jumper Wire Bundle 6 Pieces	Adafruit	Alligator Clip Leads	1	3.95	3.95
Hitech D980TW Servo	Servo City	Servo Motor to drive mechanism shaft	1	169.99	169.99
Spline Servo to Shaft Coupler	Servo City	Shaft coupler	1	12.99	12.99
Oil Embedded Mounted Sleeve Bearing (5912K13)	McMaster-Carr	Bearing for aft section of shaft	1	9.73	9.73
Female Header Pins	NBHP	Female header pins for circuit prototype	1	5.6	5.6
Prototype Circuit Boards	Paxcoo Direct	Prototype solder boards for subscale	1	8.99	8.99
PCB Revision 1	OSH Park	Printed Circuit Board	1	56.5	56.5
PCB Revision 2	OSH Park	Printed Circuit Board	1	73.5	73.5
Tenergy 30C 7.4V 2200 mAh (3-pack)	Tenergy	Battery (Note: 3 pack)	1	36.99	36.99
Tenergy TLP 2000 Universal Charger	Excess Inventory	Battery Charper for Li-Ion or LiPo batteries	1	0	0
Toggle Switch	Excess Inventory	Toggle Switch	2	0	0
Fireproof Battery Case	Colcase	Battery case for safe Li-Po storage	1	12.99	12.99
10 uF Electrolytic Capacitor - Pack of 10	Adafruit	Capacitors for voltage regulation circuit	1	1.95	1.95
5 V voltage regulator	Adafruit	voltage regulator	3	0.75	2.25
HDPE 0.375"x12"x12" Sheet	McMaster-Carr	High Density Polyethylene	1	11.03	11.03
Delrin Sheet 0.5"x12"x12"	McMaster-Carr	Delrin	1	46.71	46.71
Delrin Sheet 0.25"x12"x12"	McMaster-Carr	Delrin	1	30.57	30.57
Delrin Sheet 0.5"x12"x24"	McMaster-Carr	Delrin	1	91.74	91.74
Clear Polycarbonate 0.25"x12"x12"	McMaster-Carr	Polycarbonate for motor and bearing plates	1	15.89	15.89
Steel Threaded Rods	McMaster-Carr	Threaded rods for integration	4	1.04	4.16
Lock Nuts	Excess Inventory	Lock nuts for integration rods	8	0	0
L-6", D-5/16" Drive Shaft (1497K2)	McMaster-Carr	Shaft connecting motor and mechanism	1	11.52	11.52
Machine Key Stock (3/32")	McMaster-Carr	Key stock for connecting keyed shaft to crosspiece. 3/32"	1	1.24	1.24
5/16" lock collar	McMaster-Carr		1	2.2	2.2
5/16" two piece lock collar	McMaster-Carr		2	4.48	8.96
Ball Joint Rod End (60645K78)	McMaster-Carr	Male end of Tie Rod	6	5.81	34.86

Ball Joint Rod End (60645K61)	McMaster-Carr	Female end of Tie Rod	6	5.95	35.7
Steel-Nylon Lock Nuts (pack of 100)	McMaster-Carr	Lock Nut for tie rod	1	2.91	2.91
microSD Card	Excess Inventory	SD card for datalogging	2	0	0
Nylon Screws	McMaster-Carr	Various sized screws for assembly	1	33.91	33.91
Nylon Standoffs	McMaster-Carr	Various sized standoffs for assembly	1	63.6	63.6
M3 screws	McMaster-Carr	M3 Screws	1	5.24	5.24
3D Printed Battery Case	Custom Machined	Case for battery	1	0	0
Molex Connectors	Newark element 14	Molex connectors for PCB	1	13.69	13.69
0.250" bore Spline to Servo Coupler (525150)	Servo City	Servo to Shaft coupler (new after fit issues)	1	4.99	4.99
1/4" bore pillow through block (535110)	Servo City	Bearing for new shaft	1	5.99	5.99
Keyed Shaft, 0.25" Diameter (8488T2)	McMaster-Carr	New shaft	1	20.02	20.02
0.25" two piece lock collars (6436K12)	McMaster-Carr	lock collars for 0.25" shaft	4	4.41	17.64
Rubber Cushioned U bolt	McMaster-Carr	U bolt for forward bulkhead handling	1	5.06	5.06
0.25" lock washers	Digi-Key	100 pack of lock washers	1	9.62	9.62
0.25" flat washers	Digi-Key	100 pack of flat washers	1	10.97	10.97
Shipping Costs + Tax (Total)	Various	Sum of Shipping costs and Misc. Taxes	1	125.85	125.85
		TOTAL COST			1190.52
		Allocation			1750
		Margin			559.48
Payload Components	Vendor	Description	Qty	Price Per Unit ($)	Total Cost ($)
Pixhawk 4 Autopilot and Neo-M8N GPS Combo	GetFPV	Pixhawk 4	1	219.99	219.99
Raspberry Pi 3 Model B	Micro Center	RPi3 B	2	29.99	69.98
Multirotor Carbon Fiber T-Style Propeller 7x2.4 Black (CW/CCW) (2pcs)	Hobbyking	Carbon Fiber Prop	4	4.75	19.00
Lumenier 18A 32bit Silk ESC OPTO (2-4s)	GetFPV	Electronic Speed Controller	6	9.99	68.41
Hobbyking &#8482 Propeller 7x3.8 Black (CW/CCW) (2pcs)	Hobbyking	Plastic Prop	5	2.55	12.75
Adapter Rings (E)	APC Propellers	Thin Electric Adapter Rings	1	2.49	5.83
T-Motor MN1806 KV1400	T-MOTOR	Motor	6	25.90	155.40
Turnigy o-tech 4500mAh 3S 35 70C Lipo Pack w/XT-90	Hobbyking	Battery	2	40.25	80.50
500mW Transceiver Telemetry Radio Set V3 433 MHZ	Holybro	500mW Telemetry Set 433MHz	2	45.00	118.60
Raspberry Pi Camera Board v2 - 8 Megapixels	Adafruit Industries	Raspberry Pi Camera	1	29.95	42.51
Carbon Fiber Tube 0.25 X 0.32 X 60 INCH	Rock West Composites	Carbon fiber tubes for deployment	2	39.99	131.63

Nylon Threaded Rod 5/8"-11 Thread Size, 6ft Long	McMaster Carr	Leadscrew	1	51.56	83.81
FEETECH FS90R (2 Pack) - 360° Rotation | Continuous Rotation Robotic Servo	FEETECH	Beacon Servo for Delivery	1	10.95	10.95
MDS-Filled Cast Nylon Sheets	McMaster Carr	Fore and aft bulkhead assemblies	1	351.37	386.76
Nema 14 Stepper Motor 0.9deg 0.4A 11Ncm/15.6oz.	STEPPERONLINE	Stepper Motor for Linear, Translational Motion (Deployment)	1	19.90	19.90
Continuous Rotation 360 Degree Ball Bearing Servo Arduino	FEETECH	Servo Motor for Rotational Motion (Deployment)	1	17.95	17.95
Nylon Hex Nut 5/8"-11 Thread Size	McMaster Carr	Hex nuts for leadscrew	1	11.24	11.24
Duracell Coppertop A23 Alkaline 12V Batteries	Amazon	Battery for Deployment	2	7.45	14.45
9-DOF Absolute Orientation IMU BNO055	Adafruit	Sensor for Orientation Correction	1	34.95	48.27
Flange Supports for Carbon Fiber Tubes	In House	Placed on Back Bulkhead to Help Stabilize Deployment	2	0.00	0.00
Yellow Tarp 3.3 OZ, 12’x20’	Harpster Tarps	Practice FEA	1	22.99	22.99
MT60 Connectors	WST	10 Pairs MT60 3.5mm 3-wire 3-pole Bullet Connector Plug Set for RC ESC to Motor 10 Male Connectors & 10 Female Connectors	1	13.99	13.99
XT60 Bullet Connectors	LHI	LHI XT-60 XT60 Male Female Bullet Connectors Plugs for RC Lipo Battery	1	8.45	8.45
XT90 Connectors	WOAFLY	LHI XT90 Battery Connector Set for RC Lipo Battery Motor 6 Pairs Yellow,6 Male Connectors + 6 Female Connectors	1	9.89	9.89
Adafruit USB Cable	Adafruit	Power Cable for Arduino Board	1	5.65	5.65
Torsion Spring, 270 Degree Angle, Left-Hand Wound, 0.805" OD, Packs of 6	McMaster Carr	Torsion Spring	1	11.87	15.49
Torsion Spring, 270 Degree Angle, Left-Hand Wound, 0.600" OD, Packs of 6	McMaster Carr	Torsion Spring	1	8.91	12.53
MXL Series Lightweight Timing Belt Pulley, 0.63" OD	McMaster Carr	Pulley	5	35.75	39.37
Torsion Spring, 225 Degree Angle, Left-Hand Wound, 0.556" OD	McMaster Carr	Torsion spring for arm unfolding	1	7.91	7.91
Torsion Spring, 225 Degree Angle, Left-Hand Wound, 0.461" OD	McMaster Carr	Torsion spring for arm unfolding	1	7.54	7.54
5.8GHz 40CH FPV Wireless AV Video Receiver	Amazon	Receiver	1	20.99	20.99

FPV Transmitter EACHINE 5.8GHz 72CH Switchable Transmission	Amazon	Transmitter	1	22.99	22.99
Video Audio Capture Card Device Adapter VHS/VCR/TV to DVD Converter	Amazon	Converter support	1	15.05	15.05
LM2937ET-10/NOPB Low Voltage Regulator	Mouser Electronics	Regulator	2	12.14	12.14
LanLan 5Pcs 23A/A23 Battery (12V) Clip Holder Box Case Black	Amazon	Holder	1	7.99	7.99
Female Threaded Round Standoff, 1-1/4" Long, 1/4" OD, 8-32 Thread Size	McMaster Carr	Standoffs for struts	4	1.23	6.42
Aluminum Threaded Rod, 2" Long, 8-32 Thread Size	McMaster Carr	Threaded rods for struts	1	17.24	18.74
Aluminum Hex Nut, 8-32 Thread Size	McMaster Carr	Nuts for struts	1	4.44	5.94
Female Threaded Round Standoff, 1/2" Long, 1/2" OD, 10-32 Thread Size	McMaster Carr	Standoffs for struts	4	0.81	4.74
Passivated 18-8 Stainless Steel Pan Head Phllips Screw, 10-32 Thread Size	McMaster Carr	Screws for drone	1	8.90	10.40
Aluminum Threaded Rod, 1" Long, 8-32 Thread Size	McMaster Carr	Threaded rods for struts	1	12.30	13.80
Hook and Loop Cable Ties, 13" Overall Length	McMaster Carr	Velcro straps	1	11.33	12.83
Torsion Spring, 225 Degree Angle, Right-Hand Wound, 0.556" OD	McMaster Carr	Torsion spring for arm unfolding	1	7.91	9.41
FrSky Taranis Compatible Receiver X8R 8-Channel 2.4 GHz	Amazon	Receiver	1	35.97	35.97
DC/DC Converter - 5V 5W	SparkFun Electronics	Servo regulator	1	4.95	4.95
EasyDriver - Stepper Motor Driver	SparkFun Electronics	Stepper motor driver	1	14.95	30.56
LDO Voltage Regulators	Mouser Electronics	Regulator	1	1.55	10.21
Bolts and nuts for Securing Tracks Together (16 pairs)	In House	Secure tracks together around rotating bulkhead	16	0.00	0.00
Bolts for Securing Aft Bulkhead/Tracks Inside Rocket	In House	Secure aft tracks to inside of rocket	8	0.00	0.00
Eyebolts	In House	Eyebolts for Locking Mechanism	4	0.00	0.00
Braided Fishing Line	In House	Wire for Locking Mechanism	1	1.00	0.00
Non-Isolated DC/DC Converters 36-V, 1-A Step-Down DC-DC	Mouser Electronics	10V 1A regulator	1	6.43	15.43
Black Socket Head Screw, M2 x 0.4 mm Thread, 10 mm Long	McMaster Carr	Longer M2 screws	1	11.55	19.23
Aluminum Decorative Round Head Slotted Screws	McMaster Carr	Screws for drone	1	12.22	16.06
Aluminum Nylon-Insert Locknut	McMaster Carr	Locknuts	1	3.67	7.51
E-flite 800mAh 3S 11.1V 30C LiPo 18AWG JST Battery	Amazon	Battery for Deployment	1	30.65	32.80
Ximimark 433MHz ASK Transmitter/Receiver Module Kit STX882+SRX882	Amazon	Transmitter/receiver pair for deployment	1	7.59	7.59

ARDUINO MKR Zero (with HEADERS)	Amazon	Arduino for deployment	1	24.09	24.09
Aluminum coupler (leadscrew-shaft)	In House	Coupler piece for gear motor shaft & leadscrew connection	1	0.00	0.00
Aluminum coupler (bulkhead-gear motor)	In House	Coupler piece for gear motor & bulkhead connection	1	0.00	0.00
Actobotic Gear Motor 116 RPM	Amazon	Gear motor to drive leadscrew rotation	1	74.99	74.99
		TOTAL COST			$ 2,102.53
		Allocation			$ 3,250.00
		Margin			$ 1,147.47
STEM Engagement Items	Vendor	Description	Qty	Price Per Unit	Total Cost ($)
Estes Viking Rockets (12 pack)	Estes Rockets	Model rockets	1	79.99	79.99
A8-5 Engines	Estes Rockets	Engines for remaing Estes Alpha Rockets	2	10.29	20.58
Miscellaneous Materials	N/A	Smaller items for activities	1	199.43	199.43
		TOTAL COST			$ 300.00
		Allocation			$ 300.00
		Margin			$ 0.00

A Safety

A.1 Project Risks

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Timeline	Insufficient planning or scheduling; failure to hold individual members accountable for responsibilities.	Falling behind schedule for construction or documentation; missing NASA deadlines.	3D	1. Trello, Overleaf, and Slack will be used to ensure team and squad coordination in writing, testing, and construction. 2. In the event that the team falls behind, members will put in extra work until the team is back on schedule. 3. Leads will hold their members, and each other, accountable to deadlines.	1. All NASA document submission dates will be met. 2. The subscale rocket will be ready to fly by the subscale date. 3. The subscale rocket will provide useful scaled information for all squads.	3C
Budget	Insufficient planning or frugality of material purchases; insufficient annual team funding or sponsorship.	Inability to purchase materials or cover transportation costs; depleting team account or taking on debt.	2D	1. All material costs will be determined prior to construction. 2. Travel/transportation costs will be planned out. 3. The team will pursue additional sources of funding when necessary.	1. The team's yearly costs will be less than the team's yearly funds. 2. A running sum of all costs and funds up to the present day for that academic year is being kept. 3. The total costs incurred by the squads will stay within their respective allotted budgets.	2C
Personnel	Team members quitting the team.	That team member's responsibilities will go unfulfilled.	1D	In the event that a team member quits, their responsibilities will be spread among other members.	The squad lead of the departed member will reassign construction and testing responsibilities.	1D
Equipment and Facilities	Improper tool use; lack of experience with tools or surrounding facility.	Physical injury to personnel; denial of access to facilities and tools.	2C	1. Every team member will have proper knowledge and training of required tools. 2. A safety committee member will always be present in the workshop during build sessions. 3. Personal protective equipment will always be used.	1. Every member will be checked off for basic safety and tool training. 2. Personal protective equipment will be provided in every construction space.	2C
Launch	Improper launch procedures; defective launch components such as igniters or motors.	Catastrophe at takeoff; failure to launch; excessively horizontal launch angle.	4B	1. Rocket will be thoroughly inspected before launch. 2. All launch checklists and procedures will be carried out. 3. The team mentor, David Brunsting, will assist the team at every launch.	1. Launch checklists will be created and reviewed. 2. Each squad will develop a proper procedure for inspecting and clearing their system for launch.	4B

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Recovery	Premature recovery system activation; no recovery system activation.	Damage to the rocket and its systems; physical injury to personnel; damage to private property.	3C	1. The recovery squad will ensure that the recovery system functions properly through construction, testing, and launch. 2. On launch days, the recovery checklists will be carried out. 3. Recovery functionality will be verified at a full-scale test launch.	1. Recovery will verify a > 90% success rate for deploying the parachute through testing. 2. Recovery will develop a proper procedure for inspecting, arming, and clearing their system for launch.	3A
UAV	Insufficient securing during flight.	Induced spin or tilt on rocket flight.	3B	1. The UAV squad will ensure that their system functions properly through construction, testing, and launch. 2. On launch days, the UAV and checklist will be carried out. 3. UAV functionality will be verified at a full-scale test launch.	1. UAV will verify a > 90% success rate for remaining secure during flight. 2. UAV will verify a > 90% success rate for success deployment and flight of the vehicle. 3. UAV will develop a proper procedure for inspecting, arming, and clearing their system for launch.	3A
ABS	Unbalanced forces on rocket; insufficient securing during flight.	Induced spin or tilt on rocket flight; failure to hit precise apogee.	3B	1. The ABS squad will ensure that their system functions properly through construction, testing, and launch. 2. On launch days, the ABS checklist will be carried out. 3. ABS functionality will be verified at a full-scale test launch.	1. ABS will verify a > 90% success rate for remaining secure during flight. 2. ABS will verify a > 95% chance of no structural failure of their system, especially relating to the drag tabs or the load-bearing rods. 3. ABS will develop a proper procedure for inspecting, arming, and clearing their system for launch.	3A
Resources	Failure of suppliers to provide materials; insufficient planning or communication of required materials, equipment, and facilities.	Inability to construct rocket or its systems; construction of rocket or its systems with suboptimal material; time delay in waiting for required facility access.	2C	1. Each squad will outline necessary materials, equipment, and facilities prior to construction. 2. Year-long budget and spending plans will be implemented.	1. Each lead has submitted a list of materials to the safety officer. 2. A running list of purchases of materials by individuals squads will be kept.	2C

A.2 Personnel Hazards

A.2.1 Construction Hazards

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Direct contact with strong adhesive, such as epoxy	Failure to use/improper use of gloves when working with adhesives	Skin irritation, possible allergic reaction	2C	1. Nitrile gloves are available and required for any team member working with adhesives such as epoxy.	1. Procedures for using epoxy have been created and are enforced during any construction or repair operations.	2A
Contact with the spinning bit of a portable drill	Improper use of a portable drill	Cut or burn to the area of contact	2B	1. Team personnel must be certified to use a power drill before using one during construction.	1. The machine shop certification process involves the signing of a safety rules form and a quiz to ensure that the team members know how to properly use a tool before using one during construction.	2A
Contact with the spinning bit of a dremel	Improper use of a dremel	Cut or burns to the area of contact	2B	1. Team personnel must be certified to use a dremel before using one during construction.	1. The machine shop certification process involves the signing of a safety rules form and a quiz to ensure that the team members know how to properly use a tool before using one during construction.	2A
Contact with the sanding surface of a belt/disk sanding machine	Improper use of a belt/disk sanding machine	Sanding burns and cuts to the area of contact	3B	1. Team personnel must be certified to use the belt/disk sanding machine before using one during construction.	1. The tool certification process for the Belt/Disk sanding machine involves signing a safety rules from, passing a quiz on proper operation of the machine, and demonstrating competency with the machine to Notre Dame machine shop personnel.	3A
Projectiles/ Shrapnel in the eyes	Use of power tools, such as dremels, drills, or sanding machines without safety glasses	Potentially serious eye damage	3B	1. Safety glasses shall be worn at all times when any machines or power tools are being used in the shop.	1. Safety glasses are available on a shelf just outside the machine shop. 2. Before being allowed to participate in construction, team members must be certified to do so. The machine shop certification process involves signing a safety rules form and passing a safety quiz on general shop rules, such as the use of safety glasses.	3A
Dust inhalation	Sanding or cutting material without proper ventilation and/or respiratory protection.	Lung and sinus irritation of inflammation. Potentially serious long-term effects.	3C	1. A shop vac must be attached to the debris duct of any dust-producing machine when in operation. 2. A dust mask must be worn at all times when performing an action that produces dust, such as sanding or cutting of raw materials.	1. Dust masks are available to team members in the workshop. 2. Team members must be certified on a machine to work with the machine. The tool certification process involves passing a quiz on safe operation and, in the case of the belt/disk sander, demonstrating competency with the machine.	3A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Contact with spinning blade of a miter saw	Lack of attention while cutting with a miter saw.	Serious cuts	4B	1. Personnel must be certified to use a miter saw before using one during construction.	1. The tool certification process for the miter saw involves signing a safety rules from, passing a quiz on proper operation of the machine, and demonstrating competency with the machine to Notre Dame machine shop personnel.	4A

A.2.2 Testing Hazards

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Electrical shock from battery or capacitor.	Electrical component discharges while personnel are touching the leads.	Potential for serious injury to personnel	3B	1. All electrical circuits must be deactivated before modification. 2. The voltage across any circuit element to be modified should be measured using a multimeter before modification.	1. Procedures for electrical system testing have been created and are strictly enforced. 2. Multimeters are available in the workshop and senior design lab for use during electrical system testing.	3A
Personnel exposure to harmful chemicals or chemical fire	Contact with broken or exploded batteries.	Chemical fire burns or skin irritation	3B	1. New batteries were purchased and used in construction of the electrical systems. 2. Personnel must use gloves when handling batteries, to prevent chemical burns from punctured batteries. 3. Batteries must be protected from overcharging or overdischarging. 4. Batteries must be kept in fireproof battery bag when charging or not in use.	1. Safety and reliability were primary drivers when selecting batteries. These batteries are known to be in new condition and were purchased from a reputable retailer. 2. Gloves are available in the workshop and at any outside test sites for use when handling batteries. 3. Batteries are only used in conjunction with power controllers and only charged in conjunction with protective charging circuits. 4. Fireproof bags, specifically intended for large lithium-polymer batteries, are available to the team and are used during storage and charging of batteries. 5. Procedures for electrical system testing have been written and are strictly enforced.	3A
Overheated electronics cause fire	Battery, servo motor or other electronic device receives more current than it was designed to.	Battery, servo or other electronic device overheats and causes burns or fire.	3B	1. Microcontrollers and power distribution boards should be used to prevent sensitive electronics from drawing or providing more current than they were designed. 2. All motors and electronics should be chosen such that the maximum current draw is less than the maximum current that the powering batteries can provide.	1. Power controllers on both the UAV payload and ABS subsystem, as well as an on-board voltage regulator on the recovery altimeters, prevent overdrawing from the powering batteries. 2. UAV batteries, ABS batteries, and recovery batteries have all been sized so as to be capable of providing more current than the associated motors and other electronics draw at max load.	3A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
UAV flies into personnel during testing.	UAV testing performed in close proximity to crowds of personnel.	Flying UAV could strike personnel, causing injury.	3B	All UAV testing must be done in an open area with adequate room for the UAV to fly away from personnel.	A drone field near campus was used for initial flight testing of the UAV. Full testing of the UAV was done at a rocket launch site.	3A
Personnel exposed to ignited e-match	Personnel is in close proximity to e-match during e-match altimeter testing.	Potential for burns to personnel.	3B	1. The minimum possible number of people should be in the vicinity when testing e-matches. 2. Personnel that must be in the vicinity of the e-match to perform the test must be wearing heat-resistant gloves and safety glasses. 3. Proper procedure for carrying out an e-match test must be followed at all times.	1. E-match tests were performed by one person, the minimum number of personnel needed in accordance with the testing procedures. 2. Heat resistant gloves and safety glasses are available to personnel at the test site for use during e-match testing. 3. Procedure for e-match testing was written and enforced during testing.	3A
Personnel receives burns during black powder ground test.	1. Personnel in close proximity to rocket during black powder ground testing. 2. Premature ignition of black powder charge while preparing for black powder ground testing.	Potential for serious burns or other injuries to personnel.	4B	1. Leads to the black powder charge must be shunted when not actively in use to prevent premature ignition. 2. Black powder charges shall only be prepared by the team mentor. 3. A minimum number of personnel should be used to prepare the black powder test. 4. Procedures for black powder ground testing must be followed as written.	1. Until just before the ground test, the two leads of the black powder charge were twisted together to prevent a potential difference from forming across them, in accordance with the procedures. 2. The team mentor, Dave Brunsting, prepared the black powder charges used during black powder ground testing, in accordance with the procedures. 3. After the black powder charge was installed in the charge well, only the team mentor was allowed access to the rocket. One person was the minimum number of personnel capable of perfroming a black powder ground test.	4A

A.2.3 Launch Hazards

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Rocket launches at a large angle with the vertical	1. The rocket is unstable or overstable. 2. The launch rail is set up incorrectly.	1. The rocket could launch into the crowd, potentially causing severe injury 2. The rocket could drift outside the launch radius, causing property damage or injury to bystanders	4B	1. All launches have are performed in accordance with NAR guidelines on proper rail setup and launch angle 2. RSO recommendations for launch angle and rail setup are followed 3. The rocket has been constructed to have a static stability of between 2 and 2.8.	1. The team mentor, a Tripoli member and level 2 HPR certified, was present for the first test launch, and gave recommendations for launch rail setup and proper launch rail angle. He will be present for all future launches. 2. Section A.7.2.7 details procedures for placing the rocket on the rail and raising it to the pad. 3. The center of gravity of the rocket is measured before every launch to confirm that the static stability of the rocket meets the requirements, as per Section A.7.2.5 of the launch procedures. The static stability was found to be 2.37, which is within the required stability margin.	4A
Motor failure during launch	1. Motor dropped or incorrectly assembled 2. Motor igniter incorrectly installed in the motor	Potential for explosion that could cause injury to team personnel and bystanders. Possible inhalation of toxic fumes by team personnel or bystanders.	4B	1. NFPA minimum distance tables are be enforced during all launches of the rocket. 2. Team mentor, David Brunsting, is the only person to handle and insert the rocket motor. Dave has level 2 High Power Rocketry certification through Tripoli Rocket Association. 3. The motor and igniter are be visually inspected prior to every launch.	1. Team mentor, Dave Brunsting, inspects all motors and igniters to be used by NDRT in accordance with Section A.7.2.6 of the launch procedures. 2. The team uses a Cesaroni L1395 motor, a reliable commercial motor sold by a reputable vendor. 3. Team mentor Dave Brunsting will assemble and install all motors used by NDRT, in accordance with Section A.7.2.6 in the launch procedures.	4A
Personnel hit by rocket falling in ballistic trajectory	1. Failure of altimeter to ignite black powder charge 2. Failure of black powder charge to separate the rocket at apogee. 3. In-flight disconnection of the altimeter-powering batteries.	Potential for death or severe injury to personnel if hit by falling rocket	4B	1. All recovery electronics are designed in such a way that the failure of one piece of the system will not compromise the system's ability to separate the rocket. 2. All recovery electronics have been tested to confirm that they are capable of properly igniting the e-matches. 3. The black powder charges are sized such that they are capable of separating the rocket. 4. Black powder ground tests have been performed to confirm the sizing of the black powder charges. 5. Any batteries to be used for launch are fully charged or new.	1. The recovery system features three independent altimeter-battery-ejection charge systems, with any of the three redundant altimeters capable of fully separating the rocket. 2. Through e-match-altimeter tests, the altimeter-battery combination was found to be capable of igniting an e-match at the proper time. 3. Black powder ground tests confirmed that 5 grams of black powder is enough to fully separate the rocket. 4. Section A.7.3.2 of the launch procedures includes checking the charge of the recovery batteries during the Pre-Departure Inspection of the recovery system.	4A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Personnel hit by rocket falling at higher than intended speeds	1. Failure of the Chute Releases to allow the parachute to open during rocket descent 2. Improper folding of the parachute during assembly	Potential for severe injury to personnel if hit by rocket	4B	1. The Chute Releases are set up in such a way that failure of one Chute Release will not impact the recovery of the rocket 2. The parachute is folded in a consistent way that will allow it to easily open after the Chute Release as stopped restraining the parachute	1. Two Chute Releases are used in series around the main parachute, such that either Chute Release can successfully untether the parachute. 2. The Chute Releases have been tested using the inbuilt Chute Release testing program. They have been found to be successful at quickly releasing the parachute. 3. The Chute Releases were found to release at the intended altitude during the full-scale flight. 4. Section A.7.3.3 of the launch procedures details the parachute folding process that will be used for all parachutes in the rocket.	4A
Personnel hit by rocket falling at intended speeds	Improper conduct during a launch	Potential for serious injury to personnel if hit by falling rocket	3C	1. All participants in launch procedures must demonstrate knowledge of the hazards and safety procedures associated with a launch.	1. Participants in launch proceedings are required to sit through a launch safety briefing and be required to pass a quiz on launch safety before they will be allowed on the launch site	3A
Premature ignition of motor	1. Motor or motor igniter incorrectly handled 2. Ignition wires have live voltage during igniter instillation	Potential for burns to personnel installing motor igniter	3B	1. The team mentor is the only one who handles and inserts the motor igniter. 2. The motor and igniter are be visually inspected prior to launch.	1. Section A.7.2.8 of the launch procedures dictate that the team mentor is the only person who is to handle and install the rocket motor or igniter. 2. Section A.7.2.8 of the launch procedures call for checking the ignition wires for live voltage prior to igniter instillation, to prevent premature ignition on the pad.	3A

A.2.4 Recovery Hazards

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Personnel burned by premature black powder ignition.	1. Improper handling of black powder charges or the rocket with live powder charges in it. 2. Unintentional voltage difference comes across the leads of a live black powder charge	Potential for serious burns or other injury to personnel.	3B	1. When not in active use, the leads to the black powder charge are be shunted together. 2. The batteries that power the altimeters are be turned off until the rocket is vertical on the launchpad.	1. Section 3.3.3.2 details procedures for ground testing of the recovery system. These procedures were followed as written during the tests. 2. Section A.7.3.7 of the launch procedures states that the recovery system must be unpowered until the rocket is vertical on the launchpad. These procedures were followed as written during the Vehicle Demosntration Flight.	3A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Personnel hit by rocket falling in ballistic trajectory	1. Failure of altimeter to ignite black powder charge 2. Failure of black powder charge to separate the rocket at apogee. 3. In-flight disconnection of the altimeter-powering batteries.	Potential for death or severe injury to personnel if hit by falling rocket	4B	1. All recovery electronics are designed in such a way that the failure of one piece of the system will not compromise the system's ability to separate the rocket. 2. All recovery electronics have been tested to confirm that they are capable of properly igniting the e-matches. 3. The black powder charges are sized such that they are capable of separating the rocket. 4. Black powder ground tests have been performed to confirm the sizing of the black powder charges. 5. Any batteries to be used for launch are fully charged or new.	1. The recovery system features three independent altimeter-battery-ejection charge systems, with any of the three redundant altimeters capable of fully separating the rocket. 2. Through e-match-altimeter tests, the altimeter-battery combination was found to be capable of igniting an e-match at the proper time. 3. Black powder ground tests confirmed that 5 grams of black powder is enough to fully separate the rocket. 4. Section A.7.3.2 of the launch procedures includes checking the charge of the recovery batteries during the Pre-Departure Inspection of the recovery system.	4A
Personnel hit by rocket falling at higher than intended speeds	1. Failure of the Chute Releases to allow the parachute to open during rocket descent 2. Improper folding of the parachute during assembly	Potential for severe injury to personnel if hit by rocket	4B	1. The Chute Releases are set up in such a way that failure of one Chute Release will not impact the recovery of the rocket 2. The parachute is folded in a consistent way that will allow it to easily open after the Chute Release as stopped restraining the parachute	1. Two Chute Releases are used in series around the main parachute, such that either Chute Release can successfully untether the parachute. 2. The Chute Releases have been tested using the inbuilt Chute Release testing program. They have been found to be successful at quickly releasing the parachute. 3. The Chute Releases were found to release at the intended altitude during the full-scale flight. 4. Section A.7.3.3 of the launch procedures details the parachute folding process that will be used for all parachutes in the rocket.	4A
Personnel hit by rocket falling at intended speeds	Improper conduct during a launch	Potential for serious injury to personnel if hit by falling rocket	3C	1. All participants in launch procedures must demonstrate knowledge of the hazards and safety procedures associated with a launch.	1. Participants in launch proceedings are required to sit through a launch safety briefing and be required to pass a quiz on launch safety before they will be allowed on the launch site	3A

A.2.5 Unmanned Aerial Vehicle Hazards

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Personnel exposure to harmful chemicals or chemical fire	Contact with broken or exploded batteries	Chemical fire burns burns, or skin irritation	3B	1. New batteries have been purchased and have been used in construction of the UAV. 2. Personnel wear latex gloves while handling batteries. 3. Batteries are protected from overcharging or overdischarging.	1. New batteries have a significantly decreased chance of breaking or exploding. 2. Latex gloves can reduce the severity of, or prevent entirely, a chemical burn. 3. Protective charging circuits are used when charging the UAV batteries that protect the batteries from overcharging. 4. Commercial power controllers are used on the UAV to prevent the motors from drawing more current that the batteries can provide.	3A
Personnel struck by falling UAV	UAV separated from housing during flight	Death or severe personnel injury	4C	1. UAV is fastened in the rocket be fastened using 0.25” diameter stainless steel hairpin cotter pins. 2. UAV housing is attached to the rocket via a double thickness bulkhead. 3. Nose cone is be secured to the rocket body by a locked lead screw.	1. Increased thickness of cotter pins, and the material choice significantly increase the failure shear load of the pin. 2. A double thickness bulkhead is far less likely to fracture and detach from the body tube or the connection to the UAV housing. 3. In the event of the UAV separating from housing, a locked nose cone will likely contain the loose UAV, preventing it from leaving the body tube.	4A
Personnel cut by propeller blades	Interacting with UAV with propellers spinning	Personnel injury	2C	Personnel do not interact with UAV while the UAV is powered on	Per safety procedures, the UAV batteries are fully disconnected when personnel are interacting with the UAV.	2A
Personnel struck by flying UAV	1. Excessive wind during test flight. 2. Improper flying of the UAV during testing.	Personnel injury	4B	1. The UAV is not to be flown when the wind is above 20 mph. 2. The UAV is only to be flown by designated personnel who are trained to do so.	1. If winds are over 20 mph, the UAV is to be be disabled and removed manually, as outlined in launch procedures. 2. The UAV is only be flown by a specific team member who has past experience in flying recreational UAVs.	4A
Personnel injured by exposed wires	Propellers cut wires, exposing loose wires.	Personnel injury	3C	Personnel do not interact with UAV while the UAV is powered on.	Per safety procedures, the UAV batteries are fully disconnected when personnel are interacting with the UAV.	3A
UAV flies into personnel during testing.	UAV testing performed in close proximity to crowds of personnel.	Flying UAV could strike personnel, causing injury.	3B	All UAV testing will be done in an open area with adequate room for the UAV to fly away from personnel.	The UAV will only be tested at local drone fields or at rocket launch sites.	3A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Overheated electronics cause fire	Battery, motor or other electronic device receives more current than it was designed to.	Battery, motor or other electronic device overheats and causes burns or fire.	4B	Microcontrollers and power distribution boards are used that prevent sensitive electronics from drawing or providing more current than they were designed.	All motors and electronics have been chosen such that the max current draw is less than the maximum current that the powering batteries can provide.	4A
Overheated electronics cause burns	Battery, motor or other electronic device receives more current than it was designed to.	Personnel injury	4B	Microcontrollers and power distribution boards are used that prevent sensitive electronics from drawing or providing more current than they were designed.	1. All motors and electronics have been chosen such that the max current draw is less than the maximum current that the powering batteries can provide. 2. If the electronics appear to be smoking , heat-resistant gloves are to be worn by all team members needing to interact with the UAV.	4A
Sparking inside UAV	Faulty wiring or electrical connection	Potential for fire	3B	1. All wiring connections are be soldered. 2. Electrical engineering students and advisers have checked connections to ensure no errors have been made in construction.	1. Soldered wires have a significantly decreased chance of failure. 2. Checking wiring connections several times can greatly reduce the risk of negligent mistakes and faulty connections, which are the main modes of failure in wiring.	4A

A.3 Failure Modes and Effects Analysis

A.3.1 Vehicles FMEA

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Rocket bulkhead failure	1. Structurally insufficient materials. 2. Improperly applied epoxy.	1. Rocket could shear, resulting in partial mission failure, or serious injury. 2. Subsystem could be ripped out.	4B	1. The manufacturer's instructions for mixing epoxy were observed and followed. 2. Bulkheads were sized properly as to take the structural load induced by flight. 3. Properly applied fillets for the epoxy.	1. Materials have been chosen specifically for specific structural purposes. 2. Inspection of the epoxy fillets have been performed to ensure the proper application of epoxy. 3. Calculations have been run on the bulkheads sizes and materials as to ensure that they are capable of withstanding the forces sustained in flight.	4A
Rocket is dropped	Improper handling and carrying of launch vehicle.	Fractures in body of rocket, resulting in partial mission failure.	3B	The Safety Officer ensures at least three people hold the rocket at all times when it is being moved.	Procedures and checklists for rocket handling have been created and are followed at all times.	3A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Fin can malfunctions.	1. Improper construction of fin can. 2. Insufficient strength of fin can.	Rocket can become aerodynamically unstable and shear, resulting in possible total mission failure.	4B	1. The fins have been properly constructed and are capable of taking the maximum loads sustained during launch and recovery. 2. The fins have properly epoxied into the fin can.	1. Calculations have been performed to ensure fin can strength during all stages of flight. 2. Fin Can has bee inspected for structural sufficiency with no cracks or moving epoxy joints. 3. Fins are orthogonal to the body as constructed.	4A
Motor failure	Improper installation of motor.	1. Could result in total mission failure.	4B	The team mentor is the only one who handles and inserts the motor.	Section A.7.2.6 of the launch procedures dictates that the team mentor is the only team personnel to handle the motor. The mentor has level 2 High Power Rocketry certification through Tripoli Rocket Association.	4A
Premature ignition of motor	1. Motor or motor igniter incorrectly handled 2. Ignition wires have live voltage during igniter instillation	Rocket fails to launch at proper angle and could impact the ground.	3B	1. The team mentor is the only one who handles and inserts the motor igniter. 2. The motor and igniter are be visually inspected prior to launch.	1. Section A.7.2.8 of the launch procedures dictate that the team mentor is the only person who is to handle and install the rocket motor or igniter. 2. Section A.7.2.8 of the launch procedures call for checking the ignition wires for live voltage prior to igniter instillation, to prevent premature ignition on the pad.	3A
Loss of Rocket Aerodynamic Stability	The static stability of the rocket is not as predicted.	The rocket fails to travel in a vertical path, causing lower than expected apogee, increased aerodynamic and structural loading, and possible contact with the ground.	4B	1. The stability of the rocket has been modeled using as-built component weights in OpenRocket and RockSim, confirming safe stability. 2. The center of gravity of the rocket is measured before flight to confirm stability.	1. Section A.7.2.5 of the launch procedures describes the process of measuring the Center of Gravity of the rocket during flight. 2. The rocket was observed to fly straight during the Vehicle Demonstration Flight, confirming stability of the airframe.	4A

A.3.2 Recovery FMEA

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Failure of the rocket to separate at apogee	1. Failure of altimeter to ignite black powder charge 2. Failure of black powder charge to separate the rocket at apogee. 3. In-flight disconnection of the altimeter-powering batteries.	Rocket hits the ground at extremely high speed, causing large damage to the rocket and payloads.	4B	1. All recovery electronics are designed in such a way that the failure of one piece of the system will not compromise the system's ability to separate the rocket. 2. All recovery electronics have been tested to confirm that they are capable of properly igniting the e-matches. 3. The black powder charges are sized such that they are capable of separating the rocket. 4. Black powder ground tests have been performed to confirm the sizing of the black powder charges. 5. Any batteries to be used for launch are fully charged or new.	1. The recovery system features three independent altimeter-battery-ejection charge systems, with any of the three redundant altimeters capable of fully separating the rocket. 2. Through e-match-altimeter tests, the altimeter-battery combination was found to be capable of igniting an e-match at the proper time. 3. Black powder ground tests confirmed that 5 grams of black powder is enough to fully separate the rocket. 4. Section A.7.3.2 of the launch procedures includes checking the charge of the recovery batteries during the Pre-Departure Inspection of the recovery system.	4A
Failure of the parachute to open at the correct altitude	1. Failure of the Chute Releases to allow the parachute to open during rocket descent. 2. Improper folding of the parachute during launch setup.	Rocket descends with higher-than-designed speed, potentially causing damage to the fins or airframe.	3B	1. The Chute Releases are be set up in such a way that failure of one Chute Release will not impact the recovery of the rocket. 2. The Chute Releases are individually tested prior to flight. 3. The parachute is be folded in a consistent way that allows it to easily open after the Chute Release has stopped restraining the parachute.	1. During launch, two Chute Releases are set up in series, such that the tension restraining the parachute will be released if either Chute Release activates. 2. Procedures and checklists for testing the Chute Releases prior to flight have been created and are followed during tests. 3. Section A.7.3.3 details procedures for folding the parachute. Theses procedures are followed as written during testing and flight.	3A
Failure of the opened parachute to adequately slow down the rocket	Improper sizing of the parachute.	Rocket descends with higher-than-designed speed, potentially causing damage to the fins or airframe.	3B	The parachute has been chosen such that the rocket descends at a speed such that the heaviest section of the rocket has less than 75 ft-lbs of kinetic energy at landing.	The kinetic energy of the heaviest section of the rocket under the chosen main parachute is 58.47 ft-lbs, which is below the alloted 75 ft-lbs.	3A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Parachute separates from the rest of the rocket during descent	1. Broken shock cord. 2. Broken quick-link or eyebolt connection.	Rocket descends at high speed and likely severely damaged on impact with the ground.	4B	1. Shock cords have been selected such that they are capable of holding significantly greater loads than would be experienced in a normal flight. 2. Any sharp objects that could cut or weaken the shock cords during descent will be covered. 3. Eyebolts, quick-links and other load-bearing fittings have been selected such that they are capable of holding more load than would be experienced in a normal flight.	1. The 9/16 inch nylon shock cords that is used has a breaking strength of 2400 lbs, significantly greater 512 lbs of force that is be experienced in flight. 2. The current design does not contain any sharp edges or other threats to the shock cord that needs to be covered. 3. The quick links that are used has a maximum working load of 1760 lbs, significantly greater than the 512 lbs of force that is be experienced in flight. 4. The eyebolts that are be used have a working strength of 1400 lbs, significantly greater than the 512 lbs of force that is be experienced in flight.	4A
Rocket drifts further than intended during descent.	1. Improperly sized parachute. 2. Chute Release allows the main parachute to open earlier than intended.	Rocket could drift outside of the launch field, complicating recovery or potentially causing damage to property or the environment.	2D	1. The descent of the rocket is be staged to reduce the descent time, and therefore the drift distance. 2. The parachute has been sized such that the drift radius of the rocket is within the mission specifications. 3. The Chute Releases are individually tested prior to flight to ensure proper operation.	1. Calculations have been done to ensure that the rocket will not drift outside of a 2500 ft radius during descent in up to 20 mph winds. 2. Procedures and checklists for testing the Chute Releases prior to flight have been created and are enforced during launch.	2B

A.3.3 Air Braking System FMEA

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Power supply failure in electrical system.	Under charged batteries, poor electrical connections between components and PCB.	Tabs fail to extend and rocket over shoots apogee.	3C	1. Batteries have been be chosen with adequate power to survive delays on launch pad. 2. Physical control switches ensure system is only active when necessary. 3. All electrical connections have been made with solder or purpose-built connectors and electrical tape or shrink wrap if necessary. 4. Separate switches power and fully arm the system so it does not run unnecessarily.	1. Trade study performed on available batteries to choose brand that meets our needs. 2. Team members are trained in pre-launch operation of control switches and be able to identify if battery needs to be replaced/charged. 3. Connections are tested prior to launch with multimeter and by running system. 4. Status LEDs alert operator if system is not correctly enable or loses power during launch preparation.	3A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Incorrect or missing sensor data.	Malfunction in sensor sampling, improper component install, poor data filter code performance.	The system functions improperly by extending tabs too early or too late for correct apogee.	2D	1. Sensors are be securely integrated with microcontroller through soldered PCB. 2. Highest performing sensor has been chosen given size and cost restraints. 3. Sensors have been be installed in acceptable operating environment. 4. Kalman filter is utilized to limit effects of bad sensor readings.	1. Trade study has been performed to choose sensors that best meet our needs. 2. Multiple sensors were purchased and ground tested to find best data fidelity. 3. Physical needs (i.e. holes in rocket body for altimeter) are accounted for. 4. Filtering code has been be peer-reviewed and tested for accuracy.	2B
Undesired microcontroller command signals.	Bad control code algorithm, mistaken connections with microcontroller.	Microcontroller takes good sensor input, but sends bad control commands to system extending tabs at wrong time.	3B	1. Reliable microcontrollers have been researched and chosen. 2. Multiple peer reviews and tests used on control code. 3. Clearly labeled PCB connections ensure proper connections with sensors. 4. Component selection and written code ensure low latency between sensor input and tab motion.	1. Trade study done on best available device for our needs. 2. Control code has been verified through peer review and ground testing. 3. PCB was reviewed prior to fabrication and schematic available during assembly to prevent incorrect connections.	2A
Broken mechanical system.	Excessive force to snap drag tabs, jammed gears, seized motor.	Tabs are unable to position themselves correctly to bring rocket to proper apogee.	4B	1. High strength materials have been chosen to withstand expected forces plus factor of safety. 2. Minimum number of gears are used to avoid dangers of overly complex system. 3. Reliable motor brand has been chosen. 4. Fragile components (wires, plastic clips) are be securely fastened and covered to avoid damage during flight.	1. Trade study has been performed on motor brands. 2. Ground testing with physical components avoids unexpected launch failures. 3. Tight tolerances on components prevents.	3B
Operator error.	System arming and power switches toggled incorrectly in preparation for flight.	Air brake not ready for launch and does not deploy.	3C	1. Switches are be labeled and easily accessible within rocket body. 2. Status LEDs provide feedback to user that system is correctly enabled.	1. System arming responsibility delegated in advance of launch. 2. Selected operator is trained on all pre-flight procedures related to Air Braking System.	3A
Impossible target apogee.	Selected motor propels rocket to altitude outside of range compatible with drag tab guidance to target.	Drag tabs unable to slow rocket sufficiently to stop where specified, or rocket motor not powerful enough to reach desired altitude.	3B	1. Motor sizes have been researched to ensure rocket slightly overshoots target apogee and allow rocket to be adequately slowed by air brake. 2. Weight and shape analysis has performed on rocket design to model system and predict apogee for system with no tab extension.	1. All significant changes in weight are be documented to recalculate predicted apogee, with ballasts used as necessary. 2. Drag tabs are be sufficiently large to accommodate large amount of overshoot by chosen motor.	3A

A.3.4 Unmanned Aerial Vehicle FMEA

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
UAV falls during flight or fails to start	Defective wiring	Mission failure	4C	1. All wiring connections have been soldered. 2. Electrical engineering students and advisors have checked the connections to ensure no errors have been made in construction.	1. Soldered wires have a significantly decreased chance of failure. 2. Checking wiring connections several times greatly reduces the risk of negligent mistakes and faulty connections, which are the main causes of failure in wiring.	4A
UAV stops flying before beacon delivery	Insufficient battery charge	Mission failure	4C	1. The battery is charged sufficiently before flight. 2. A battery with sufficient capacity has been selected to enable sufficient flight time.	1. Section A.7.5.2 of the launch procedures describes procedures for checkin UAv battery levels prior to launch. 2. The UAV has been flown and shown to have sufficient flight time for mission completion.	4A
UAV crashes to ground	Motor failure	Mission failure or personnel injury	4C	1. Motors have been thoroughly tested before flight. 2. Motors have been selected with reliability in mind.	1. Increased motor testing reduces the risk of motor failure. Flight tests and practices can be conducted on campus with an advisor, which allows for extensive testing. 2. A motor which is known for its reliability is less likely to fail.	4B
UAV crashes to ground	Props detach from motors	Mission failure or personnel injury	4C	1. A nylon-insert lock nut will be used to secure the prop to the motor. 2. Both right-hand and left-hand thread nuts will be used. 3. UAV team will double check that correct nuts are used and securely fastened.	1. Nylon-insert lock nuts have a lower chance of becoming detached from the motors during flight compared to typical non-locking nuts. 2. Clockwise-rotating motors will tighten left-hand threaded nuts and counter clockwise-rotating motors will tightne right-hand threaded nuts. 3. Checking nut thread direction and tightness can greatly reduce the risk of negligent mistakes and loose nuts, which are common mistakes.	4B
Beacon is not deployed	Servo motor failure	Mission failure	4C	1. Motors will be thoroughly tested before flight. 2. The servo motor will be selected with reliability in mind.	1. Increased motor testing reduces the risk of motor failure. Flight tests and practices can be conducted on campus with an advisor, which will allow for extensive testing. 2. A motor which is known for its reliability is less likely to fail.	4B

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
UAV is unable to launch	Stepper or servo motor failure to separate the nose cone from the body tube	Flight and mission failure	4C	1. Motors will be thoroughly tested before flight. 2. The servo motor will be selected with reliability in mind.	1. Increased motor testing reduces the risk of motor failure. Flight tests and practices can be conducted on campus with an advisor, which will allow for extensive testing. 2. A motor which is known for its reliability is less likely to fail.	4B
UAV is unable to launch	Locking mechanism on the UAV legs is unable to be disengaged	Flight and mission failure	4B	1. Unlocking mechanism will be tested several times. 2. Multiple redundancies will be built into the unlocking mechanism. 3. The servo motor driving the UAV out of the body tube will deliver sufficient power.	1. Increased testing reduces the risk of failure of the locking mechanism. 2. Adding redundancy reduces the risk of total system failure, as a backup will be present. 3. The selected servo motor can deliver far more force than the shear pins require to disengage from the legs.	4A
UAV is unable to launch	Switch and/or remote mechanism fails to power on the UAV	Flight and mission failure	4C	1. Power on mechanism will be tested several times. 2. Multiple redundancies will be built into the system that powers on the UAV.	1. Increased testing reduces the risk of failure of the system which powers on the UAV. 2. Adding redundancy reduces the risk of total system failure, as a backup will be present	4A
UAV fails during flight	Propellers cut wires	Power and/or function is disabled, causing the UAV to fall	4B	1. All wires will be taped sufficiently to prevent loose strands of wire from entering the radius of the propellor. 2. Tape will be re-applied before every launch to ensure the tape is secure and wires are safely out of the propeller's radius.	1. All wires will be assessed before every flight to ensure that no piece of any wire is in danger of being cut. 2. While disabled, propellers can be manually spun to verify that wires are safely outside the spin radius.	4A
UAV fails during flight	Propellor arm breaks during deployment or flight.	Flight and mission failure	4B	1. Arms will be tested for strength and durability. 2. A member of the UAV Squad will have access to a remote controller to maneuver the UAV away from people in the event it is not able to correct the flight path.	1. Increased testing reduces the risk of an arm on the UAV breaking. 2. Testing may provide a reason to redesign the arm to better support the propellor. 3. Manual control over a broken system is more reliable than a computer that does not recognize people in the area.	4A
UAV is not able to fly correctly with telemetry	High winds	Mission failure	4C	A member of the UAV Squad will have access to a remote controller to use if winds exceed 10 mph.	1. A manually controlled UAV without telemetry will be more effective in maneuvering gusts of wind while completing the mission. 2. Readings of wind, done from several weather websites, will aid in determining what the default flight method will be.	4A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
UAV is not able to fly correctly	Dangerously high winds	Flight and mission failure	4C	If winds are over 20 mph, the UAV will be disabled and removed manually, as outlined in launch procedures.	1. The UAV cannot safely be controlled in winds above 20 mph, even with manual control without telemetry. 2. Readings of wind, done from several weather websites, will aid in determining what the default flight method will be.	4A
UAV is unable to fly correctly	One or more motors fail during flight	Mission failure	4C	1. Electrical engineering students and advisers will double check all wiring before launch. 2. All servo motors and electronics related to flight success will be tested prior to launch.	1. Checking for loose wires or broken wires will ensure that the system is constructed correctly, and that the system will function as planned. 2. Testing will ensure the servo motors operate correctly and that the system works as planned.	4A
Nose cone is not removed	Steel hairpin cotter pins do not unlock	Flight and mission failure	4B	1. The wire attached to the steel hairpin cotter pins is significantly shorter than the length of the payload section. 2. The steel hairpin cotter pins and wires will be tested.	Testing will ensure that the pins unlock at the correct time, and that the bulkhead is removed appropriately.	4A
Nose cone is not removed as planned	Track system fails and gears do not initiate the nose cone removal	Flight and mission failure	4B	The deployment system will be tested to ensure the lead screw rotates appropriately, and that the platform moves correctly as a result.	Testing will ensure accurate function of the screw and track system that will position the UAV in the correct position to take-off.	4A

A.3.5 Launch Operations FMEA

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Airframe pieces out of alignment	Improper assembly of the rocket	Potential for damage to the couplers or airframe.	3B	1. Stands have been created to ensure that the rocket pieces are all at the same level during assembly. 2. The airframe is assembled according to defined procedures.	Section A.7.2.3 of the launch procedures detail assembly operations.	3A
Airframe dropped during or after assembly	Lack of care during launch operations	Potential for damage to the airframe, nosecone, fins or payloads.	4B	1. Stands have been constructed to rest the rocket on during transport and assembly. 2. The rocket airframe is assembled according to defined procedures.	Section A.7.2.3 of the launch procedures detail assembly operations.	4A
Payload or subsystem improperly integrated into rocket	Improper assembly of rocket or rocket subsystem	Potential for damage to rocket airframe, subsystem or payload	4B	Launch operations personnel must be aware of how the rocket subsystems fit together and secure into the rocket airframe.	Section A.7.2.3 of the launch procedures detail assembly and integration operations.	4A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Parachute folded improperly during rocket assembly	Mistake made during parachute folding.	Parachute could become stuck in rocket during descent.	4B	Recovery personnel follow defined procedures for folding a parachute.	Section A.7.3.3 of the launch procedures detail parachute folding procedures.	4A
Motor is damaged during assembly	Motor is dropped or improperly assembled	Potential for motor explosion	4B	Motors are assembled and installed by the team mentor, who is certified to do so.	Section A.7.2.6 of the launch procedures require that the team mentor assembles and installs all of the motors to be used by the team.	4A
Motor igniter installed incorrectly	Personnel installing the igniter do not know how to do so	Potential for motor explosion	4B	Igniters are installed by the team mentor, who is certified to do so.	Section A.7.2.8 of the launch procedures require that the team mentor inspects and installs all igniters to be used by the team.	4A
ABS subsystem set up incorrectly	Mistake made during subsystem assembly or integration.	ABS does not function properly, causing rocket to achieve incorrect apogee.	2B	ABS assembly and setup procedures are be followed at all times.	Section A.7.4.2 of the launch procedures detail the setup of the ABS system during active launch.	2A
UAV payload incorrectly assembled or set up	Mistake made during UAV assembly, setup, or integration.	UAV fails to function properly when activated	3B	UAV assembly, setup and integration procedures are followed at all times during launch.	Section A.7.5.5 of the launch procedures detail UAV setup and integration procedures.	3A
Rocket incorrectly loaded onto rail	Lack of care during launch operations	1. Failure to launch and potential damage to the airframe 2. Rocket could come off the pad at an angle, resulting in further mission failure	3B	The rocket will be loaded onto the pad in a proper fashion	Section A.7.2.7 details procedures for placing the rocket onto the launch pad.	3A

A.3.6 Launch Support Equipment FMEA

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Launch rail at high angle with vertical	1. Launch rail and pad set up improperly. 2. Rocket improperly loaded onto launch pad.	1. Rocket will not reach target apogee. 2. Rocket could drift further than expected.	3B	1. All launches are be done in accordance with NAR guidelines on proper rail setup and launch angle. 2. RSO recommendations for launch angle and rail setup are considered during setup.	1. All launches are be done with an experienced RSO present and giving recommendations. 2. The team mentor, a Tripoli member and level 2 HPR certified, is be present to aid with launch rail setup and recommendations for launch angle, taking into account wind and crowd location. 3. Section A.7.2.7 details procedures for proper loading of the rocket onto the launch pad.	3A
Launch controller unit fails to ignite motor	Faulty wire, wire connection, or battery in the launch control unit or the ignition circuitry.	Rocket will not launch	2B	All launches are be done in collaboration with a registered rocketry club. The club's launch control unit will be used.	Flight proven launch control units are unlikely to fail.	2A
Launch ignition wires are live during igniter installation	Failure to check ignition wires prior to ignitor instillation.	Motor could ignite prematurely, injuring personnel	4B	1. The ignition wires are checked prior to igniter instillation 2. The team mentor installs all igniters that are to be used by the team.	1. Section A.7.2.8 of the launch procedures specifically requires checking the ignition wires prior to igniter instillation. 2. Section A.7.2.8 of the launch procedures requires that the team mentor install all igniters that are to be used by the team.	4A

A.3.7 Payload Integration FMEA

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Subsections are not properly secured	Shear pins and/or assembly screws not properly installed during assembly	Rocket sections, payloads or subsystems could separate from the rocket in flight, causing damage to the rocket or preventing operation of one or more subsystems.	4B	An inspection of the entire rocket will be done prior to flight, specifically to ensure that the subsystems and payloads are secured and operable.	1. Team officers and subsystem leads will perform inspection, looking primarily to confirm proper securing of sections and operation of each individual subsystem 2. A pre-launch inspection checklist and procedures have been created and will be properly filled out	4A
Premature separation of the rocket	1. Shear pins are not inserted 2. Incorrect number of shear pins used	Possible damage to the rocket airframe, parachute, parachute rigging, and other rocket subsystems and payloads.	4B	Inspection of the rocket is done before the rocket is on the launch pad to confirm presence of proper numbers of shear pins.	Section A.7.2.3 of the launch procedures require inspection of the rocket prior to launch.	4A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Rocket payload or subsystem separates from main rocket airframe during flight.	Assembly screws not properly installed	Rocket subsections separate from airframe during descent, causign damage to the rocket airframe or subsystems.	4B	Full inspection of the rocket is done before the rocket goes to the launch pad to ensure that it is properly assembled	Section A.7.2.3 of the launch procedures require inspection of the rocket prior to launch.	4A
Epoxy failure during flight	1. Epoxy is improperly mixed 2. Epoxy is improperly set	Bulkhead or centering ring detaches from the rocket airframe during flight	4B	1. Specific time was set aside during construction to allow the epoxy to properly set before more work is done on the airframe 2. Epoxy was be mixed according to manufacturer recommendations	Procedures and checklists for rocket construction have been created and were followed as written.	4A
Centering ring failure during flight	1. Centering rings are improperly epoxied 2. Centering rings are improperly aligned	1. Motor causes damage to the rocket airframe 2. Motor creates moment on the rocket, altering the flight path and therefore the rocket apogee and drift distance.	4B	1. During manufacturing, care was taken to properly align the centering rings 2. Before flight, the centering rings is inspected for damage	Procedures and checklists for construction and instillation of centering rings have been created and were followed as written.	4A
Bulkhead failure during flight	1. Bulkheads improperly aligned during construction 2. Bulkheads improperly epoxied during construction	Rocket payloads or subsystems could separate from the airframe during flight, causing damage or preventing operation	4B	1. Care was taken to ensure that the bulkheads are properly aligned during construction. 2. Epoxy was mixed and applied in accordance with manufacturer instructions	Procedures for bulkhead installation have been created and were followed as written.	4A
Airframe Couplers fail to keep rocket together in flight	1. Couplers are not the proper length 2. Couplers are improperly epoxied	Rocket shears or slips during the motor burn, causing severe damage to the airframe and altering the rocket apogee and drift distance	4B	1. Couplers were made to be at least 1 caliper in length 2. Care was taken to ensure that the couplers are properly epoxied into the body tube. 3. Epoxy was mixed according to manufacturer guidelines	Procedures for airframe construction and coupler installation have been created and were followed as written.	4A

A.4 Environmental Hazards

A.4.1 Environmental Hazard to Rocket

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Rain	Local weather patterns	Damage to electrical systems, potential for battery leakage, inability to launch	4C	1. Launches are conducted on day with less than or equal to 30% chance of precipitation 2. Waterproof bags are used to protect sensitive equipment	At least one member of safety team checks local forecast for predicted launch day precipitation at least 7 days prior to launch and notify the team lead of adverse conditions. The team complies with all decisions made by NASA representatives regarding precipitation. .	1B
High Winds	Local weather patterns	Adverse effects on launch angle, reduction of altitude, increased drifting, inability to launch, UAV capabilities	4C	Launches are conducted on days with low chance of winds in excess of 15 mph or gusts greater than 20 mph.	At least one member of safety team checks the local forecast for predicted launch day winds 72 hours in advance and notifies the team lead of adverse conditions. The team lead is responsible for authorizing launches with respect to wind reports.	2C
Trees, moist ground, man-made obstacles in drift radius	Local terrain and built environment	Damage to rocket systems, potential for battery puncture and leakage, inability to recover rocket	3B	1. Launches are conducted on days with low chance of winds in excess of 15 mph to prevent excessive drifting if trees are in estimated drift radius. 2. Launches are not to be conducted if the projected landing of the rocket will take place in an inaccessible area (eg. the allowable radius includes a body of water in the direction of the wind).	At least one member of safety team checks local terrain and mark obstacles in the predicted drift radius on a satellite map printout. If necessary, an NDRT recovery or safety member will survey the site before launch to verify obstacles and report to leads, who will make the final decisions regarding launch using wind data.	2B
Low Cloud Cover	Local weather patterns	Inability to launch	4C	Launches are conducted on a day of no cloud cover or cloud cover in excess of 6,000 feet above ground level.	At least one member of safety team checks the local forecast for predicted launch day cloud cover on the NOAA's Aviation Weather Service Ceiling Forecast website at least 24 hours before launch.	1B
High Humidity	Local weather patterns	Excessive moisture can prevent motor ignition, cause battery leakage	4C	Electronics, motor are stored in waterproof bag until launch time if the dew point is within 30 degrees of the actual temperature.	At least one member of safety team checks the local forecast for predicted launch day humidity at least 24 hours prior to launch. The team lead may elect to leave sensitive equipment in watertight bags regardless of current or predicted humidity to reduce the chance of a motor misfire or battery short circuit.	2B

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Extreme Temperatures and UV Exposure	Local weather patterns, limited cloud cover	Battery depletion or explosion, prevent electrical components from functioning, induce critical failures, reduce separation of rocket, melt/damage adhesives, lead to launch pad fire	4C	1. Batteries are be checked for charge immediately prior to launch 2. Batteries are removed from direct sunlight until launch time 3. The rocket is assembled and placed in an area out of direct sunlight until it is time to start launch procedures.	The team complies with all decisions made by NASA representatives regarding temperature. A safety member checks the predicted UV forecast at least 24 hours prior to launch. The team lead may elect to construct the rocket in a covered area regardless of the UV index at time of launch.	2C
Unlevel launch pad	Moist ground, uneven terrain, failure to level	Unpredicted launch angle and trajectory can be potentially life threatening to viewer at the launch site.	4B	Launch pad is leveled prior to launch.	At least one member of the safety team signs off on the launch pad's level during launch procedures.	2B
Unexpected winds at apogee	Unpredictable winds at apogee not detected from ground	Will affect the ability for the UAV to deploy, stabilize at apogee	4D	Launches are conducted on a day with a low chance of winds in excess of 15 mph or gusts greater than 20 mph. The UAV was also tested in conditions that exceed this amount of wind in the event of stronger than anticipated winds at apogee.	NDRT Officers monitor the forecast at altitudes of up to 6000 feet using the NOAA's Aviation Weather Service at least 24 hours before launch. At least one UAV team member signs off on the functionality of the UAV's performance in windy conditions.	2D

A.4.2 Rocket Hazard to Environment

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Release of hydrogen chloride, toxic fumes, reactive chemicals	Burning of motors	Hydrogen chloride dissociates to form hydrochloric acid in water, toxic fumes contribute to biodegradation of ammonium perchlorate, chemicals deplete ozone	2E	The amount of hydrochloric acid, toxic emissions, and reactive chemicals produced over one season is negligible	Used motors are properly disposed of according to SDS sheets from the manufacturer and in accordance with applicable local, state, and federal waste guidelines.	1E
Carbon dioxide emission	Travel to and from launch site	Addition of greenhouse gas, heat to atmosphere	2E	Carpooling and commercial air travel produce a negligible effect of carbon dioxide emission per capita.	Occupancy in each vehicle used for transportation to and from events is maximized.	1E

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Fire on launch pad, grass fire	Burning of motors, electrical component short circuit	Ignition, electrical systems, motor all create heat and have potential to spark, causing a fire on the pad, in the rocket, or on the surrounding grassland	3B	Appropriate fire extinguishing materials are be present at launches, wire connections are checked before launch.	At least one member of safety team verifies that fire extinguishing materials are present as part of pre launch sign off and in accordance with NASA guidelines. The launches are conducted at least 50 feet from any grass or flammable material.	3A
Groundwater contamination	Leakage upon landing, improper disposal of batteries	Chemicals react in water, potentially leading to human ingestion and illness, disruption of natural processes	2B	NDRT follows procedures outlined in SDS sheets should chemical spills, leaks occur, and will follow SDS guidelines on disposal of used batteries and chemicals. All hazardous chemicals should be in water resistant compartments and be contained after landing.	Used batteries, motors are properly disposed of and all leaks are immediately reported to local, supervising organization that has jurisdiction over launch site. Note that any leaks from used motors are harmless to the environment according to the manufacturer's specifications.	2A
Battery leakage	Excessive heat, excessive humidity, battery puncture, damaged casing	Chemicals react in water, potentially leading to human ingestion and illness, potential reaction to cause fire, dangerous to handle	4B	Proper precautions, including those recommended by the manufacturer, are used to prevent the leakage of batteries. Proper PPE is required when handling used batteries if they are suspected of leaking.	At least one member of safety team verifies that fire extinguishing materials and PPE are present and verifies that launch conditions are NOT favorable for battery leakage or explosion.	4A
Waste	Plastic scraps and other components of the rocket may detach from the rocket during the mission	Sharp waste can lead to harm to animals upon ingestion, humans may be harmed if components' chemicals enter into groundwater supply	2B	Recovery is responsible for verifying all parts are accounted for when retrieving the rocket.	Trash bags are brought to the launch site in accordance with launch procedures.	1B

A.5 NAR High-power Rocket Safety Code

Topic	NAR Description	Team Compliance
Certification	I will only fly high power rockets or possess high power rocket motors that are within the scope of my user certification and required licensing.	Team mentors are Level 2 certified and the team will only use a maximum of L class motors.
Materials	I will use only lightweight materials such as paper, wood, rubber, plastic, fiberglass, or when necessary ductile metal, for the construction of my rocket	All design squads, especially the vehicle design squad, will refrain from using materials that do not meet the lightweight requirement. If there is uncertainty, the team will check with the NASA competition officials.

Topic	NAR Description	Team Compliance
Motors	I will use only certified, commercially made rocket motors, and will not tamper with these motors or use them for any purposes except those recommended by the manufacturer. I will not allow smoking, open flames, nor heat sources within 25 feet of these motors.	The team will not use any motors, other than those used by certifiable and trusted rocket motor manufacturers. Motor use will be supervised by team mentors, will be only for the purpose of launching the rocket, and will be under controlled and safe condition.
Ignition Systems	I will launch my rockets with an electrical launch system, and with electrical motor igniters that are installed in the motor only after my rocket is at the launch pad or in a designated prepping area. My launch system will have a safety interlock that is in series with the launch switch that is not installed until my rocket is ready for launch, and will use a launch switch that returns to the "off" position when released. The function of onboard energetics and firing circuits will be inhibited except when my rocket is in the launching position.	The team's mentors will install all ignition systems and will only do so properly, and according to the NAR regulations outlined here.
Misfires	If my rocket does not launch when I press the button of my electrical launch system, I will remove the launcher's safety interlock or disconnect its battery, and will wait 60 seconds after the last launch attempt before allowing anyone to approach the rocket.	Team mentors, Safety officer, and Captain must all approve any attempts to approach the rocket in the case of misfires. Even then, it will only be done well after a 60 second waiting period, and will be done only by the team mentors and essential personnel after the area has been determined to be safe.
Launch Safety	I will use a 5-second countdown before launch. I will ensure that a means is available to warn participants and spectators in the event of a problem. I will ensure that no person is closer to the launch pad than allowed by the accompanying Minimum Distance Table. When arming onboard energetics and firing circuits I will ensure that no person is at the pad except safety personnel and those required for arming and disarming operations. I will check the stability of my rocket before flight and will not fly it if it cannot be determined to be stable. When conducting a simultaneous launch of more than one high power rocket I will observe the additional requirements of NFPA 1127.	The team will follow all launch instructions given by the Range Safety Officer, and will comply with all rules stipulated here. Additionally, the Safety officer will give a 5 second warning to all personnel in the area prior to launch.
Launcher	I will launch my rocket froma stable device that provides rigid guidance until the rocket has attained a speed that ensures a stable flight, and that is pointed to within 20 degrees of vertical. If the wind speed exceeds 5 miles per hour I will use a launcher length that permits therocket to attain a safe velocity before separation from the launcher. I will use a blast deflector to prevent the motor's exhaust from hitting the ground. I will ensure that dry grass is cleared around each launch pad in accordance with the accompanying Minimum Distance table, and will increase this distance by a factor of 1.5 and clear that area of all combustible material if the rocket motor being launched uses titanium sponge in the propellant.	The team will only use rails provided by NAR, and will fully comply with this rule.
Size	My rocket will not contain any combination of motors that total more than 40,960 N-sec (9208 pound-seconds) of total impulse. My rocket will not weigh more at liftoff than one-third of the certified average thrust of the highpower rocket motor(s) intended to be ignited at launch.	Rocket design and motor selection will comply with this rule.
Flight Safety	I will not launch my rocket at targets, into clouds, near airplanes, nor on trajectories that take it directly over the heads of spectators or beyond the boundaries of the launch site, and will not put any flammable or explosive payload in my rocket. I will not launch my rockets if wind speeds exceed 20 miles per hour. I will comply with Federal Aviation Administration airspace regulations when flying, and will ensure that my rocket will not exceed any applicable altitude limit in effect at that launch site.	Weather and wind conditions will be evaluated in the week prior to a launch day, as well as on launch day, if conditions are determined to be unsafe, the team will not launch. All necessary FAA waivers and notices will be acquired and in place prior to launch. The team will comply with all launch day determinations made by the Range Safety Officer.

Topic	NAR Description	Team Compliance
Launch Site	I will launch my rocket outdoors, in an open area where trees, power lines, occupied buildings, and persons not involved in the launch do not present a hazard, and that is at least as large on its smallest dimension as one-half of the maximum altitude to which rockets are allowed to be flown at that site or 1500 feet, whichever is greater, or 1000 feet for rockets with a combined total impulse of less than 160 N-sec, a total liftoff weight of less than 1500 grams, and a maximum expected altitude of less than 610 meters(2000 feet).	Team launches will only take place at NAR/TRA events. The Range Safety Officer has final say on all matters regarding safety issues.
Launcher Location	My launcher will be 1500 feet from any occupied building or from any public highway on which traffic flow exceeds 10 vehicles per hour, not including traffic flow related to the launch. It will also be no closer than the appropriate Minimum Personnel Distance from the accompanying table from any boundary of the launch site.	The team will comply with this rule and any determination the Range Safety Officer makes on the day of launch.
Recovery System	I will use a recovery system such as a parachute in my rocket so that all parts of my rocket return safely and undamaged and can be flown again, and I will use only flame-resistant or fireproof recovery system wadding in my rocket.	The Recovery Design Squad will be responsible for designing, testing, constructing, and verifying a safe recovery system that will fully comply with this rule. A pre-launch checklist must be checked off by recovery and signed by the Captain and Safety Officer.
Recovery Safety	I will not attempt to recover my rocket from power lines, tall trees, or other dangerous places, fly it under conditions where it is likely to recover in spectator areas or outside the launch site, nor attempt to catch it as it approaches the ground.	The team will comply with this rule and any determinations made by the Range Safety Officer on launch day. If a safe recovery is not possible for the team, proper authorities will be contacted to ensure a complete and safe recovery.

A.6 Failures/Hazards Identified During Test Flight

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
Main parachute deploys earlier than the intended	Nomex parachute protection slips out from around the parachute at apogee, causing the JollyLogic Chute Release to release the parachtue early	Main parachute deploys at apogee, increasing descent time and rocket drift during descent.	3B	Parachute and Nomex parachute protection will be folded in such a way such that the parachute does not slip out at apogee.	Procedures for parachute Nomex folding have been created and will be used.	3A
Hex nut of nosecone retention system comes loose	Epoxy fails due to insufficient surface contact area between hexnut and fore bulkhead	Nosecone no longer retained by primarily intended means	3D	1. Increase in surface contact area between hex nut and fore bulkhead to allow for greater strength of epoxy bond 2. Bulkhead will be flipped around so that there is also lip for hex nut to pull against.	1. New bulkhead will be machined to allow for greater surface contact area 2. Assembly of fore bulkhead will allow for hex nut to also be exerting load directly on bulkhead rather than through epoxy	3A

Hazard	Cause	Effect	Pre	Mitigation	Verification	Post
UAV platform flange shears under flight loading	3D printed material fails under shear loading due due to exceeding material ultimate shear stress	UAV no longer secured inside payload bay	4E	1. Platform material will be 3D printed out of stronger material 2. Flanges will be made from very strong materials 3. Platform-flange will interface so that flange is integrated into full body of platform	1. Platform will be 3D printed out of ASA, which has much higher strength than ABS 2. Flanges will be machined out of 6063 Aluminum to ensure high strength 3. Platform will be printed with holes for longer flanges to fit into, so that the flanges will exert force through entire platoform body rather than along one surface.	4A
Rocket descends at higher than intended speeds	1. Failure of the Chute Releases to allow the parachute to open during rocket descent 2. Improper folding of the parachute during assembly 3. Failure to properly size the parachute	Potential for damage to the airframe or payloads	4B	1. The Chute Releases are set up in such a way that failure of one Chute Release will not impact the recovery of the rocket 2. The parachute is folded in a consistent way that will allow it to easily open after the Chute Release as stopped restraining the parachute 3. The parachute sizing calculations have been re-checked to ensure proper parachute sizing	1. Two Chute Releases are used in series around the main parachute, such that either Chute Release can successfully release the parachute. 2. The Chute Releases have been tested using the inbuilt Chute Release testing program. They have been found to be successful at quickly releasing the parachute. 3. The Chute Releases were found to release at the intended altitude during the full-scale flight. 4. Section A.7.3.3 of the launch procedures details the parachute folding process that will be used for all parachutes in the rocket. 5. A larger than previously intended parachute is being used in light of rechecked calculations.	4A
Zip Tie loop physical failure	High acceleration during liftoff caused high force from battery onto zip tie loop.	Loose battery, possible disconnection of ABS electronics	3D	1. 3-D printed battery case securely contains the batteries such that in-flight forces cannot detach the batteries. 2. Battery case mounted to ABS using epoxy.	Shake test performed on ABS system to ensure no disconnects or mounting failures on the system.	3A
Inaccurate data from ABS accelerometer	Too low of a data sampling rate	Not changing states, and therefore tabs never extending	3C	1. Increase data sampling rate 2. Rely more heavily on altitude data than acceleration data	1. Achieve a higher data sampling rate in ground testing. 2. Perform calibration procedures for the accelerometer per the manufacturer data sheet.	3A
Vehicle overshoots predicted apogee.	Incorrect simulation of rocket weights and finishes	Rocket reaches apogee higher than intended, reducing mission success.	3B	Individually weighing and modeling of rocket components in OpenRocket	Simulations have been modified since the Vehicle Demonstration Flight to match real-life flight data	3A

A.7 Launch Concerns and Operation Procedure Checklists

These checklists have been approved by the Safety Officer, Technical Design Leads, and Team Captains such that together they outlines the necessary steps to complete a safe and successful test launch of the full scale rocket. Checklists should be carefully read so that whenever noted, proper caution and cognizance can be exercised.

In the case of an unforeseen situation or nonstandard event such as (but not limited to) a Catastrophe at Take Off (CATO), a punctured or damaged battery, improperly assembled (too tight or too loose) payload, see the Troubleshooting Safety Checklist, which is not completely exhaustive, but does offer instructions for a variety of situations ranging in severity and probability of occurrence. Should an event or situation that is not covered in the safety checklists be encountered during launch exercises, members should exercise their best discretion and approach an officer, the team mentor, the team's graduate student advisor, or the range safety officer for instructions on how to proceed.

A.7.1 General Safety Checklist

A.7.1.1 General Pre-Departure Checklist

⚠**Ensure Toolbox 1 contains:**

- ☐ Top Section:
  - ☐ Assorted Pens/Pencils
  - ☐ Razors
  - ☐ Exacto Knives
  - ☐ Metal Files
  - ☐ Drill Bits
  - ☐ Assorted Screws
  - ☐ Hand Drill
- ☐ Middle Section:
  - ☐ Wire Cutters
  - ☐ Needlenose Pliers
  - ☐ Bluntnose Pliers
  - ☐ Screwdrivers (Flathead)
  - ☐ Screwdrivers (Phillips)
  - ☐ Dial Caliper
  - ☐ Ruler
  - ☐ Tape Measure
  - ☐ Ratchet Screwdriver/Socket Wrench Set
  - ☐ Allen Hex Wrench Set
- ☐ Bottom Section:

  - ☐ Loose Wires Box
  - ☐ Crescent Wrench Set
  - ☐ Safety Glasses
  - ☐ Level
  - ☐ Allen Hex Wrench Set
  - ☐ Sandpaper (60 grit and 200 grit)
  - ☐ Multimeter
  - ☐ Wire Cutters
  - ☐ Wire Strippers

⚠**Ensure Toolbox 2 contains:**

- ☐ Top Section:
  - ☐ Sharpies
  - ☐ Allen Wrenches
  - ☐ Labeled hardware bags for each technical design squads
- ☐ Bottom Section:
  - ☐ Dusk Masks
  - ☐ 6 Minute Cure Resin and Hardener (epoxy)
  - ☐ Nitrile Gloves
  - ☐ Cotton Swabs
  - ☐ Masking Tape
  - ☐ Adjustable Wrench
  - ☐ Drill Bit Set
  - ☐ Rocket Camera Pack
  - ☐ Multimeter

⚠**Ensure the following items are packed**

- ☐ 1 Fully Stocked First Aid Kit
- ☐ 5 Pairs Safety Glasses
- ☐ 1 Pair Heat Resistant Gloves
- ☐ 2 Dust Masks
- ☐ 1 Box Nitrile Gloves
- ☐ 1 Pair Cut Resistant
- ☐ Fire Resistant Battery Bags
- ☐ 3 Fully Stocked Rocket Team Tool Boxes
- ☐ 1 Hand Drill with Fully Charged Battery (in carrying case)
- ☐ Drill bit case with standard range of bit
- ☐ 1 Copy of each checklist in possession of respective technical lead

- ☐ 1 Copy of all checklists in possession Safety Officer (back up)

⚠**Following actions must be completed prior to departure from campus.**

- ☐ Team Captain reminds all drivers of destination and necessary instructions for arriving at the launch site
- ☐ Team Captain should remind all members of basic launch day safety.
- ☐ Account for all members expected to attend the launch and ensure that each member has a seat in a car
- ☐ Safety Officer ensures that all attending members attended pre-launch ORR and passed necessary competency quiz
- ☐ Safety Officer must sign off with technical leads to ensure that pre-departure checklists have been filled out

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: __________

A.7.1.2 General Pre-Flight Assembly Procedure

☐ Team mentor instructs team on procedures and rules specific to launch site and overseeing rocketry club

☐ Safety Officer reminds team members of procedure for catastrophic events such as CATO and Ballistic events

☐ Safety officer ensure that a team member is assigned to follow assembly of each subsystem and fill out the respective checklist in order to ensure that the procedure is being properly followed

⚠**Once rocket is assembled, follow procedures outlined for bringing rocket to launch pad and performing final pre-flight preparations**

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: __________

A.7.1.3 Launch Procedures

⚠**Note that the following should be followed closely, or else it could result in significant personnel injury and/or mission failure**

⚠**The following must be completed by the LCO and RSO only, after ensuring that the range is completely clear, and all igniters are properly installed.**

- ☐ Activate launch ignition system
- ☐ Ensure continuity of ignition system and desired igniter
- ☐ Begin 10 second countdown
- ☐ Upon completion of countdown, press and hold ignition button to ignite motor
- ☐ If after 2 minutes the motor is not visibly igniting, deactivate launch ignition system and proceed to start CATO contingency plans detailed in A.7.6.

⚠**This concludes the steps that must be completed by the LCO and RSO.**

⚠**The following steps apply to all individuals presents at the launch site.**

- ☐ All members should be alert to their surroundings, and observe the rocket as it leaves the pad.
- ☐ Team members should visually track the flight of the rocket
- ☐ Team members that are still visually tracking the rocket should confirm this verbally, and by pointing to the rocket.
- ☐ If visual of the rocket is lost, team members should verbally confirm this and begin to search for the rocket to regain visual.
- ☐ Separation, drogue deployment, and main deployment events should be visually confirmed by team members, and communicated by those who are able to see these events.

⚠**In the event that any of these events are not confirmed, please refer to A.7.6 for contingency plans regarding ballistic events.**

- ☐ As the rocket comes down, the expected landing area should be cleared of any personnel and should be noted for retrieval.
- ☐ Upon confirmation of touchdown and/or loss of visual, team members may begin to move toward the landing site to retrieve the rocket.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: __________

A.7.1.4 General Post-Flight Inspection Procedure

☐ Locate Rocket

☐ Inspect landing site for potential hazards. A team officer must clear the site for approach.

☐ If the site is not cleared, see troubleshooting checklist or consult officer for further instruction.

☐ Collect shroud lines to prevent the parachute from dragging the rocket.

☐ Take pictures of the rocket in its landed state.

☐ Ensure all black powder charges have successfully ignited. If not, refer to the Troubleshooting procedures.

☐ Separate the rocket into sections and transport it back to the team base of operations.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: __________

A.7.2 Vehicle Squad Safety Checklist

A.7.2.1 Vehicle Pre-Departure Checklist

⚠**Ensure that the following items are packed before leaving campus. Check should be performed the morning of the launch.**

- ☐ Nose Cone
- ☐ Fore Body Tube
- ☐ Aft Body Tube
- ☐ Fin Can
- ☐ Shear Pins
- ☐ 6 Locking Screws
- ☐ 6 Minute Epoxy
- ☐ Sandpaper
- ☐ Screwdriver
- ☐ Fiberglass/Carbon Fiber/Transition
- ☐ 31” Recovery Tube
- ☐ Hand Drill
  - ☐ Drill Bit Index
- ☐ Crescent Wrench (adjustable)
- ☐ Motor Retainer (if not attached to motor mount)
- ☐ Camera plastic Bag
  - ☐ Includes SD Card, Camera, Washers and Nuts
    - ☐ 6 washers (5 small, 1 medium)
    - ☐ 2 locknuts
  - ☐ Paper towel backup for camera mount filling (stuffing the bottom)
- ☐ 5 Sheet metal screws for soft separation
- ☐ Spare set of all locking screws

A.7.2.2 Vehicle Pre-Departure Inspection

⚠**The following inspection should be performed prior to departure from campus. Failure to perform inspection can result in defects in the rocket going unnoticed until launch, potentially resulting in rocket or subsystem failure.**

- ☐ Inspect the body tubes and couplers for cracks or deformations to ensure they have not been damaged during storage.
- ☐ Ensure all epoxy fillets are in good condition without presence of chips or cracks.
- ☐ Ensure the items are stored in their proper locations and in such manner as to not cause physical damage.

☐ Ensure the fin can is stored on the rocket holder so as not to damage the fins during transportation.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: __________

Vehicle Design Lead: ______________________________ Date: __________

A.7.2.3 Rocket Assembly and System Integration

⚠**Failure to properly perform vehicle assembly or system integration can result in subsystem failure or premature separation of the rocket.**

⚠**Note that all the following steps must be completed in the order specified. Prior to proceeding to next step, ensure that all necessary steps have been completed by pertinent payload squads.**

☐ Insert the ABS System into the fin can, using the four tie rods as guidance.

☐ Ensure that ABS tabs are not obstructed by airframe.

☐ Bolt the ABS to the fin can using washers and nuts on the tie rods.

☐ Perform UAV integration. The UAV team is responsible for preparation of the UAV deployment system and securing the nosecone to the mechanism. For more information, see the UAV Deployment System Preparation section of the UAV Pre-Flight procedures.

☐ Perform recovery integration. The recovery team is responsible for preparation of the parachute deployment system, shock cords, and parachutes. For more information, see CRAM Integration and Parachute Installation sections of the Black Powder Recovery System procedures.

☐ Secure the recovery body tube and main parachute bay together with screws.

☐ Insert the fore section of the rocket into the recovery section, mating the couplers.

☐ Lock the Aft separation point with 5 screws

☐ Insert shear pins to complete and secure the connection between the sections.

A.7.2.4 Flight Camera Integration

☐ Insert the MicroSD card into the back of the camera

☐ Press power button

☐ Wait for steady yellow light from camera

☐ Press the button with a video camera on it

☐ If camera is flashing yellow, it is recording video and sound

☐ Make sure there is sufficient padding for camera to be pushed towards the top of the tie rods

☐ Insert into transition section so the lens is pointing out

☐ On the edge closest to the lens, place 3 small washers and loosely fit a lock nut onto the tie rod

☐ On the edge further from the lens, place the medium washer and then 2 small washers and loosely fit the lock nut on the tie rod

☐ If the camera does not fit, or has too much space to move, repeat previous 4 steps.

☐ If a proper fit is achieved, tighten lock nuts with crescent wrench.

☐ Perform shake test of assembly

A.7.2.5 Center of Gravity and Stability Check

⚠**The following steps should be performed by the Vehicle Design Lead Riley Mullen. If not careful while finding Cg, the rocket body and payloads could be damaged from being bent or dropped.**

⚠**The Center of Gravity and Stability Check should be performed after successful rocket and subsystem assembly and llation.**

- ☐ Perform Center of gravity (Cg) test to ensure the center of gravity matches the simulated center of gravity.
- ☐ Mark these the measured Cg and simulated Cg on the rocket.
- ☐ Mark predicted center of pressure on the rocket.
- ☐ Ensure calculated stability corresponds to the predicted value.
- ☐ Ballast as necessary to maintain a stability margin > 2 calipers or within 10% of prediceted margin (whichever is greater).

⚠**This concludes the steps that must be completed by Vehicles Lead.**

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ________________________________ Date: __________

Vehicle Design Lead: ________________________________ Date: __________

A.7.2.6 Motor Assembly and Installation

⚠**The following steps shall be performed ONLY by the team mentor. The Motor is highly energetic, and Dave is the only one on the team who is qualified to handle and install the motor.**

⚠**Motor Assembly and Installation should be performed after rocket assembly and before launch pad preparation.**

☐ Remove the motor from its packaging.

☐ Check that the motor is properly assembled according to manufacturer's instructions and inspect the motor for defects.

☐ Insert the propellant into the casing, ensuring that two spacers precede the propellant.

☐ Screw on the rear closure.

☐ Insert the motor into the rocket, ensuring proper motor direction.

☐ Attach the motor retainer.

☐ Check for a secure fit.

⚠**This concludes the steps that must be completed by the team mentor.**

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: ____________

Team Mentor: ______________________________ Date: ____________

Vehicle Design Lead: ______________________________ Date: ____________

A.7.2.7 Vehicle Setup and Launch Pad Preparation

⚠**Failure to properly prepare the vehicle on the launch pad can result in the rocket launching at a dangerous angle.**

☐ Register with LCO and RSO at launch site

☐ Lower the launch rail such that it is parallel to the ground.

☐ Slide the rocket onto the rail, motor-first, so that the rail buttons properly slide on the inside of the rail.

☐ Set rail angle to be 90° to the ground with added with a maximum of 7° into the wind.

☐ Raise the launch rail to the and orientation.

☐ Allow payload and subsystem teams to activate systems.

A.7.2.8 Igniter Installation

☐ Clear all personnel except for the team mentor.

⚠**The following steps detail the igniter installation and must be performed by the Team Mentor. Installing the igniter is a process that involves an energetic (the motor), and thus should be performed by qualified personnel only.**

☐ Check that the ignition wires, connected to launch control system, do not have a live voltage across them. This can be done by lightly touching the clips to each other, watching for sparks. If no sparks are thrown, it is safe to proceed.

☐ Remove the igniter clips from the igniter.

☐ Ensure that the igniter has properly exposed ends which are split apart.

☐ Insert the igniter into the motor.

☐ Attach the clips to the igniter, ensuring good contact.

⚠**This concludes the steps of igniter installation that must be completed by the Team Mentor.**

☐ Clear launch area of **all** personnel and retreat to spectating area

☐ If motor does not ignite when planned, wait 5 minutes before approaching.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: ____________

Team Mentor: ______________________________ Date: ____________

Vehicle Design Lead: ______________________________ Date: ____________

A.7.2.9 Post-Flight Vehicle Inspection

⚠ **Wait for approval from an officer to approach the rocket. They must first determine if the landing site and rocket are safe for recovery, or if there is a hazard present.**

- ☐ Ensure only members that have completed the ORR quiz are approaching the vehicle.
- ☐ Assess the landing site and vehicle for potential hazards, such as fire or smoke

⚠ **Do not approach unless given approval to do so by the safety officer**

- ☐ Examine the recovery section for unexploded black powder charges, if any are found, see the procedure outlined in the troubleshooting procedure section.
- ☐ Document state of rocket with photographs before moving any part
- ☐ Disconnect quick links where possible so that rocket can be transported more easily.

A.7.2.10 Motor Removal

⚠ **The following steps must be completed by the Team Mentor.**

⚠ **Failure to wear proper personal protective equipment during motor removal can result in burns to personnel.**

⚠ **Note that either leather gloves or heat resistant gloves can be used for the next step, but at least one must be used.**

- ☐ Using appropriate PPE, remove the motor retainer from the rocket.

⚠ **Team mentor Dave Brunsting will dispose of used motors.**

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ____________________ Date: __________

Vehicle Design Lead: ____________________ Date: __________

A.7.3 Recovery Squad Safety Checklist

A.7.3.1 Recovery Pre-Departure Checklist

⚠**Ensure the following items are packed. Check should be performed the morning before a launch, prior to leaving campus.**

☐ CRAM body
☐ CRAM core
☐ Raven 3 altimeters (3)
☐ Fully charged 9 volt alkaline batteries (3)
☐ 9 volt battery boxes (3)
☐ CRAM upper bulkhead
☐ CRAM Upper Filler
☐ CRAM lower bulkheads (4)
☐ CRAM retainment rods (3)
☐ 1/4-20 hex nuts (9)
☐ Washers (6)
☐ Lever Nut wire connectors (6)
☐ E-matches (6)
☐ Ensure mentor has secured black powder
☐ Eyebolts (2)
☐ Quick Links (4)
☐ Nylon shock cord (30 ft)
☐ Main parachute (14ft)
☐ Drogue Parachute (2ft)
☐ JollyLogic Chute Release (2)
☐ Chute Release Tether (2)
☐ Chute Release Bands (2)
☐ Large Nomex Parachute Protector
☐ Small Nomex Parachute Protector
☐ Laptop with Featherweight Interface Program installed
☐ Data cable for Raven altimeters
☐ Fire-retardant cellulose wadding
☐ Talcum Powder
☐ Sealing Clay

⚠**Checklist must be checked off by the Recovery Lead before departure for the launch site.**

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: __________

Recovery Design Lead: ______________________________ Date: __________

A.7.3.2 Recovery Pre-Departure Inspection

⚠**Failure to perform pre-departure inspection could allow critical defects to go unnoticed until launch, potentially causing recovery system failure.**

- ☐ Inspect fore recovery bulkhead for fatigue or failure in bulkhead and epoxied seal.
- ☐ Inspect aft recovery bulkhead for fatigue or failure in bulkhead and epoxied seal.
- ☐ Lay out the shock cord and tie knots in the locations where the drogue and main parachutes will be attached to mark their locations.
- ☐ Ensure that the ends of the main shock cord have loops to accept quick links. Check for holes or wear.
- ☐ Check the 9-volt and chute release batteries to ensure full charge.
- ☐ Connect each altimeter to a 9 volt battery throught the mounted screw terminals and connect the altimeter to a laptop through the mini-USB connector. Check the programming of the altimeter to confirm proper deployment programming.
- ☐ Ensure that 6 lever nut wire connections are properly epoxied to the upper CRAM bulkhead.

⚠**Pre-Departure Inspection must be checked off by recovery lead Joe Gonzales before departure for the launch site.**

A.7.3.3 Parachute Folding and Chute Release Installation

⚠**Incorrectly folding a parachute could result in tangling or catching on the rocket after deployment, which can result in dangerously fast rocket descent.**

⚠**Parachute folding should done after arriving at the launch site, and before installing the parachute in the rocket.**

- ☐ Connect parachute to quick link.
- ☐ Raise parachute into the air, making sure that all shroud lines are straight untangled.
- ☐ Pull the parachute flat, and then fold in half to bring all of the shroud lines into a nice orderly group.
- ☐ Fold both sides of the parachute to the middle tightly so that the parachute easily slides in and out of the launch vehicle.
- ☐ Continue by folding the parachute in half again and then zig zagging the main lines back and forth onto the parachute.
- ☐ Fold the parachute in half again so that the loop at the top of the parachute is visible.
- ☐ Attach both chute releases to the quick link connection using the chute release tethers.
- ☐ Use one chute release band to connect the releasable pin on one of the chute releases to the band connection on the other, creating a system of two chute releases in series.
- ☐ Wrap the chute releases around the folded parachute, and connect the releasable pin of the other chute release to the band connection of the first. This should created a system that contains the parachute until one of the chute releases activates.
- ☐ Ensure that both chute releases are on and programmed to the correct release altitude.
- ☐ Attach the Nomex parachute protector to the shock cord near the parachute connection.
- ☐ Wrap the folded parachute in the Nomex parachute protector.

⚠**Each parachute should be checked by Recovery Lead before installation into the rocket.**

A.7.3.4 CRAM Assembly

⚠**Incorrectly assembling the CRAM could cause the rocket to fail to separate at apogee, leading to a dangerous ballistic descent.**

⚠**Care should be taken at all times when performing any steps related to the use of black powder or e-matches. Black powder and e-matches are both potentially dangerous energetics that can be ignited by most ignition sources, including sparks, heat, or electrical potential.**

- ☐ For each battery box, run the red, positive wire through the CRAM filler and CRAM upper bulkhead, and connect them the to the corresponding lever nut wire connections epoxied to the top of the bulkhead.
- ☐ Connect red wires from the lever nut wire connectors on the top of the bulkhead to the corresponding positive port on the altimeters.
- ☐ Connect the negative of each battery box to the "GND" on the corresponding altimeter.
- ☐ Connect blue wires from the "Apo" terminal on each altimeter to the corresponding ground lever wire nut connection on the upper bulkhead.
- ☐ Ensure that each battery box has a charged battery in it and that the power switch is in the "off" position.
- ☐ Using zip-ties, attach each altimeter to the back of the corresponding battery box.
- ☐ Using electrical tape, attach the three battery boxes to the central CRAM core.
- ☐ Bolt the CRAM upper bulkhead, body, and lower bulkhead together using tie rods, washers and hex nuts.

⚠**The next step must be performed by NDRT team mentor, Dave Brunsting.**

- ☐ Create three ejection charges using an e-match and black powder. Ensure that the e-match loose wires are shunted together to prevent accidental ignition of the black powder.
- ☐ Re-check to ensure that the battery box switches are all in the "off" position.
- ☐ Connect each loose ejection charge wire to its corresponding lever wire connector.
- ☐ Place each ejection charge in its corresponding PVC charge well.
- ☐ Cover each charge well with painter's tape to keep the charge in place.
- ☐ Ensure all wire holes in the CRAM upper bulkhead are plugged with sealing clay.

⚠**The CRAM assembly should be checked by recovery lead Joe Gonzales before installation.**

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: __________

Recovery Design Lead: ______________________________ Date: __________

A.7.3.5 CRAM Integration

⚠**Failure to properly integrate the CRAM into the rocket could result in rocket separation failure and a dangerous ballistic descent.**

⚠**CRAM integration can only be done after CRAM assembly is fully completed.**

- ☐ Feed the aft end of the shock cord through the top of the assembled CRAM.
- ☐ Connect a quick link to the aft end of the shock cord
- ☐ Connect the quick link to the eyebolt embedded in the aft recovery bulkehad. Ensure that is tightly screwed closed.
- ☐ Insert the assembled CRAM into the fore end of the recovery tube, ensuring proper alignment with the body tube markings, air holes, and pressure ports.
- ☐ Bolt the CRAM to the epoxied-in aft recovery bulkhead, ensuring tight connection with hex nuts.
- ☐ Ensure that the switch ports and air holes in the CRAM are visible from the holes in the airframe.

⚠**Proper CRAM integration should be checked by both the Recovery Lead and Vehicle Lead.**

A.7.3.6 Parachute Installation

⚠**Failure to properly install the parachute could result in failed parachute deployment and dangerously fast rocket descent.**

⚠**Parachute installation can only be done after parachute folding and CRAM installation.**

- ☐ Ensure that both the drogue and main parachutes are properly connected to the shock cord and enclosed in the Nomex parachute protectors.
- ☐ Re-check to ensure that both chute releases are on and operable.
- ☐ Connect the fore end of the shock cord to the eyebolt in the fore recovery bulkhead with a quick link, ensuring that the quick link is screwed closed.
- ☐ Fold the excess shock cord together in an accordion fashion and loosely tape it together with a single layer of painter's tape.
- ☐ Place several handfuls of cellulose recovery wadding in the recovery tube, near the top of the CRAM.
- ☐ Lightly coat the outside of the main and drogue parachutes with talcum powder.
- ☐ Place the folded main parachute in the recovery tube.
- ☐ Place the folded drogue parachute in the recovery tube.

⚠**Parachute installation should be checked off by recovery lead Joe Gonzales.**

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: __________

Recovery Design Lead: ______________________________ Date: __________

A.7.3.7 Deployment System Arming

⚠**System arming should only be done when the rocket is vertical on the launch pad, just prior to launch.**

⚠**Failure to properly arm the recovery system may lead to rocket separation failure and a dangerous ballistic descent.**

- ☐ Using a screwdriver, flip the switch on one of the battery boxes to the "on" position.
- ☐ Listen to the beep sequence of the altimeter. The Raven should give 9 low beeps, indicating a 9-volt charge on the battery, and then enter a sequence in which it gives one high beep, then three low beeps. This indicates that one of the deployment channels (the "Apo" channel) is connected, and the other channels are disconnected. Deviation from this beep sequence is a problem that needs to be corrected before launch.
  - ☐ Repeat the arming sequence for the other two altimeters.

⚠**Proper system arming should be checked by the Recovery Lead.**

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: __________

Recovery Design Lead: ______________________________ Date: __________

A.7.3.8 Recovery Post-Flight Inspection

- ☐ Before touching the rocket, take pictures in landed state, paying specific attention to the positions of the shock cord and parachutes.
- ☐ Ensure all three ejection charges have properly fired. If this is not the case, follow Troubleshooting procedures relating to removal of black powder charges from the rocket.
- ☐ Bring launch vehicle back to staging table and remove the CRAM. Turn off all but the main altimeter and invert the CRAM.
- ☐ Listen to and record the altitude provided by the Raven altimeter.
- ☐ Inspect the parachutes, chute releases, shock cords, CRAM, bulkheads, connections, and launch vehicle for any damage sustained during the flight.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: __________

Recovery Design Lead: ______________________________ Date: __________

A.7.4 ABS Safety Checklist

Launch procedures for the Air Braking System (ABS) shall begin under the discretion of ABS lead Eric Dollinger. ABS power and integration steps will begin under the discretion of Vehicles lead Riley Mullen. This shall be done to minimize the time between loading the ABS into the fin can and the time of launch to reduce the risk of draining the battery prematurely. ABS launch procedures shall consist of inspection of the payload for defects, powering of the system, inspection of the status LEDs for proper controller startup, and installation into the fin can of the rocket.

A.7.4.1 ABS Pre-Departure Checklist

⚠**Ensure the following items are packed**

- ☐ Assembled Air Braking System
- ☐ Assembled ABS Electronics
- ☐ ABS Electronics Toolbox
- ☐ Wrench set
- ☐ Allen Wrench set
- ☐ Screwdriver set
- ☐ Fire-Proof Battery case
- ☐ Digital Multi-meter
- ☐ Wire Strippers
- ☐ 6-32 nylon screws
- ☐ 10-32 nylon screws
- ☐ 6-32 nylon lock nuts
- ☐ 10-32 nylon lock nuts

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: __________

ABS Design Lead: ______________________________ Date: __________

A.7.4.2 ABS Pre-Flight Setup

☐ Inspect Air Braking System for proper construction assembly and material defects. After ensuring power is disconnected, inspect the mechanical system for loose screws and bent components, particularly the drag tabs.

⚠**Hazards: -Damage to the ABS and rocket may occur as a result of dangerous conditions created if a mechanical defect is not identified.**

☐ If physically inspecting the mechanism, ensure power is disconnected to reduce risk of pinching of fingers.

☐ With the battery disconnected from the printed circuit board, Inspect electronics for secure connections and component mounting.

☐ Inspect the battery for punctures, swelling, chemical odors, or other signs of defects.

⚠**If a battery defect is detected, the battery should immediately be placed in the fire proof battery case and the ABS lead and Safety officer should be notified. A backup battery should be inspected and installed in the event of a defective battery. Under no circumstances should a potentially defective battery be flown.**

☐ Install the battery and ensure the snap cover battery case cover is secured.

☐ Ensure the proper control code has been installed on the Arduino MKR Zero.

☐ Ensure the SD card is inserted in the Arduino prior to powering the system.

⚠**Hazards: if the SD card is not inserted prior to powering the Arduino, data cannot be stored to the SD card and system failure will occur.**

☐ After receiving confirmation from Vehicles lead Riley Mullen that the vehicle is prepared for the installation of the Air Braking System, connect the battery's molex connector to the printed circuit board and flip the power switch.

☐ Confirm that the power-LED has lit.

☐ Inspect the status LEDs for the sensors and SD card to ensure the Arduino controller is properly receiving sensor data and writing to the SD card.

☐ In the event that these lights do not turn on, notify ABS lead Eric Dollinger or a member of the ABS control coding group immediately.

⚠**Hazard: If data is not properly measured and stored, mission failure occurs.**

☐ If ABS is to be active for this flight, turn on the Arming switch. Ensure that the arming LED turns on.

☐ Check that the drag tabs are flush with the support plates.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: __________

ABS Design Lead: ______________________________ Date: __________

A.7.4.3 ABS Integration

☐ Under the direction of Vehicles lead Riley Mullen, begin installing the ABS into the fin can. The ABS integrates via 4 threaded steel rods which run through dedicated holes in the bulkheads of the ABS.

☐ Ensure that the ABS fully slots into the fin can and sits evenly.

☐ Inspect the drag tab cutouts in the fin can to ensure that the tabs are visible and have clearance to extend.

⚠**Hazard: If the tabs do not fit properly in the cut slots of the fin can, jamming is likely to occur which leads to mission failure and potential motor stalling, increasing the risk of damage to mechanical components, the motor, and the battery.**

☐ Place one #10 washer and a locknut on each of the threaded rods at the top of the forward ABS bulkhead to secure them to the fin can.

☐ Inspect through the barometric vent holes to ensure that the LEDs are still lit and indicate the system is not prematurely in the launched state.

☐ Make a final inspection of the system's installation for any obvious defects or abnormalities.

☐ Get a signature of approval from ABS lead Eric Dollinger, Vehicles lead Riley Mullen, and Safety lead Jed Cole.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________ Date: __________

ABS Design Lead: ______________________ Date: __________

A.7.4.4 ABS Post-Flight Inspection and Data Retrieval

⚠**Post launch inspection**

- ☐ Use a wrench to unscrew the lock nuts from the integration rods at the forward bulkhead of the ABS. Remove the locknuts and washers.
- ☐ Check that the drag tabs are fully retracted to avoid jamming the ABS in the fin can while removing. Note if that tabs are not retracted.
- ☐ Carefully remove the ABS from the fin can by lifting with the U bolt at the forward bulkhead of the ABS.
- ☐ Inspect the avionics system for power and status LED indication to determine if power was lost during flight or landing.
- ☐ Flip the power switch to turn off the system.
- ☐ Inspect the battery for damage. If damaged, place in the fire-proof battery case for safe storage.
- ☐ Inspect and note any damage to the mechanical system or payload assembly.
- ☐ Remove the micro SD card from the Arduino MKR Zero.
- ☐ Insert the microSD card into the SD card adapter and plug into a laptop. Open the data log file on the SD card and verify successful flight metrics.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________ Date: __________

ABS Design Lead: ______________________ Date: __________

A.7.5 UAV Safety Procedure

A.7.5.1 UAV Pre-Departure Checklist

- ☐ **Deployment Electrical Components**
  - ☐ 116 RPM 3-12V Planetary Gearmotor w/ Encoder (104:1 ratio) #638298
  - ☐ FS5106R servo motor
  - ☐ E-flite 800mAh 3S 11.1V 30C LiPo 18AWG JST Battery
  - ☐ BNO055 sensor
  - ☐ Ximimark 433MHz ASK Wireless Remote Control Transmitter and Receiver Module Kit STX882+SRX882 With Copper Spring Antenna
  - ☐ Arduino MKR Zero (with HEADERS)
- ☐ **UAV Body Mechanical Components**
  - ☐ 4 arms
  - ☐ 2 body plates
  - ☐ 4 aluminum struts
  - ☐ 2 left-hand wound torsion springs
  - ☐ 2 right-hand wound torsion springs
  - ☐ 4 aluminum spacers
  - ☐ 4 one inch long, 8-32 threaded rods
  - ☐ 8 locknuts
  - ☐ 8 hex nuts
  - ☐ Ratcheting Screwdriver Bit Set
- ☐ **UAV Platform Components**
  - ☐ 5 R-clips
  - ☐ Roll of braided fishing line
  - ☐ Scissors
  - ☐ 3D-printed platform with epoxied aluminum flanges
  - ☐ 2 nylon hex nuts
  - ☐ 30lb J-Braid fishing line
  - ☐ Epoxy
- ☐ **UAV Body Electrical Components**
  - ☐ 5 motors (1 is a backup)
  - ☐ 5 ESCs (1 is a backup)
  - ☐ Pixhawk 4
  - ☐ 2 Raspberry Pi 3 Model B (one back)
  - ☐ 5 carbon fiber props (1 is a backup)

- ☐ Turnigy 4500mAh LiPo
- ☐ LiPo battery fireproof bag
- ☐ 2 Raspberry Pi Camera Module V2 (1 is a backup)
- ☐ Power Distribution Board
- ☐ BEC voltage regulator
- ☐ Adapter Rings
- ☐ Battery charger/low-voltage checker
- ☐ Cable zip ties
- ☐ Velcro straps
- ☐ Metric screws (for motors)
- ☐ EACHINE VTX03 Super Mini 5.8 GHz 72CH FPV Transmitter (on ground)
- ☐ UCEC Video Capture USB 2.0 (on ground)
- ☐ 5.8GHz 40CH FPV Wireless AV Video Receiver (on drone)
- ☐ MT60 Connectors
- ☐ XT60 Bullet Connectors
- ☐ XT90 Connectors
- ☐ FrSky Taranis X9D Plus 2.4 GHz ACCST Radio
- ☐ 3 Laptops: one ground station laptop with QGroundControl and two laptops with VLC Media Player

☐ **Beacon Delivery Subsystem**

- ☐ 1 3D-printed beacon platform
- ☐ 2 3D-printed NDRT beacons
- ☐ 2 FS90R servos (1 is a backup)

☐ **UAV Deployment Mechanical Components**

- ☐ Aft rotating bulkhead
- ☐ Fore rotating bulkhead
- ☐ Aft L-cross-section track
- ☐ Aft O-shaped internal ring gear
- ☐ Fore L-cross-section track
- ☐ Fore O-shaped track
- ☐ Pinion for orientation correction
- ☐ 2 carbon fiber tubes
- ☐ Leadscrew
- ☐ Aluminum coupler for gear motor shaft and leadscrew attachment
- ☐ Aluminum coupler for gear motor and aft rotating bulkhead attachment
- ☐ 12 Self-tapping screws for aft L-cross section attachment to fiberglass body tube
- ☐ 2 nylon hex nuts

☐ 2 aluminum couplers for carbon fiber tube and aft rotating bulkhead attachment
☐ 12 bolts for attachment of aft L-cross-section track to aft O-shaped internal ring gear
☐ 12 washers for attachment of aft L-cross-section track to aft O-shaped internal ring gear
☐ 12 hex nuts for attachment of aft L-cross-section track to aft O-shaped internal ring gear
☐ 12 bolts for attachment of fore L-cross-section track to aft O-shaped track
☐ 12 washers for attachment of fore L-cross-section track to aft O-shaped track
☐ 12 hex nuts for attachment of fore L-cross-section track to aft O-shaped track

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: __________

UAV Design Lead: ______________________________ Date: __________

A.7.5.2 Checking UAV Battery Levels

⚠**Failure to confirm the charge on the Lithium-Polymer battery can result in the battery running out of charge mid-flight, which will cause mission failure and potentially resulkt in damage to the UAV.**

⚠**Lithium-Polymer batteries are potentially dangerous energetics and must be treated with care. Any batteries that are suspected to be damaged should be immediately placed in a fireproof battery bag, and the Safety Officer informed.**

- ☐ Insert Lithium-Polymer voltage reader into the balance charging connector on the battery.
- ☐ Verify each cell has a 4.2 voltage potential.
- ☐ Balance charge on a balance charger if voltage is between 3.0 V and 4.2V.
  - ☐ Do not use batteries with voltages below 3.0 V.
  - ☐ Do not use batteries with unbalanced cell voltages.

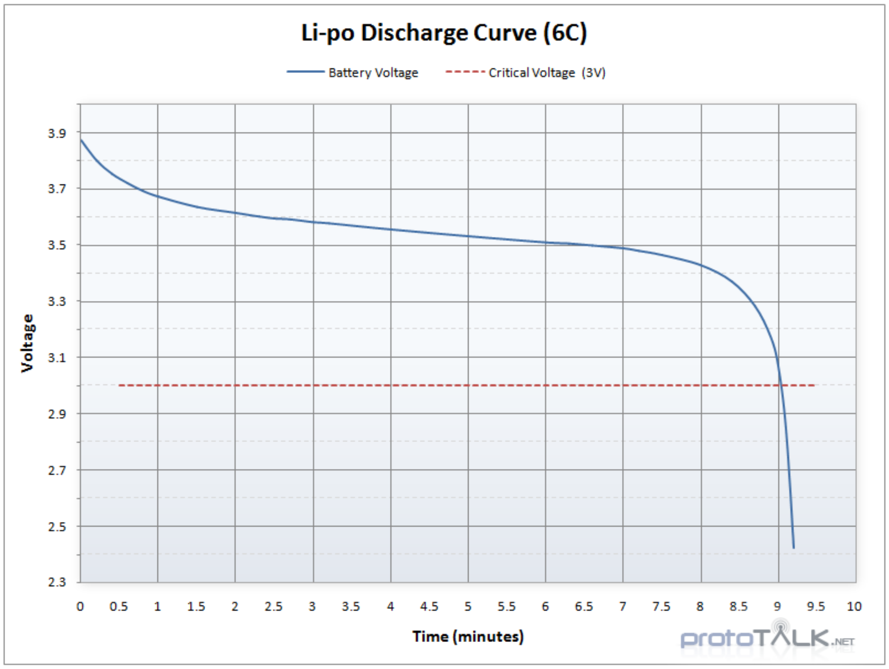


Figure 106: Lithium-polymer voltage discharge curve

A.7.5.3 Wiring Up the ESC

⚠**Failure to properly wire up the ESC can result in UAV failure, potentially mid-flight.**

- ☐ Disconnect battery.
- ☐ Follow motor and ESC numbering according to Figure 107, below.
- ☐ Follow proper motor and ESC numbering.
- ☐ Connect each signal wire to the correct location on the Power Distribution Board. The Power Distribution Board has pins M1, M2, M3, and M4 that control the corresponding motor.

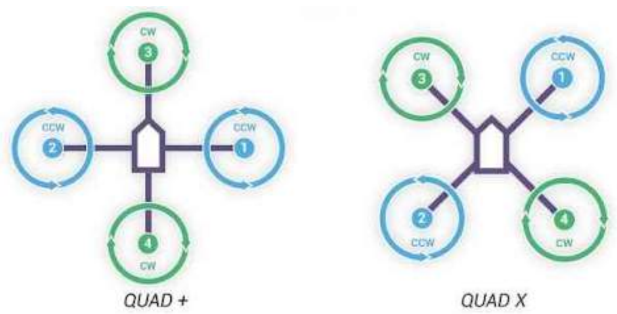


Figure 107: Motor numbering and orientation for UAV configuration

A.7.5.4 Confirming UAV Motor Spin Direction

⚠**Failure to confirm the spin direction of the UAV propellers can result failure of, or damage to, the UAV.**

- ☐ Remove propellers from UAV.
- ☐ Apply masking tape to motors.
- ☐ Turn on transmitter with throttle at zero power.
- ☐ Connect battery.
- ☐ Provide power to motors.
- ☐ Check the direction of rotation by examining the masking tape.
- ☐ Reverse rotation direction on incorrect motors by swapping two wires between the ESC and motor.

⚠**Ensure propellers are mounted correctly.**

- ☐ Disconnect battery.
- ☐ Following Figure 107, mount two clockwise propellers and two counterclockwise propellers.
- ☐ Mount two clockwise propellers and two counterclockwise propellers.
- ☐ Insert hex key into through-hole on fastening bolt and hand tighten.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ________________________________ Date: ____________

UAV Design Lead: ________________________________ Date: ____________

A.7.5.5 UAV Deployment System Preparation and UAV Installation

⚠**Failure to properly prepare the UAV deployment system can result in failure of the UAV to deploy or potentially failure to retain the UAV in flight, causing damage to the payload.**

- ☐ Ensure that the aft rotating bulkhead and track mechanism is locked in place via the FS5106R servo.
- ☐ Ensure that the belt and pulley system is in working order via a short test to check that the movement of one arm is synchronized with the movement of the remaining three arms of the UAV.
- ☐ Fold the arms of the UAV into the proper position, ensuring that the torsion springs are in place and in compression. At this time, also ensure that both buttons for the button-on-arm electronic trigger are compressed via the two contacts.
- ☐ Check that all electronics are mounted properly and safely to the top plate of the UAV.
- ☐ Inspect 4500mAh LiPo battery for punctures, swelling, chemical odors, or other signs of defects.
- ☐ Check that the 4500mAh LiPo is properly and safely secured between the two plates of the UAV.
- ☐ Inspect that the other deployment electronics are secured on the aft rotating bulkhead and are fully functional.
- ☐ Check that the Beacon Delivery Subsystem contains both beacons.
- ☐ Check that the Raspberry Pi Camera Module V2 is mounted on the UAV and can stream video to the CPU on the ground.
- ☐ Make sure that each of the four props has enough clearance to spin.
- ☐ Tie the polyethylene fiber wire to the four eyebolts mounted on the aft rotating bulkhead, and tie the other end of the wire to four stainless steel cotter pins.
- ☐ Secure each of the four aluminum struts of the UAV into each of four 3D-printed custom pipe flanges mounted on the UAV platform for deployment.
- ☐ Insert the four stainless steel cotter pins through the flanges and the struts to ensure that the UAV will be properly restrained during flight.
- ☐ Complete a brief shake test to ensure that the pins were inserted correctly so that the UAV will not move during flight.
- ☐ Connect the fore rotating bulkhead, housing, and nosecone section by reversing the direction of the leadscrew in order to screw the fore bulkhead onto the leadscrew to proper orientation.
- ☐ Place the entire system inside the rocket and align it so that the holes on the bulkhead housing align with the holes on the surface of the rocket body.
- ☐ Insert screws into the designated holes and ensure the system is secured by conducting a shake test.
- ☐ If time allows, conduct a test with full deployment sequence as a final check for the electronic and mechanical components of the system.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: __________

UAV Design Lead: ______________________________ Date: __________

A.7.5.6 UAV Startup with Active Telemetry

⚠**Failure to properly activate the UAV can result in UAV, and ultimately mission, failure.**

- ☐ Turn on 2.4 GHz Taranis transmitter.
- ☐ Place throttle at zero and throw the mission switch to manual flight (Position UP).
- ☐ Have a second person plug in battery.
- ☐ Plug in computer pair of 433 Hz telemetry set.
- ☐ Connect the UAV to QGroundControl software on laptop.
  - ☐ When the pilot is ready to fly, have a second individual press and hold the safety switch on the GPS module mounted on the UAV.
- ☐ Once the area is clear, the pilot should arm the UAV by placing the throttle stick in the DOWN and RIGHT position.
  - ☐ On "Comm Links" page, click on the correct serial port and click "Connect".
- ☐ From the computer, define the mission in QGroundControl.
- ☐ Pilot may choose to takeoff or remain on the ground.
- ☐ Flip the mission switch down to autonomous mode (Position DOWN).
- ☐ The autonomous software will override manual controls to takeoff, navigate to destination, and land.
- ☐ Pilot can take over manual control at any point by flipping the mission switch to manual flight (Position UP)
- ☐ Once the UAV has landed, pilot disarms UAV by placing throttle stick in the DOWN and LEFT position.
- ☐ Once the UAV is disarmed, the UAV may be approached.
- ☐ Press and hold the safety switch.
- ☐ Disconnect the battery.

A.7.5.7 UAV Startup without Telemetry

⚠**UAV Startup Procedure – without telemetry**

⚠**Failure to properly activate the UAV can result in UAV, and ultimately mission, failure.**

- ☐ Turn on 2.4 GHz Taranis transmitter.
- ☐ Place throttle at zero and throw the mission switch to manual flight (Position UP).
- ☐ Have a second person plug in battery.
- ☐ When the pilot is ready to fly, have a second individual press and hold the safety switch on the GPS module mounted on the UAV.
- ☐ Once the area is clear, the pilot can arm the UAV by placing the throttle stick in the DOWN and RIGHT position.
- ☐ Pilot may takeoff and fly as needed.
- ☐ Once the UAV has landed, pilot disarms UAV by placing throttle stick in the DOWN and LEFT position.
- ☐ Once the UAV is disarmed, the UAV may be approached.

☐ Press and hold the safety switch.

☐ Disconnect the battery.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: __________

UAV Design Lead: ______________________________ Date: __________

A.7.5.8 UAV Post-Flight Inspection

⚠**Removal of UAV if deployment system fails or takeoff fails**

- ☐ Pilot disarms UAV by placing throttle stick in the DOWN and LEFT position.
- ☐ Remove nose cone manually, if not removed by deployment system.
- ☐ Once the UAV is disarmed, the UAV may be approached.
- ☐ Press and hold the safety switch.
- ☐ Disconnect the battery.
- ☐ If the steel cotter pins are still connected to the flanges and struts of the UAV, manually disconnect the steel cotter pins.
- ☐ Manually position the track system so the UAV can be easily lifted out of the opening.
- ☐ Remove UAV using hands.

⚠**Deployment System Examination**

- ☐ Unscrew the screws connecting the rocket body from the bulkhead housing and carefully remove the system from the rocket.
- ☐ Inspect the system to check for any broken parts, misplaced components, or any other defects. Check the LiPo battery for any signs of damage.
- ☐ Disconnect the system by removing the component with the nose cone, fore bulkhead, and housing.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: ______________________________ Date: ______________

UAV Design Lead: ______________________________ Date: ______________

A.7.6 Troubleshooting Safety Checklist

A.7.6.1 Catastrophic Motor Failure (CATO)

A catastrophic motor refers to any major failure of the rocket motor that occurs while the motor is burning. It is typically characterized by some form of explosion or fire on the rocket.

⚠**DO NOT attempt to catch any falling rocket. A rocket that has undergone a motor failure may be on fire and could be in an uncontrolled, rapid descent. Take care and precaution when following the proceeding steps.**

☐ After the rocket lands, ensure it is not on fire. If it is on fire, maintain a safe distance until the fire goes out.

⚠**The following steps should be performed with heat resistant gloves. Any parts handled after a CATO event will most likely be very hot, which can cause severe burns or other injuries. If handling any parts with jagged edges, handle with leather gloves, as these will provide protection from sharp and jagged edges and heat.**

☐ DO NOT touch the motor end of the rocket. It is likely to still be hot after the motor burn. Carry the rocket back by the shock cord or very top of the fin can section.

☐ Using heat-resistant gloves, take the motor retainer off and pull the motor out of its mount.

☐ Examine the motor to ensure that all of the propellant has burned off. Occasionally, slivers of propellant will be left in the motor casing after an motor failure. If there is propellant, consult the team mentor for the best way to remove and dispose of the propellant.

☐ Carefully remove all batteries from the rocket and place them in a fireproof battery bag. DO NOT use these batteries in another launch, as they may be internally damaged.

  ☐ Recover what data can be recovered from the various data storage units in the rocket payloads and subsystems.

A.7.6.2 Failure to Separate at Apogee

If the rocket fails to separate at apogee, it will descend in a rapid, nose-down, ballistic trajectory that can cause severe injury if it strikes a person.

⚠**Always be looking at the rocket as it comes down. It is helpful to point at the rocket as it descends to alert others to the trajectory.**

⚠**If the rocket appears to be coming in your direction, quickly but calmly walk away from your current area.**

☐ Wait for the team Safety Officer and team mentor to confirm that the rocket is safe before touching the rocket.

☐ After bringing the rocket back to the launch preparation area, remove the motor casing and all batteries, placing the batteries in a fireproof battery bag.

⚠**DO NOT use these batteries in another launch, as they may be internally damaged.**

☐ Recover what data can be recovered from the rocket and its payloads.

A.7.6.3 Altimeter Issue on the Launch Pad

The Raven altimeter performs a continuity check before flight to ensure that all ejection charges are properly connected. Should the altimeter fail this check on the launch pad, the altimeters may need to be removed and examined.

⚠**Ensure that the battery box switches are in the "off" position. Failure to turn off the altimeters could result in unintentional black powder ignition.**

☐ Take the rocket off of the launch pad and back to the preparation table.

☐ Take the shear pins out of the rocket and separate the sections.

☐ Remove the parachute, Nomex protector and shock cords from the rocket.

☐ Unscrew the locking screws connecting the fin can and recovery tube sections of the rocket.

☐ Unbolt the CRAM from the aft recovery bulkhead.

☐ Slide the CRAM out of the rocket.

⚠**Recheck to ensure that the battery box switches are in the "off" position. Failure to do so could result in unintentional black powder ignition.**

☐ Disconnect the black powder charges from the lever nut wire connections.

☐ Unbolt and remove the CRAM upper bulkhead and filler.

☐ Remove the CRAM core and examine the altimeter wire connections for defects. If none are detected, plug the Raven altimeters into a computer for diagnostics. Consult the user's manual for more information.

A.7.6.4 Tight Fitting Parachute

If the folded parachute is very tight inside the parachute bay, it may not slide out upon separation, which will result in the rocket descending much faster than normal. This can happen with both spring-powered and black powder recovery systems.

⚠**DO NOT attempt to force the parachute into the bay. This can prevent clean separation at apogee and potentially damage the rocket or parachute.**

☐ Take the parachute out of the rocket.

☐ Unfold the parachute and refold according the standard procedures.

☐ Ensure that all folds are crisp and that the finished parachute is very tightly rolled.

☐ Reattach the Chute Releases. Ensure that the Chute Releases are turned on.

☐ Re-wrap the parachute in Nomex.

☐ Proceed to re-install the parachute in the rocket using standard procedure. A layer of talcum powder on the parachute and coupler may also help the parachute to slide out.

A.7.6.5 Binding Subsystem

A subsection or payload of the rocket may bind and become stuck while attempting to install it. This can happen to the ABS, recovery system, UAV payload or the rocket couplers.

⚠**DO NOT attempt to force the piece into the rocket. This may cause damage to the rocket or the stuck payload.**

☐ Carefully take the system out of the rocket.

☐ Ensure that the system is rotated and oriented correctly.

☐ Attempt to reinsert the system, paying careful attention to the orientation of the system and exactly what pieces are causing the issue.

☐ If the system still binds or becomes stuck, take the system out and use sandpaper to sand away the section that is binding. Repeat until the system fits into the rocket smoothly.

A.7.6.6 Ignition failure

Occasionally, a rocket motor will fail to ignite on the pad. This can be caused by numerous issues, such as faulty igniters, incorrect installation, faulty launch equipment, and damaged motor.

☐ After a failed ignition, the LCO of a launch range will typically attempt another ignition. If this fails, proceed to step 2.

⚠**The remaining steps should only be performed by the Team Mentor.**

☐ Disconnect the igniter from the ignition clips.

☐ Carefully remove the igniter from the motor.

☐ Install another igniter, paying careful attention to standard procedure, and attempt another ignition.

☐ If this ignition fails, take the rocket off the pad, take the motor out and inspect it for damage or incorrect assembly.

☐ If the motor appears in good condition and properly assembled, inspect the launch system to ensure that it is properly set up, in good condition, and has a charged battery. The range LCO should perform this inspection.

☐ Put the rocket back on the pad and attempt another ignition with a fresh igniter. If this fails, consult the team mentor for further troubleshooting.

A.7.6.7 Removing Black Powder Charges

In the unlikely event that a black powder charge remains intact during descent, the charge must be removed before regular post-launch procedures can commence.

⚠**Ensure that all altimeters are fully powered off by flipping the switches on the attached battery boxes into the "off" position.**

☐ Unscrew the locking screws that connect the fin can and the recovery tube. Disconnect the two pieces.

☐ Unbolt the CRAM from the aft recovery bulkhead.

☐ Remove the CRAM from the body tube.

⚠**Re-check to ensure that the battery box switches are in the "off" position.**

☐ Unhook the black powder charges from the level nut wire connections. Remove the charges from the charge wells.

☐ Dispose of the charges through University Hazardous Waste procedures.

A.7.6.8 Exposed and/or severed wire

Sometimes wires can become damaged or even severed. This can interfere with the wires ability to transmit current, and can pose a danger, as some wires transmit danger levels of power, which would be unsafe for personnel to be exposed to.

⚠**For personnel safety, ensure that power source is turned off and disconnected from wire being operated on**

☐ Inspect wire to see if damage is repairable

☐ If so, make repair, if not proceed to next step

☐ Inspect to see if wire can be easily replaced with a spare wire

☐ If so, replace wire, if not proceed to next step

☐ Carefully pack system up so that it does not become further damaged, and transport back to university, where system can be repaired.

A.7.6.9 Punctured or damaged battery

Extremely dangerous, if believed to be damaged at all, battery should not be used AT ALL. Instead, they should be safely rendered inert and disposed of.

⚠**PPE required is leather gloves (for heat and general protection), safety goggles (for eye protection from fumes and particulate), lab coat (to protect skin from particulate and fire), and dust mask (to help protect from inhalation hazards)**

☐ If battery is believed to be damaged, approach with caution, as it should be considered an exploding hazard. Only personnel chosen to handle it, and wearing proper PPE, should approach it.

☐ Battery should be handled with care, and held away from face and body.

☐ Place battery in fireproof battery disposal bag

☐ Bring battery to qualified and authorized disposal site

I certify and attest that the above checklists have been fully and properly completed as necessary in the event of the team encountering any of the occurrences that are described above.

Safety Officer: ______________________________ Date: __________

Team Captain: ______________________________ Date: __________

Describe the event that occurred, as well as which troubleshooting checklist was used: