University of Notre Dame
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NOTRE DAME ROCKETRY TEAM
FLIGHT READINESS REVIEW

NASA STUDENT LAUNCH 2020

LUNAR SAMPLE RETRIEVAL SYSTEM AND AIR BRAKING SYSTEM

Submitted March 2, 2020

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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
CFEA	Competition Future Excursion Area
CNC	Computer Numerical Control
CPU	Central Processing Unit
CRAM	Compact Removable Avionics Module
DSM	Digital Spectrum Modulation
ESC	Electronic Speed Controller
FEA	Finite Element Analysis
FMEA	Failure Modes and Effects Analysis
FPS	Frames Per Second
FPV	First-Person View
ID	Inner Diameter
IMU	Inertial Measurement Unit
LED	Light Emitting Diode
LiPo	Lithium Polymer
NDRT	Notre Dame Rocketry Team
OD	Outer Diameter
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 Report

1.1 General Information

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1.2 Launch Vehicle Summary

The launch vehicle is 134 in. long with a loaded mass of 798 oz. The final motor choice is a Cesaroni L1395, which will allow the vehicle to attain the target altitude of 4,444 ft after launching from a 12 ft 1515 rail. The drogue parachute is a FruityChute CFC-24 and will deploy at apogee, and at 600 ft. the the main parachute, a FruityChute Iris Ultra 120 Compact, will deploy.

1.3 Payload Summary

Lunar Sample Retrieval System

The primary payload experiment is a Lunar Ice Sample Retrieval System, which includes a Rover and an Unmanned Aerial Vehicle (UAV). The payload will be secured in the launch vehicle for flight and recovery, and a black powder charge will eject the nose cone at 450 ft. for deployment purposes. The Rover, powered by an eccenctric crank mechanism, will be activated to pull out the UAV upon landing. The autonomous UAV, with a fail-safe manual override system, will ascend and find a Competition Future Excursion Area (CFEA) using computer vision and target detection algorithms. The UAV will then descend to the CFEA, land, and transmit the GPS coordinates of the CFEA to the Rover. The Rover will deploy upon reception of the coordinates, drive to the center of the CFEA, and activate an Archimedes screw sample retrieving system. Finally, the Rover will transport the 10 mL sample 10 ft.

Air Braking System

The secondary payload experiment is an Air Braking System (ABS), which implements a control system for inducing a variable drag force in order to meet the target apogee of 4,444 ft. A set of four drag surfaces extend from the body of the launch vehicle to increase the acting drag force, therefore decreasing the projected apogee, until the target has been achieved. The system uses a Raspberry Pi microcontroller to filter and record altitude and velocity sensor data and run a closed loop PID control algorithm to adjust the extension of the drag tabs until the predicted apogee matches the target apogee. The microcontroller adjusts the extension of the drag tabs by actuating a servo motor, which drives a mechanism to deploy and retract the drag tabs.

2 Changes Since CDR

2.1 Changes Made to Launch Vehicle Criteria

Table 2: Changes Made to Launch Vehicle Criteria

Decision	Justification
Remove twist and lock telemetry retention from nosecone	Unnecessary weight. Securing will be done with a simpler and lighter design to keep stability between 2 and 3 calibers.
Recovery altimeters will no longer be powered on using Featherweight magnetic switches.	Per the advice of NASA and the team's launch manager, the rotary switches were chosen as the system's breaker. These are connected directly to the batteries and the e-matches. Rotary switches mitigate premature actuation.
The dipole antenna used in the Rocket Transmitter module was changed from the ANT-433-MHW-SMA-S to the Ready Made RC Dipole Antenna.	This was mainly to reduce weight, since the ANT-433-MHW-SMA-S is surrounded by a plastic shell that the Ready Made RC Antenna does not have. Since both antennas are dipole antennas, there is very little difference in their performance.
Telemetry LiPo battery was changed from the one cell Adafruit Lithium Ion Polymer Battery - 3.7V 2500mAh battery to the two cell Admiral 1000mAh 30C LiPo battery.	After choosing the MAAM-009560 20 dB power amplifier to amplify the signal output from the ADF7030, the system required a 5V regulated power supply to correctly bias the power amplifier. This two cell battery has a nominal output voltage of 7.2V, which allows a linear 5V regulator to be used to produce the 5V supply needed for the power amplifier.
An in-line lowpass filter with a cutoff frequency of 450MHz was added between the output of the transceiver board and the dipole antenna.	After testing the output of the transceiver boards, it was discovered that the power amplifier was outputting the main signal at 433MHz, as well as some small signals at some harmonic frequencies. This was included in the various tests of the system, and effectively eliminated the harmonic signals while producing no noticeable effects on performance.
The retention system for the onboard telemetry system was changed to a G10 Garolite retention ring and bulkhead secured by steel bolts and locknuts.	This change was made due to weight considerations, as the original design in CDR weighed significantly more. The actual weight of the additively manufactured ASA plastic nose cone was greater than anticipated, and the the telemetry system's mass budget was reduced by 25 ounces to compensate.

2.2 Changes Made to Payload Criteria

Table 3: Changes Made to Payload Criteria

Decision	Justification
Addition of ball bearings to the sliding platform standoff	To ensure that the LSRS is able to freely rotate within the Payload Bay and overcome any friction force.
Rails on the Rail Platform made from Nylon 6	To reduce the cost of manufacturing the Rail Platform, the rails of the platform were laser cut out of Nylon 6 and epoxied into the platform.
Tread placed around Rover wheels	To prevent the links of the Rover cocking during motor actuation and ensure that the eccentric crank mechanism moves properly.

2.3 Changes Made to Project Plan

Table 4: Changes Made to Project Plan

Decision	Justification
Excess Vehicle Design budget was utilized to purchase LSRS and Recovery Subsystem components	The Vehicle Design budget had greater margin than the LSRS budget as well as the budget for the Recovery Subsystem's telemetry.
Black powder testing was rescheduled for the day of each full-scale launch.	Schedule conflicts between the team leads and the launch manager prevented earlier testing.
Full-Scale testing dates were moved to February 16 for the Vehicle Demonstration Flight and February 23 for the Payload Demonstration Flight	Poor weather within a three hour radius prevented earlier testing.

3 Vehicle Criteria

3.1 Launch Vehicle Overview

The Notre Dame Rocketry Team has successfully designed, built, and flown a 134 in. tall, 864 oz. vehicle for the NASA Student Launch Initiative. In the following sections a detail description of the vehicle's construction, verification, and flights will be presented.

In Figure 1 a picture of the as built vehicle can be see in comparison to the render of the designed vehicle.

Figure 1: NDRT 2020 Competition Vehicle

The following, Figure 2, shows the measured lengths of the as-built, full-scale vehicle.

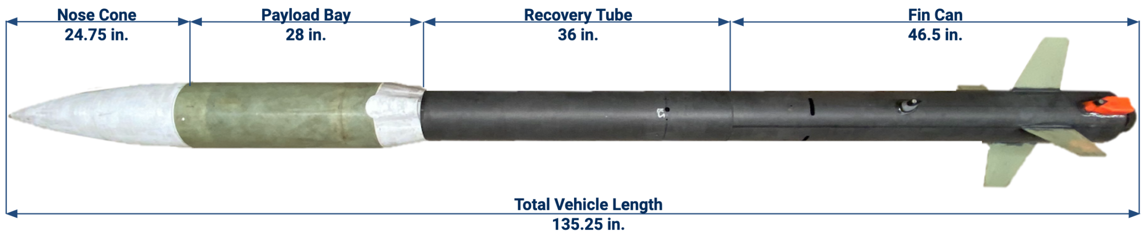


Figure 2: As-Built Measured Lengths

A breakdown of the vehicle's mass can be found in Figure 3.

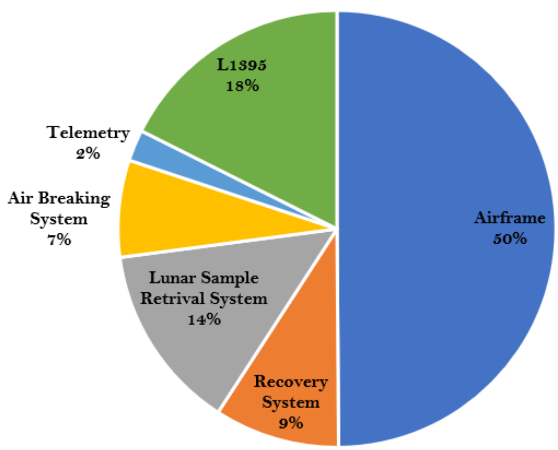


Figure 3: As Built Mass Breakdown

The target apogee was set to 4,444 ft and the motor selected for the vehicle was the L1395-BS. The vehicle is designed to overshoot the apogee to allow for actuation of an Air Breaking System (ABS) payload. Data on the selected motor can be found in Table 5.

Table 5: Ceasaroni L1395-BS Specifications

Specification	Value
Total Impulse	1011.46 lb-s
Burn Time	3.51 s
Average Thrust	314.03 lbs
Maximum Thrust	400.48 lbs
Maximum Acceleration	214 ft/s^2

The loaded static stability at rail exit was simulated and measured prior to each launch. All measurements were within the 2 and 3 caliber requirement set by the team. Figure 4 shows the measured CG and CP on the rocket which yielded a stability of 2.9 calibers.

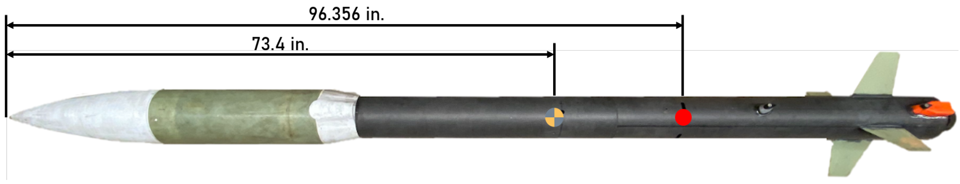


Figure 4: Measured Static Stability

The vehicle is design to have three in-flight separation points: one at the nosecone, one at the transition section, and one between the recovery tube and fin can. These separations are discussed more in depth in Section 3.6.2.

3.2 Vehicle Changes Since CDR

In order to account for the increase in weight of the student fabricated nose cone from initial estimates, the integrated twist and lock mechanism that was designed to secure the telemetry system was removed and instead replaced with a removable bulkhead. This decision was made in order to move the center of gravity farther back from the tip of the nose cone so that the static stability margin is between 2-3 calibers in order to meet Team Derived Requirement V.10. Additionally, an anomaly in construction caused the recovery bulkhead to dry at about a 10°angle. After performing solids testing on a bulkhead with a similar angle, the team determined that supports would be needed for the tilted bulkhead to perform as if it were straight. An image of the fiberglass supports as attached to the tilted bulkhead is shown in Figure 5.

Figure 5: Tilted Bulkhead Supports

3.3 Vehicle Design

The following section will describe the different aspects of the launch vehicle's technical design. This will include construction techniques, changes made since CDR, Finite Element Analysis (FEA), as well as the various NASA Requirements that were fulfilled.

3.3.1 Nose Cone

The nose cone has a tangential ogive geometry. It is 24 in. long with a 4 in. shoulder and a base OD of 8.005 in. to match the OD of the payload bay. It was 3D printed out of ASA plastic in three parts and epoxied together. The 3D printing for this component was outsourced to the Notre Dame Innovation Lab. The nose cone houses the telemetry module and bulkhead. Figure 6 depicts a rendering of the nose cone, the 3D printed nose cone parts, and the completed nose cone.

(a) Rendering (b) Before Assembly (c) As-Built

Figure 6: Nose Cone Rendering and As-Built

3.3.2 Payload Bay

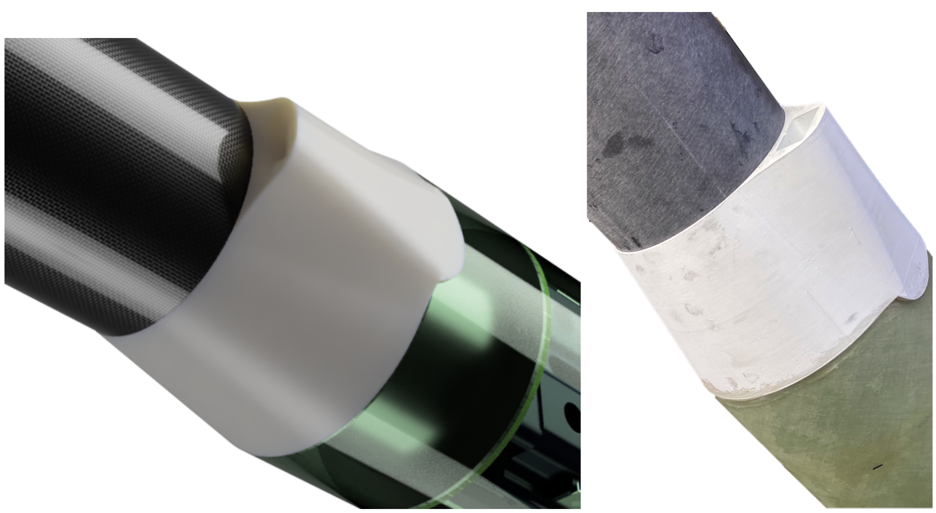
The payload bay is 23 in. in length and houses the LSRS. It was made from fiberglass body tubing for radio transparency. It connects to the transition section via coupler and centering rings, and to the nose cone via shear pins. Figure 7 depicts a rendering of the payload bay and the completed payload bay.

(a) Render (b) As-Built

Figure 7: Payload Bay

3.3.3 Transition Section

The transition section is designed to prevent flow separation over the change from a diameter of 8 in. to 6 in. It is 5 in. long, and 3D printed in ASA plastic. The transition section also has an integrated camera shroud, shown in a rendering and as-built design in Figure 8.



(a) Render (b) As-Built

Figure 8: Transition Section

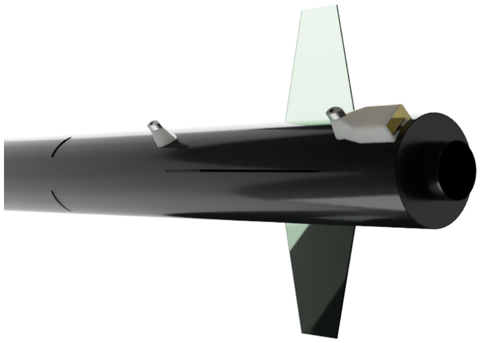
3.3.4 Recovery Tube

The recovery tube is 36 in. in length, 6.112 in. in diameter, and constructed from carbon fiber tubing. The recovery tube houses both the main and drogue parachutes, as well as the avionics module. It attaches to the transition section and the fin can via couplers and shear pins. A rendering of the recovery tube design can be seen in Figure 9, as well as an image of the completed recovery tube.

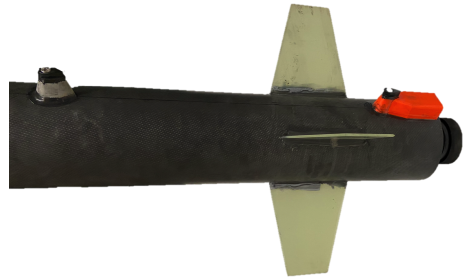
Figure 9: Render and As-Built Recovery Tube

3.3.5 Fin Can

The fin can is the same material and diameter as the recovery tube, and has a length of 44 in. It houses the air braking system, motor mount, fins, rail buttons and offsets, as well as another camera shroud. The motor mount is made from 3 in. diameter carbon fiber tubing, is 27 in. long, and sits coaxially within the fin can, held in place by three fiberglass centering rings. The rail button offsets are 3D printed from PLA plastic, and allow for the larger diameter of the payload bay to clear the rail. There are four fins, each are 0.125 in. thick fiberglass sheets with leading and trailing edges sanded onto the profile. Figure 10 shows a rendering of the assembled fin can, and an image of the completed fin can.



(a) Render



(b) As-Built

Figure 10: Fin Can

3.3.6 Bulkheads

There are multiple bulkheads throughout the launch vehicle serving various purposes. Most are cut from fiberglass sheeting, while one is machined from aluminum, as it is removable and is secured to the fin can via four screws. FEA was conducted on the bulkhead located at the transition section, which was made out of 1/4 in. thick fiberglass. This bulkhead, under a max force of 677 lbs, had a FOS of 3.7. Figure 11 shows the FEA conducted.

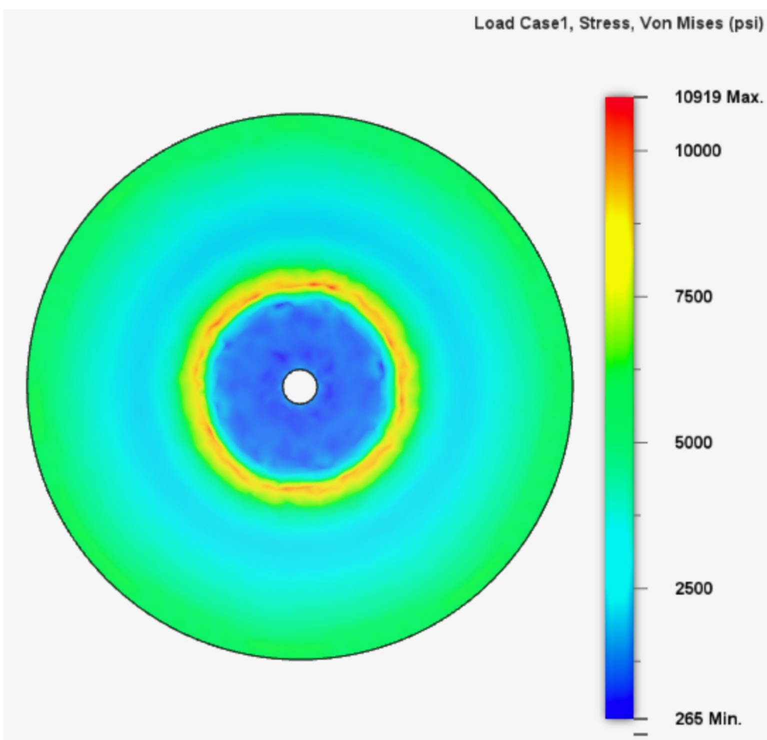


Figure 11: FEA on Payload Bulkhead (von Mises Stress)

3.3.7 Centering Rings

Centering rings are located in the transition between the 6 and 8 in. diameter and in the motor mount to ensure safe retention of these parts as well as concentric alignment of airframe components. FEA was conducted for the load bearing motor mount centering rings that have to take the total force that the motor exerts, shown in Figure 12.

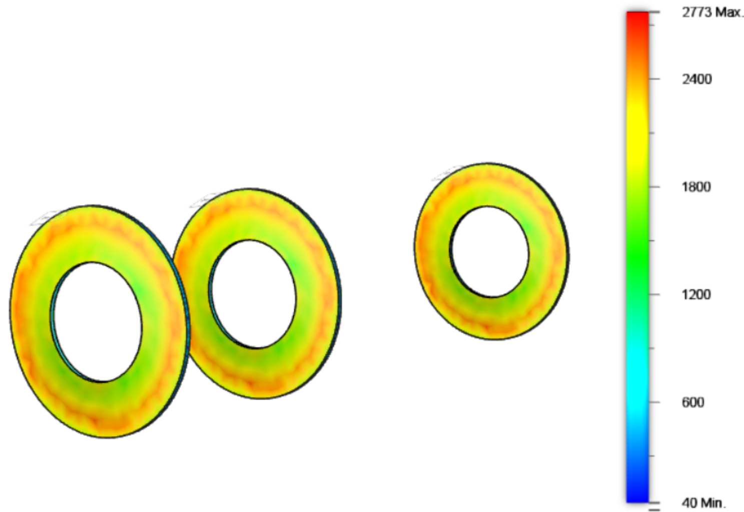


Figure 12: FEA on Motor Mount Centering Rings (von Mises Stress)

3.3.8 Couplers

There are two couplers in the launch vehicle; one is fore of the recovery tube, and the other is aft of the recovery tube. Couplers are designed to maintain structural stability at separation points. The two couplers are made of carbon fiber with ODs to match the IDs of the body tubes. The aft coupler has a length of 12 in., and the fore coupler a length of 15 in. to pass through the transition section and into the payload bay. All coupler lengths protrude at least one body tube diameter into adjacent tubes, which meets NASA Requirement 2.5.1.

3.4 Vehicle Construction

The construction of the full-scale launch vehicle was completed in 7 stages, summarized in Table 6 The entire assembly of the launch vehicle was completed in 3 weeks.

Table 6: Full-Scale Construction Plan

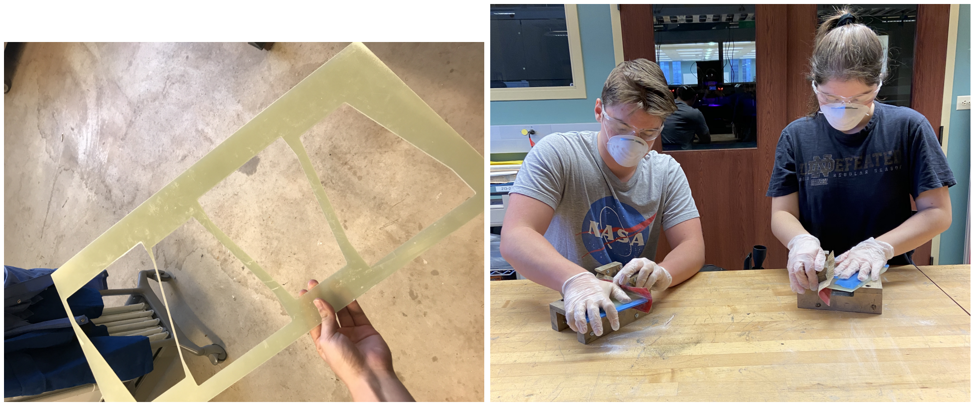
Stage	Summary	Details
1	Setup	Double-check student-fabricated part dimensions
		Print all student-fabricated parts
		Create CNC files
2	Machining	CNC bulkheads, centering rings, fins
		Sand fins to rounded leading edges and sharp trailing edges (NACA 0010)
		Cut payload bay to 23 in. long
3	Building 1	Payload Bay: Epoxy two centering rings and 1 bulkhead onto transition coupler
		Motor Mount: Expoxy two top centering rings
		Mark line for rail buttons
		Laser cut fin alignment rings
4	Building 2	Payload Bay: Epoxy coupler to payload bay and transition section to coupler
		Motor Mount: Epoxy into fin can
5	Building 3	Fin Can: Epoxy fins
		Epoxy three piece nose cone
		Recovery Tube: Epoxy twist and lock CRAM ring
6	Building 4	Fin Can: Epoxy bottom centering ring, fiberglass ABS base bulkhead, and motor retainer
7	Building 5	Epoxy rail button offsets and rail buttons
		Finalize paint job design

3.4.1 Setup

Before starting construction, the team inspected the Autodesk Fusion 360 designs to ensure all parts machined or printed in-house fit properly together. These included: the nose cone, transition section, rail button offsets, camera housing, fins, bulkheads, and centering rings. The nose cone, transition section with the integrated camera housing, and rail button offset STL files were sent to the Notre Dame Idea Center for 3D printing in-house. For the fins, bulkheads, and centering rings, CNC files were created for machining in the Student Fabrication Lab.

3.4.2 Machining

During the machining phase of construction all body tubes were cut to size, and the fins, bulkheads, and centering rings were fabricated using a Techno LC Series 4848 CNC mill. Figure 13 shows the fin cutouts and the sanding process.



(a) CNC Cutouts (b) Sanding

Figure 13: Fins

3.4.3 Payload Bay

The fiberglass body tube for the payload bay was first cut to 23 in. as it was only commercially available in six-foot sections. Two centering rings were epoxied to the 15 in. coupler and allowed to dry while a ¼ in. fiberglass bulkhead was sanded in order to achieve a tight fit before being epoxied into the coupler. The following day, the coupler was epoxied to the payload bay with the bottom centering ring flush to the end of the payload bay. Finally, the transition section was epoxied onto the coupler, shown in Figure 14.

(a) Epoxying (b) Completed

Figure 14: Payload Bay Construction: Epoxying Transition Section

3.4.4 Fin Can

Three centering rings were used to secure the motor mount to the fin can, with two centering rings placed above the fins, and one below the fins. The top two centering rings were epoxied to the motor mount and allowed to dry. Figure 15 shows these centering rings after being epoxied in place.

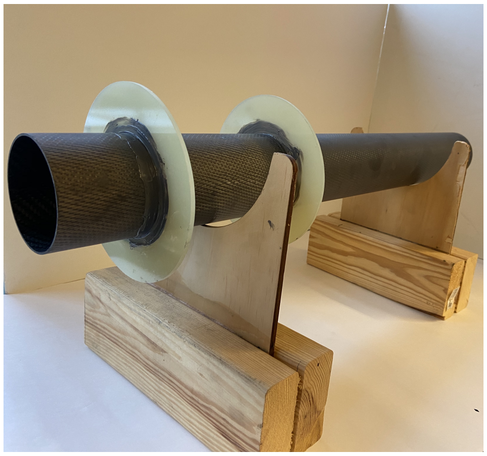


Figure 15: Centering Rings Epoxied to Motor Mount

The following day, the motor mount was epoxied into the fin can body tube and the bottom centering ring was put in place to allow the motor mount to dry perfectly concentric to the fin can Additionally, the fiberglass base ABS bulkhead was epoxied into the fin can. This stage was followed by the epoxying and alignment of the fins. Fins were epoxied to both the motor mount and fin can wall using JB Weld epoxy. A laser cut fin alignment ring was placed on the for and aft sides of the fins to ensure they were kept at a 90° angle while drying, shown in Figure 16.

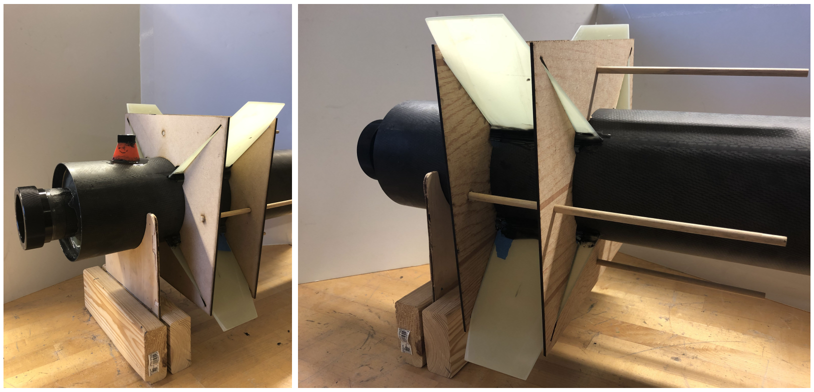


Figure 16: Fin Alignment

Next, the bottom centering ring was epoxied followed by the motor retainer ring. During the same building session, the CRAM twist-and-lock ring was epoxied into the recovery tube, rail buttons and rail button offsets were epoxied and screwed onto the fin can, and the lower coupler was epoxied onto the recovery tube.

3.5 Air Braking System

In order to reach apogee at the target altitude of 4,444 ft, the launch vehicle utilizes an Air Braking System (ABS), with the goal of inducing a controlled variable drag force during flight. ABS is the team's non-scoring payload this year. The system consists of an on-board closed-loop control system that simultaneously tracks flight data and alters the extension of a set of four drag surfaces, referred to as drag tabs. The drag tabs extend radially outward from the CP of the launch vehicle such that they act as flat plates normal to the direction of airflow. For the duration of flight from burnout to apogee, the actuation of these drag tabs is altered according to a PID control algorithm, and they remain retracted for the remainder of the flight. An image of the fully constructed system is shown in Figure 17. Its structure consists of a series of circular decks, all secured to a set of four steel threaded rods using lock nuts. At the fore end of the system is an aluminum removable bulkhead, which serves to secure the system within the launch vehicle. Aft of the aluminum bulkhead is a Nylon 6/6 deck, which provides the structure of the drag tab deployment mechanism. Aft of that deck is an HDPE deck to which the servo motor is attached, and aft of that is another HDPE deck which holds the PCB, Raspberry Pi, sensors, and batteries.

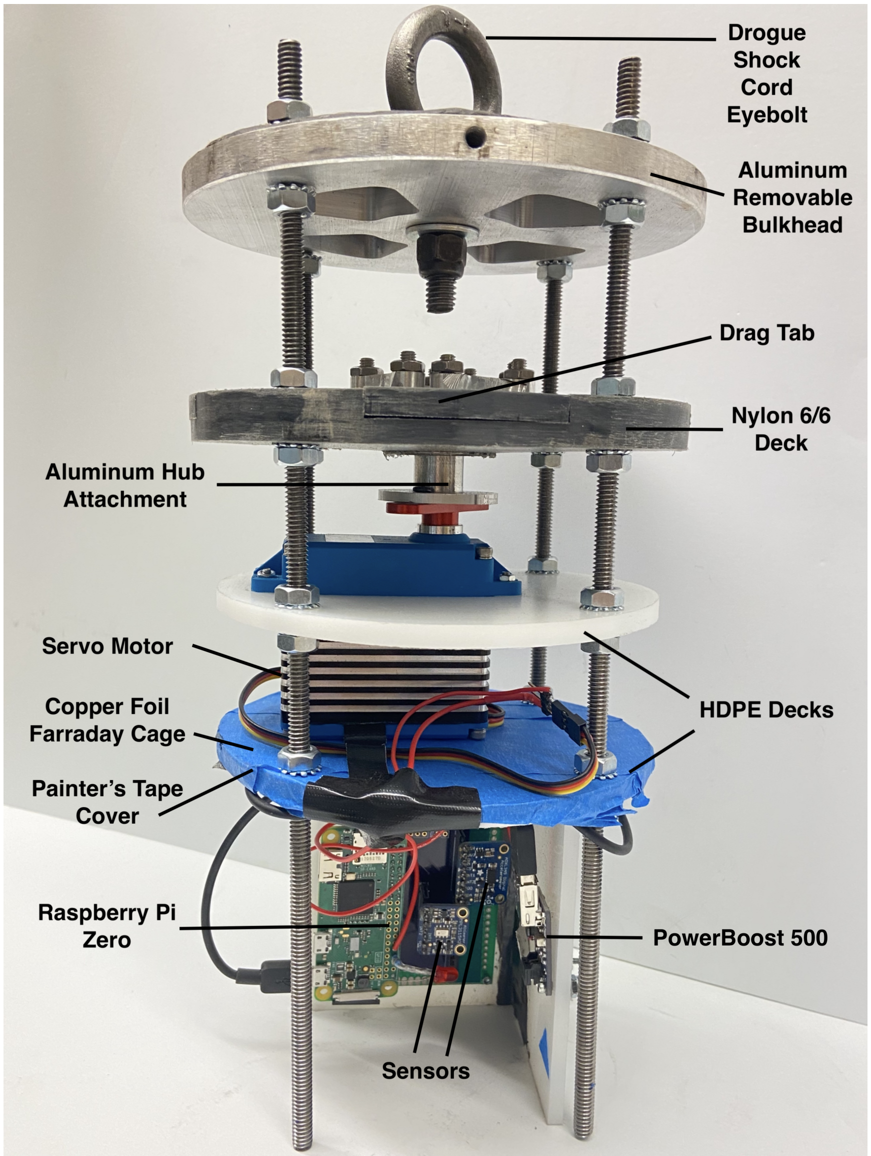
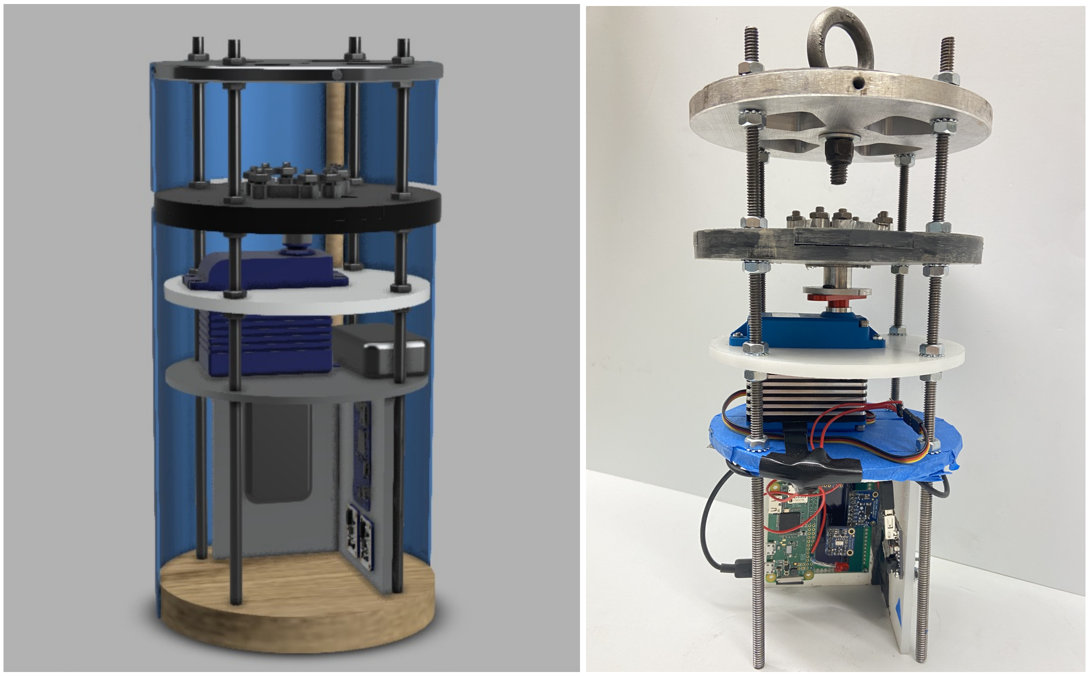


Figure 17: Fully Constructed ABS



(a) Render (b) As-Built

Figure 18: ABS Comparison to CAD Rendering

3.5.1 Mission Success Criteria

In a successful flight, ABS will bring the launch vehicle to the target apogee of 4,444 ft, within an acceptable margin of error, in a manner that does not compromise safety or stability. To verify that this objective is met, the following specific set of success criteria must be met:

ABS.MS.1 On-board sensor data shall indicate that the launch vehicle reaches apogee at an altitude of 4,444 ± 25 ft.

ABS.MS.2 Actuation of the drag tabs shall be visually confirmed by footage from the onboard camera.

ABS.MS.3 The drag tabs shall actuate at a location within ± 1 in. of the CP to ensure that they do not significantly alter the static stability margin.

ABS.MS.4 The drag tabs shall extend simultaneously and symmetrically to ensure that no destabilizing moments are generated.

ABS.MS.5 The drag tabs shall only actuate during flight after burnout has been detected.

ABS.MS.6 No components of the system shall experience structural failure at any stage of flight.

3.5.2 Drag Tab Deployment Mechanism

The primary structure of the drag tab deployment mechanism is a 1/2 in. thick Nylon 6/6 deck, which includes four 1/4 in. thick slots forming a cross through the center. There is a 1 in. diameter hole in the center of the deck, allowing an aluminum crosspiece to rotate in the center.

The ends of the crosspiece are each attached to an aluminum linkage using a shoulder screw, and the linkages are each attached to one drag tab using another shoulder screw. This provides the desired motion of the deployment mechanism, where the rotation of the center crosspiece translates to linear translation of the drag tabs along the slots in the deck. This motion can be seen in the fully constructed mechanism shown in Figure 19.

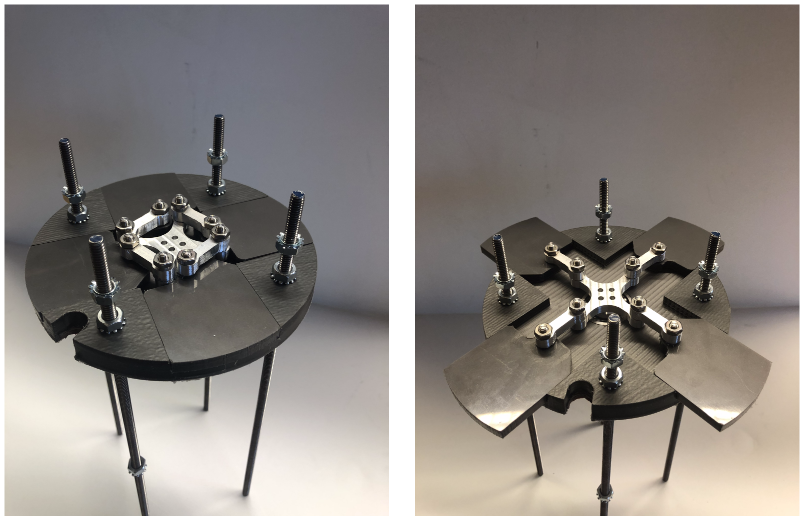


Figure 19: Drag Tab Deployment Mechanism

The rotation of the central crosspiece is controlled by a HiTec D845WP servo motor, which the team programmed to rotate to a maximum of 63° for full deployment. At full deployment, the drag tabs achieve an extension of approximately 2 in. from the outer diameter of the deck, which corresponds to a surface area of approximately 16 in^2.

3.5.2.1 Component Fabrication and Integration

The team chose to fabricate the components of the deployment mechanism, as well as the other structural decks, from raw materials using the resources available at the Notre Dame Student Fabrication Laboratory. Each component was designed using Autodesk Fusion 360, from which Numerical Control files were generated. Aluminum components were fabricated using a Haas VF 3-axis techno mill, while the Nylon 6/6 and HDPE components were fabricated using a a Techno LC Series 4848 CNC mill. The drag tabs were fabricated from a sheet of 1/4 in. thick slippery MDS-filled Nylon 6/6, which allows the tabs to move within their slots with low friction. The width of each tab was reduced by 0.005 in. to ensure that they are able to slide within their slots, and a counter-bore hole was machined at the end to allow a shoulder screw to be press-fit through it. A single fabricated drag tab is shown in Figure 20.

Figure 20: Nylon 6/6 Drag Tab with Press-fit Shoulder Screw

The slotted deck was fabricated from a 1/2 in. thick sheet of Nylon 6/6, with four 1/4 in. diameter holes drilled symmetrically around the deck to allow the threaded rods to pass through. A ball bearing was press-fit into the 1 in. diameter hole in the center to provide centering and easy rotation of the crosspiece. The fabricated slotted deck is shown in Figure 21.

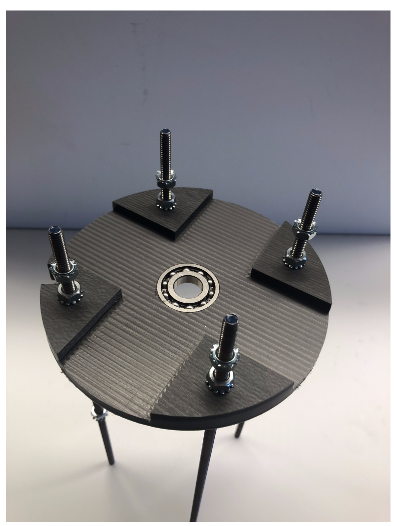


Figure 21: Nylon 6/6 Slotted Deck with Press-fit Ball Bearing

The linkages were fabricated from a 1/4 in. thick bar of aluminum, and were given 1/4 in. diameter holes on each end to allow them to rotate on shoulder screws. A fabricated linkage is shown in Figure 22.

Figure 22: Aluminum Linkage

The aluminum crosspiece needed to be fabricated in two parts: an upper half which provides the cross shape with shoulder screws to attach to the linkages, and a lower half which attaches the upper half to the servo motor through the ball bearing in the center of the deck. The upper piece, shown in Figure 23, includes four clearance holes in the center which allow it to be attached to the lower piece using #2 socket head screws. It also includes counter-bore holes at all four ends into which the shoulder screws were press-fit.

Figure 23: Upper Piece of the Aluminum Crosspiece with Press-fit Shoulder Screws

The lower half of the crosspiece includes a 5/8 in. diameter cylindrical section that passes through the ball bearing to interface with the upper half, and a bottom 1 in. diameter flat plate with clearance holes to interface with the servo motor. The holes on the top were tapped with a 2-56 thread. This piece can be seen in Figure 24. The interface of the servo motor with the crosspiece is shown in Figure 25.

Figure 24: Lower Piece of the Aluminum Crosspiece

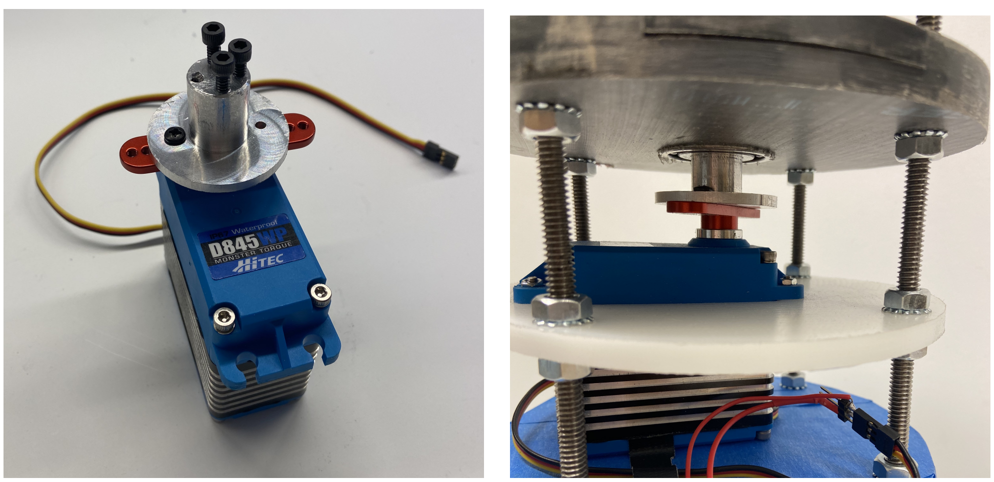


Figure 25: Servo Motor and Aluminum Hub Attachment

The removable bulkhead was fabricated using a 3/8 in. thick sheet of aluminum. It was given four 1/4 in. diameter holes symmetrically around the outside, which were tapped using 1/4"-20 threads for the threaded rods to screw into and out of. It was also given four symmetric 3/8 in. diameter holes into its outer edge, which were tapped using a 10-32 thread to allow retention of the entire system using steel button head screws passing through the fin can into the bulkhead. The fabricated bulkhead is shown in Figure 26.

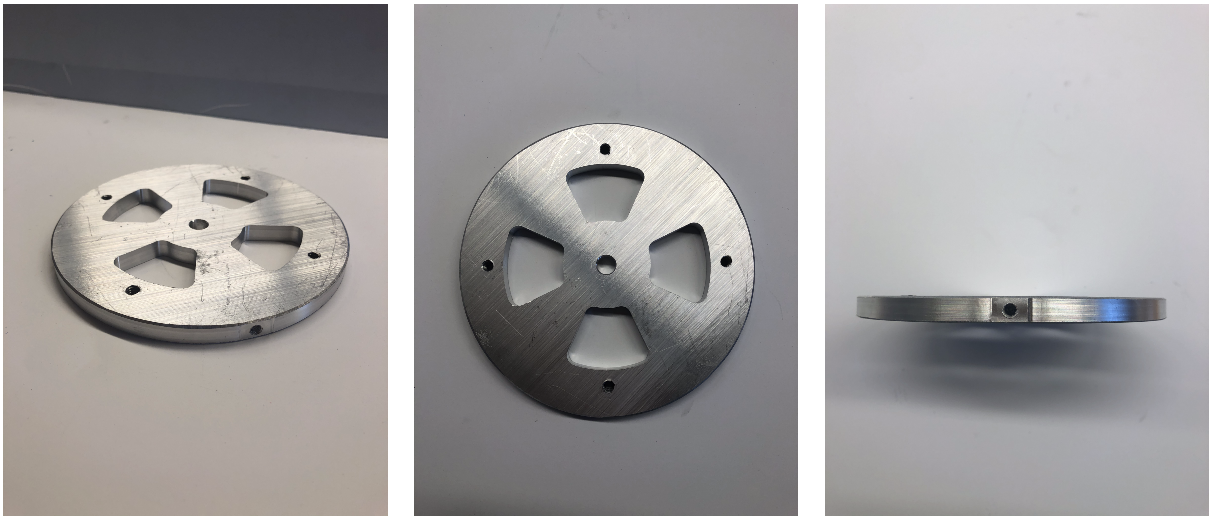


Figure 26: Aluminum Removable Bulkhead

The remaining decks securing the servo motor and the electronics were fabricated from sheets of 1/8 in. thick HDPE. Like the rest of the decks, it is secured to the threaded rods using lock nuts on both sides. This allows all of the decks to be easily realigned in the vertical direction by sliding them along the rods and tightening the lock nuts. The method of securing the decks with lock nuts is shown in Figure 27.

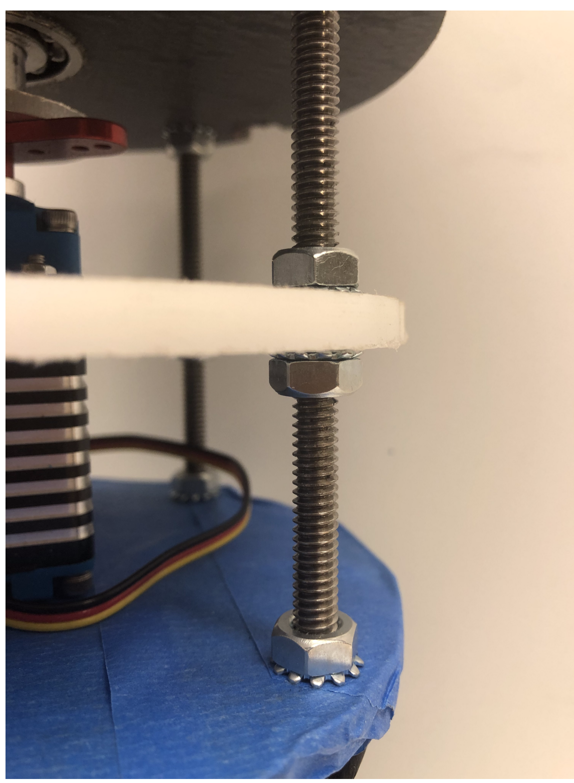


Figure 27: Lock nuts securing HDPE deck to threaded rods

The electronics deck supports two rectangular plates of HDPE, oriented vertically from the deck, into which the PCB and Powerboost 500 are secured by screws. The vertical plates are epoxied to the deck using Rocketpoxy. To create a Faraday cage between the servo motor and the rest of the electronics, the electronics deck was layered with copper tape, which was then covered up with painters tape to keep the copper from carrying any current from electronics. The electronics bay is shown in Figure 28.

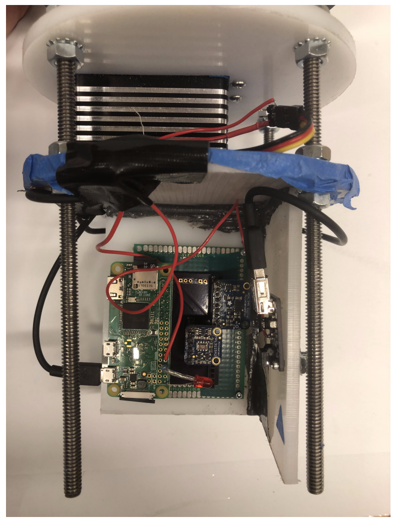
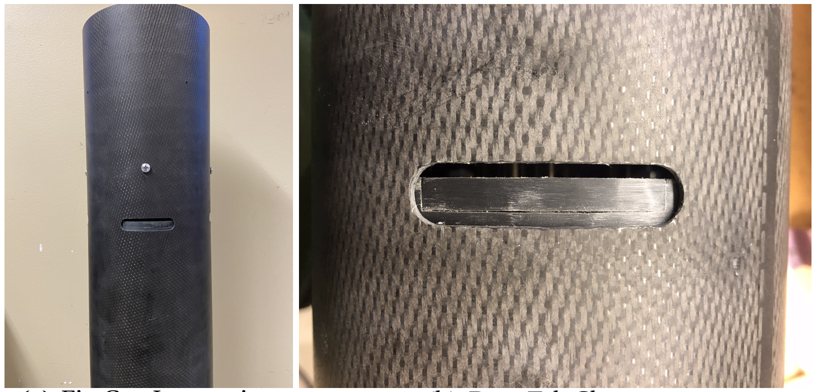


Figure 28: Electronics integrated below aft HDPE deck

3.5.2.2 System Integration

The integration of the ABS into the fin can of the launch vehicle was motivated by two main requirements: ensuring that the drag tabs are aligned with the slots in the fin can, and ensuring that the system remains secured without experiencing any displacements or structural failures during flight. The drag tabs were aligned to the slots by adjusting the vertical height of the tab deployment mechanism deck, and inserting the system into the fin can until the tabs had visible clearance through the slots. Once this was achieved, four clearance holes were drilled around the fin can to align with the holes in the aluminum bulkhead. This allowed the system to be secured in place by four steel pan head 10-32 screws through the fin can. The successfully integrated ABS is shown in Figure 29.



(a) Fin Can Integration (b) Drag Tab Clearance

Figure 29: Integrated Air Braking System Tabs

The tabs were then deployed through the slots while the system was integrated in order to ensure that the clearance is sufficient. The deployed tabs are shown in Figure 30.

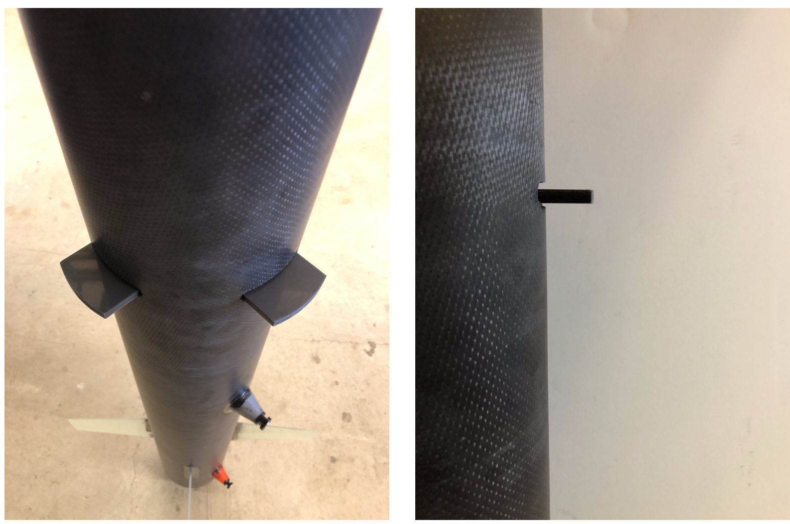


Figure 30: Drag Tab Deployment Through Fin Can Slots

3.5.3 Electrical Design

A number of necessary changes have been implemented to the electronic design of the ABS since CDR. The schematic for the updated electronics wiring is shown in Figure 31.

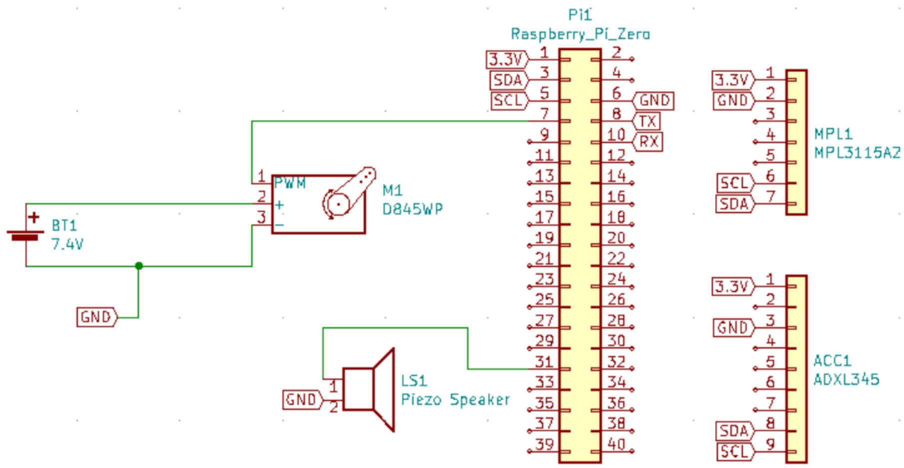


Figure 31: Schematic of Final Electronics Wiring

The primary change is that ABS is no longer utilizing a BNO055 to gather orientation data. Upon evaluation of the subscale flight data, shown in Test 7.1.6, it was found that the BNO055 sampled at a significantly lower frequency than the other sensors, and it outputted orientation data that did not make physical sense due to the ±4g sampling range for its orientation mode. The team decided to remove the BNO055 because it would likely compromise the system's ability to sample data quickly and accurately. While accurate orientation data would improve the Kalman filter's ability to correctly represent the physical state of the launch vehicle, it is not essential to the successful operation of the ABS flight controller. The team took care to confirm that the PID controller would be able to function properly without an orientation data point, and the BNO055 was removed from the system, which flew successfully without it as demonstrated in Test 7.1.6.

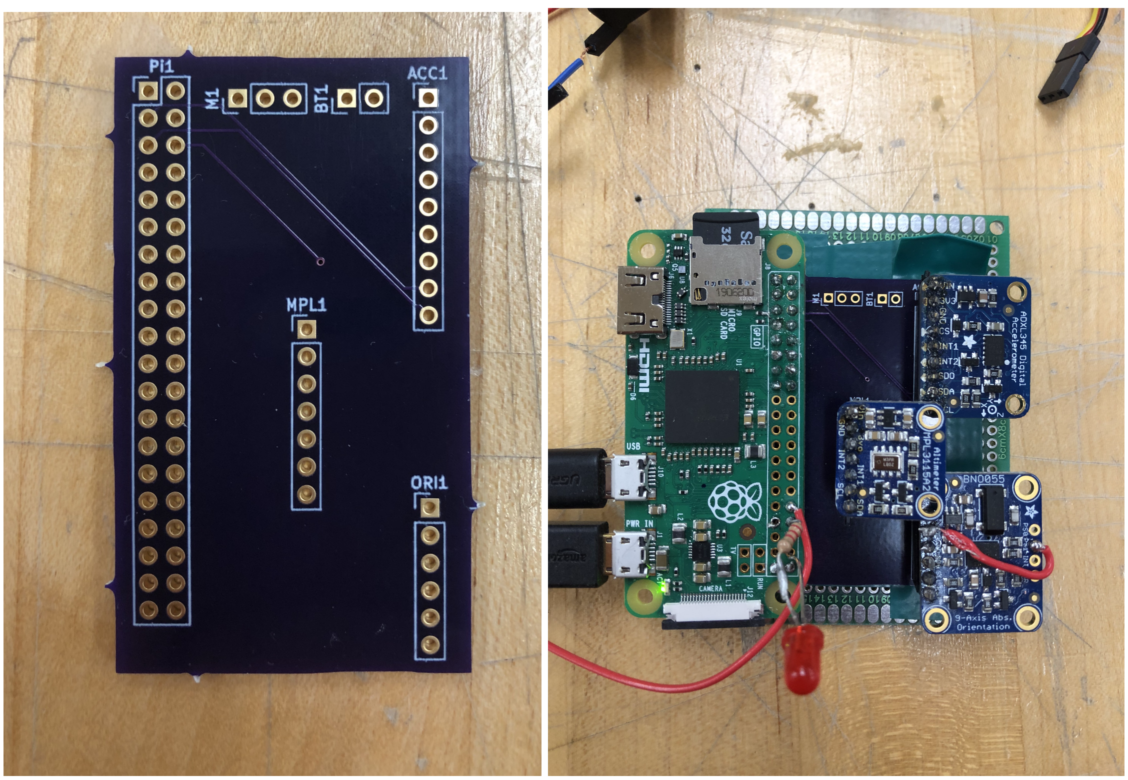
During electronics construction, it was found that a common ground between the two power sources would be necessary because the Raspberry Pi was unable to control the servo motor with PWM signals otherwise. This was implemented by soldering a wire from the ground pin of the servo battery to the ground terminal of the PowerBoost 500, which is powering the Raspberry Pi. This common ground is necessary for the PWM signals that are being sent between the Raspberry Pi and the servo.

In place of the power verification LED, a PS1240 piezo speaker will be incorporated into the system so that the team can verify that ABS is powered and collecting data once it has been integrated in the launch vehicle. The system previously included an LED for this purpose, but it proved difficult to see the LED through the barometric holes as intended. A piezo speaker will be easily heard while the system is inside the launch vehicle, and provides the additional ability to play different tones for different flight stages, which will allow the team to verify that the system has not prematurely detected liftoff.

The D845WP servo motor and its battery are separated from the rest of the electronics on their own deck. They are placed in a Faraday Cage constructed with copper tape to prevent electromagnetic interference with the sensors and the Raspberry Pi due to the high current draw of the servo motor.

3.5.3.1 Printed Circuit Board

The PCB was modelled using KiCAD, and the design was sent to Oshpark for fabrication. The as-received PCB is shown in Figure 32 before and after the electronics were implemented. Female header pins were soldered to the holes in the PCB, and male header pins were soldered to the sensors and Raspberry Pi to allow the components to be easily attached and removed. Because the PCB did not include any holes for securing it within ABS, it was soldered to a Prototyping board, which can be seen as the green board in Figure 32 (b), which includes the desired holes for integration.



(a) Plain Board (b) Sensors Attached

Figure 32: Printed Circuit Board

3.5.3.2 Batteries

In order to ensure that the system will be able to function for the full 2 hours after being placed on the launch pad, as specified in NASA Requirement 2.7, the LiPo battery powering the servo motor will be increased from a 400 mAh capacity to 1500 mAh. This change is intended to account for the current draw of the servo motor when it is being powered but not moving. Servo motor testing led to the conclusion that the servo drains its battery more quickly than predicted in CDR calculations, and the ABS is below its design weight, so a larger battery is allowable.

The 400 mAh batteries did not generate any failures in the system during the test flights, but increasing the battery size will provide assurance that the system can successfully stay powered for the required time.

3.5.4 Control Structure

The ABS is regulated by a state machine, which transitions between six stages and facilitates different functionality based on the current physical state of the vehicle. These states include: Armed, Launched, Burnout, Apogee, Overshoot, and Landed. The transitions between different stages are summarized by the updated flow chart in Figure 33.

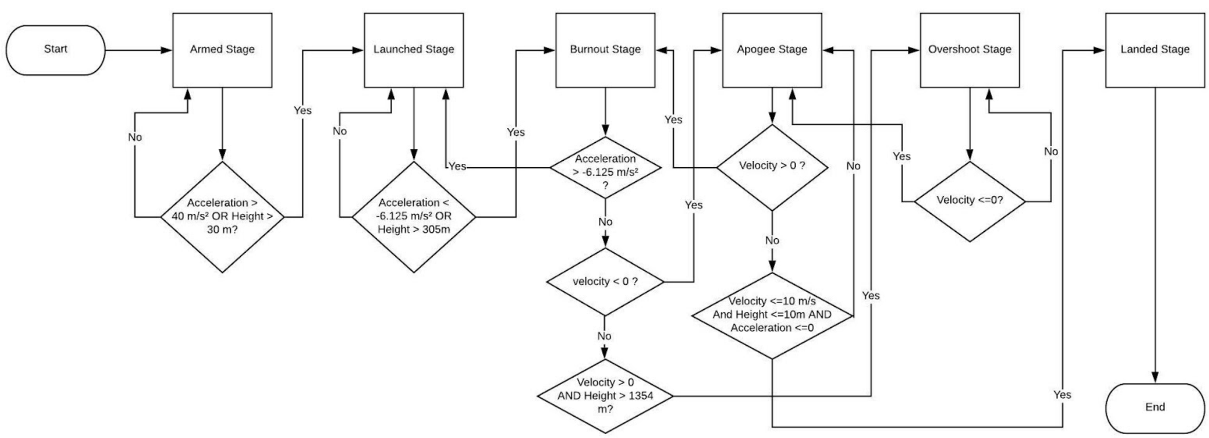


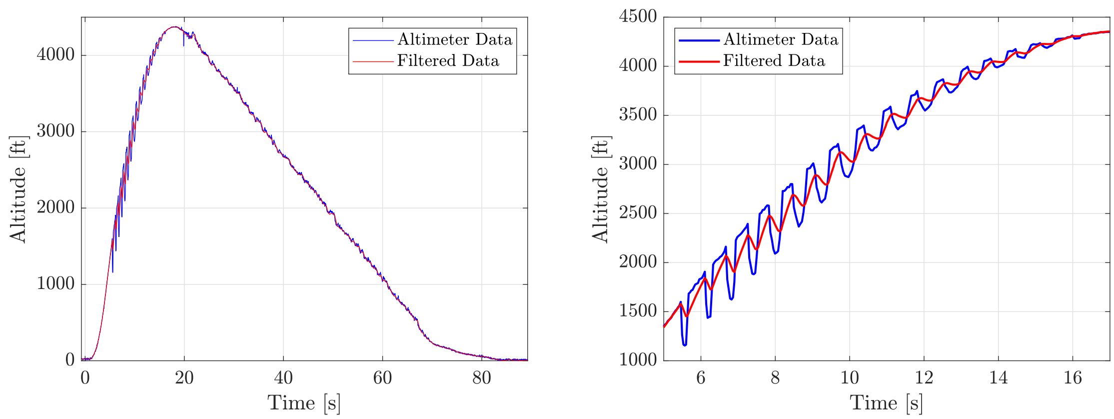
Figure 33: Updated Flow Chart of ABS Control Stages

Some changes have been made to the control structure since CDR. Specific transition thresholds were developed to reflect the expected physical behavior of the launch vehicle in a flight. Additionally, a new Overshoot stage has been added. This stage reflects a state in which the launch vehicle has exceeded the target apogee, and still has a positive velocity. In such a case, the PID control algorithm is short-circuited, and tabs are deployed to maximum extension until a negative velocity is achieved, indicating apogee. Additionally, conditions have been implemented to allow the controller to revert backwards to different stages. Because unexpected noise in the sensor data may cause an erroneous transition forwards into burnout or apogee, backwards transitions from Burnout to Launched and from Apogee to Burnout have been implemented. These transitions ensure that the system is able to correctly identify its current launch state despite noise in the sensor data.

A Kalman filter is used to translate from noisy sensor data to an accurate estimation of the current position, velocity, and acceleration of the rocket. The gain has been fine-tuned based on full-scale flight data and simulated test flights, and allows the system to combine sensor data with an internal state and information about how that state will evolve into a single, reliable estimate of the current state of the rocket. This current state is then compared to an ideal flight path and processed by a PID control algorithm, allowing sensor measurements to be translated into a servo rotation angle.

3.5.5 ABS Demonstration Flights

The Air Braking System flew in its active state in two Vehicle Demonstration Flights. In the first flight, the drag tabs did not actuate. This was due to several bugs in the control structure that were subsequently identified and fixed during software ground testing before the second demonstration flight. In the second flight, the system correctly identified the intended control stages and the drag tabs successfully deployed. This completes Requirement 2.18.1.4, which states that any payload that changes the external surface of the rocket must be active in the full-scale Vehicle Demonstration Flight. The altimeter data from the second Vehicle Demonstration Flight is shown in Figure 34, fulfilling Requirement 2.18.1.8, which requires altimeter data output to prove a successful flight.



(a) Entire Flight (b) Closeup of Burnout

Figure 34: Raw and Filtered Altitude Data

The PID control is expected to cause the drag tabs to extend fully and slowly retract as the flight state approaches the ideal trajectory, as verified by the software ground tests. However, in the video collected by the on-board camera in the transition section, it can be seen that the drag tabs fully extended and immediately retracted several times over the course of the flight. This activity corresponded to the extensions outputted by the program, indicating that the servo and the mechanism were functioning properly. The sudden drops and spikes in the measured altimeter data, shown in the closeup in Figure 34, have been identified as the cause of this unexpected motion. When passed through the Kalman filter, this data caused the velocity output to spike upwards and downwards, rapidly indicating overshoot and undershoot states to the PID algorithm, causing it to deploy and retract the tabs. The drops in measured altitude align directly with the deployment of the drag tabs, suggesting that the tabs caused a pressure change in the air passing over the barometric pressure holes aft of the tabs.

To prevent this from happening at competition, the pressure holes aft of the tabs will be closed using tape on the inside of the fin can, and static pressure will be supplied to the sensors through a tube that runs to a hole fore of the drag tabs.

3.6 Recovery System

In order to slow the vehicle as it descends from apogee, a recovery system has been implemented to deploy parachutes at different stages in the flight. At apogee, black powder ejection charges separate the vehicle and a small drogue parachute is deployed. As the vehicle reaches 600 ft AGL under the drogue parachute, a large main parachute is deployed out of a separate parachute bay via additional black powder charges. At 400 ft AGL, a black powder charge in the nose cone separates the nosecone from the payload bay, into a total of four tethered sections, descending under a single main parachute.

As it is not critical for safe recovery of the launch vehicle, the nose cone deployment system is discussed in the payload section, Section 6.

3.6.1 Parachutes, Harnesses, and Attachment Hardware

A FruityChutes CFC-24 elliptical parachute is deployed at apogee as a drogue parachute. Deploying a small drogue a parachute at apogee allows for a stable, controlled descent until main parachute deployment while limiting drift and descent time. See Table 7 for the manufacturer specifications of the drogue parachute.

Table 7: FruityChutes CFC-24 Specifications

Specification	Value
Diameter	24 in.
C_d	1.5
Shape	Elliptical
Canopy Material	1.1 oz Ripstop Nylon
Shroud Lines	220 lb Nylon
Weight	2.2 oz

The drogue parachute is protected from the black powder charges using a 24 in. Nomex blanket, which is tied to the recovery harness. Nomex is fire-resistant, preventing the hot gasses produced by the black powder from burning the nylon parachute canopy or shroud lines. Figure 35 shows the drogue parachute used in flight, alongside the Nomex blanket used to protect it.

Figure 35: Drogue Parachute and Nomex Blanket

A FruityChutes IFC-120-S parachute is deployed at 600 ft AGL to slow the vehicle to its landing velocity. The parachute was chosen due to its low packing volume and high drag coefficient. The performance of the parachute is analyzed in Section 3.7.5. See Table 8 for the manufacturer specifications of the main parachute.

Table 8: FruityChutes IFC-120-S Specifications

Specification	Value
Diameter	120 in.
C_d	2.2
Shape	Toroidal
Canopy Material	1.1 oz Ripstop Nylon
Shroud Lines	400 lb Spectra
Weight	22 oz

To protect the main parachute from the hot gasses produced by the black powder, the parachute is packed in a 13 in. Nomex deployment bag. In addition to black powder protection, the deployment bag slows the parachute's deployment sequence and keeps the shroud lines from tangling during parachute unfolding. A FruityChutes CFC-24 will be attached to the deployment bag as a pilot chute in order to pull the deployment bag off of the main parachute after vehicle separation. Figure 36 shows the main parachute, along with the pilot chute and protective Nomex. Figure 37 shows the main parachute packed in its deployment bag, as it is arranged before flight.

Figure 36: Main Parachute with Associated Rigging

Figure 37: Packed Main Parachute

Shock cords will tether the separated sections of the vehicle in flight, as well as connect the parachutes to the rest of the vehicle. Two cords will be used, one connecting the payload section to the recovery tube, along which the main parachute will be attached, and one connecting the recovery tube to the fin can, along which the drogue parachute will be attached. Both cords will be OneBadHawk 1 in. tubular nylon harnesses, each with a length of 35 ft and loops sewn into the cord at either end. The harness has a breaking strength of 4000 lbs according to the manufacturer. Figure 38 shows the drogue-side shock cord used in flight.

Figure 38: Shock Cord

Eyebolts transfer the parachute load from the shock cord to the recovery bulkheads. The eyebolts are 3/8-16 threaded galvanized steel, of forged construction, with a lifting shoulder and a 1 3/4 in shank. The eyebolts are rated for 1400 lbs of static and up to 3100 lbs of shock load. Galvanized steel was selected for its strength, availability in the required lengths, and resistance to corrosion. These eyebolts will be mated using a high-strength coupling nut, positioned in the center of the CRAM core. Oversized steel washers between the eyebolt shoulder and the CRAM bulkheads help to spread the load of parachute deployment, and split lock washers prevent the eyebolts from backing out of the coupling nut in flight. Figure 39 shows the CRAM eyebolts used in flight.

Figure 39: CRAM Eyebolts

A total of 9 quick links are used to connect the recovery elements. Five of these are heavily loaded in flight, and are constructed from 3/8 in. stainless steel. These quick links have a manufacturer-rated working load of 2700 lbs and a maximum shock load of 6000 lbs. The other four quick links are lightly loaded, used in connecting the drogue and pilot chutes, and are made from 3/16 stainless steel. Figure 40 shows the two types of quick links used in the recovery rigging.

Figure 40: Different Types of Recovery Quick Links

3.6.2 Rocket Separation

In order to determine the amount of 4F black powder needed for separation, the force necessary to break the shear pins can be calculated with Equation 1. The friction between vehicle sections is assumed to be negligible in comparison to the force of the shear pins. The pressure necessary to break the shear pins can then be calculated from Equation 2.

$$F = \tau A_s n \tag{1}$$

Symbol	Description	Units
F	Force	lb_f
τ	Shear Strength	psi
A_s	Shear Pin Area	in.^{2}
n	# of Shear Pins	N/A

$$P = \frac{F}{A_b} \tag{2}$$

Symbol	Description	Units
P	Pressure	psi
F	Force	lb_f
A_b	Bulkhead Area	in.^{2}

Because the combustion reaction of black powder occurs at high temperatures (1837 K) and relatively low pressures (less than one atmosphere), the ideal gas law can be used to find the number of moles of gas needed to produce the necessary pressure with Equation 3.

$$n_g = \frac{PV}{RT} \tag{3}$$

Symbol	Description	Units
n_g	Moles of Gas	mol
P	Pressure	atm
V	Chamber Volume	L
R	Gas Constant	L*atm/mol/K
T	Combustion Temperature	K

A simplified balanced equation for the combustion of black powder is given in Equation 4.

$$2KNO_3(s) + S(s) + 3C(s) \rightarrow K_2S(s) + N_2(g) + 3CO_2(g) \tag{4}$$

The moles of gas needed can be converted into moles of each solid component of the black powder using stoichiometry, and the moles can be converted to grams using the molar mass of each component, shown in Equations 5-7.

$$\frac{\text{mol gas}}{1} \times \frac{2\text{ mol KNO}_3}{4\text{ mol gas}} \times \frac{101.1\text{ g KNO}_3}{1\text{ mol KNO}_3} = \text{g KNO}_3 \tag{5}$$

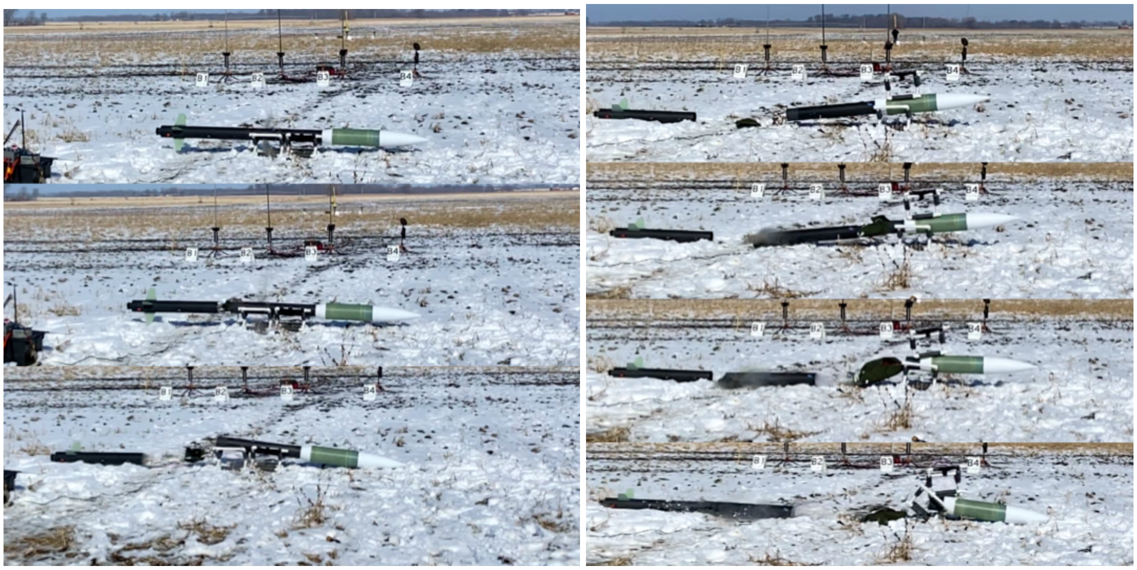
$$\frac{\text{mol gas}}{1} \times \frac{1\text{ mol S}}{4\text{ mol gas}} \times \frac{32.1\text{ g S}}{1\text{ mol S}} = \text{g S} \tag{6}$$

$$\frac{\text{mol gas}}{1} \times \frac{3\text{ mol C}}{4\text{ mol gas}} \times \frac{12.0\text{ g C}}{1\text{ mol C}} = \text{g C} \tag{7}$$

Adding the grams of each component together gives the total mass of black powder needed for the separation event, shown in Equation 8.

$$\text{g KNO}_3 + \text{g S} + \text{g C} = \text{g Black Powder} \tag{8}$$

This calculation was performed for each separation event to determine the amount of black powder needed for each charge. The amount of black powder used was rounded up based on the advice of the team mentor, the president of Michiana Rocketry, and past team experience. Ground testing confirmed the amount of black powder used for Recovery, shown in Figure 41. Full test procedures and results are in test RT1. Nose Cone ejection details can be found in Section 4.5.2 and test PDT7.



(a) Drogue Black Powder Testing (b) Main Black Powder Testing

Figure 41: Recovery Black Powder Testing

Summary of Black Powder Charge Calculations

Tables 9-11 contain a summary of the expected black powder forces, pressures, moles of gas, and mass of powder used to separate the drogue parachute compartment, the main parachute compartment, and the nose cone, respectively. All three redundant charges are listed for Recovery. Full calculations can be seen in Appendix B.

Table 9: Drogue Parachute Black Powder Ejection Charge Summary

Charge	***F*** (lb$_f$)	***P*** (atm)	n_g (mol gas)	**Calculated 4F** (g)	**Actual 4F** (g)
Initial	181	0.438	0.0148	1.0	5.0
Secondary	273	0.657	0.0222	1.5	5.0
Tertiary	273	0.657	0.0222	1.5	5.0

Table 10: Main Parachute Black Powder Ejection Charge Summary

Charge	***F*** (lb$_f$)	***P*** (atm)	n_g (mol gas)	**Calculated 4F** (g)	**Actual 4F** (g)
Initial	273	0.699	0.0665	4.5	5.0
Secondary	323	0.777	0.0741	5.0	5.0
Tertiary	323	0.777	0.0741	5.0	5.0

Table 11: Nose Cone Black Powder Ejection Charge Summary

Charge	***F*** (lb$_f$)	***P*** (atm)	n_g (mol gas)	**Calculated 4F** (g)	**Actual 4F** (g)
Nose Cone	286	0.387	0.0148	1.0	1.5

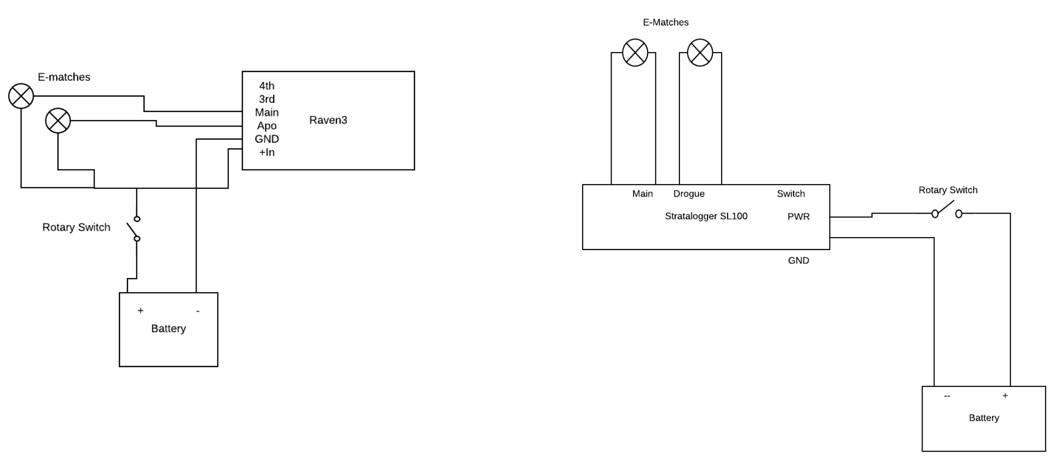
3.6.3 Electrical Elements

Parachute deployment is controlled by three redundant altimeters, each controlling one drogue and one main parachute ejection charge. The system is triply redundant, with three isolated systems. Two of these altimeters are Featherweight Raven3s, while the remaining one is a Perfectflite StratoLogger SL100. The ignition of the ejection charges is staged, as described in Table 12, to prevent multiple charges from igniting simultaneously, which can damage the vehicle. Each altimeter is powered by a 170 mAh 1S lipo battery.

Table 12: Recovery Altimeter Programming

Altimeter	Drogue Deployment	Main Deployment
Raven3 (Primary)	Apogee	600ft AGL
Raven3 (Secondary)	Apogee + 1s	550ft AGL
Stratologger SL100	Apogee + 2s	500ft AGL

Each altimeter is connected to a soldered perfboard through the on-board screw terminals an header pins. On the Raven3 perfboards, the battery ground is connected to the altimeter's GND port and the positive contact is connected to the rotary switch. From here, the positive is split to enter both the +In on the Raven3 and the e-matches. The other side of each of the e-matches is connected to the corresponding output port the Ravens. The Stratologger board is set up in a similar fashion, with the rotary switch input into the switch port on the Stratologger. Both wiring diagrams are shown in Figure 42

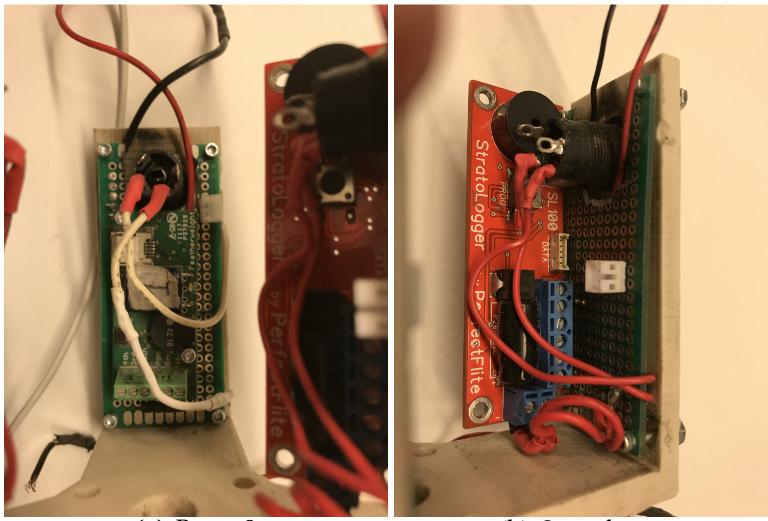


(a) Raven3 (b) Stratologger

Figure 42: Altimeter Wiring Diagrams

The switches employed in the system must conform to two requirements: they must be easy to access and use, but they must also resist any in-flight turbulence that might turn them off or tear them apart. Magnetic switches were initially considered, but the uncertainty of whether the magnet would accidentally actuate an undesired switch prompted the removal of these from the system. Instead, rotary switches were chosen as the system's breaker. These are connected directly to the batteries and the e-matches.

The perfboards are mounted to the avionics bay using 2-56 screws and nuts. Nonconductive clay is used on the corners of the perfboard to dampen vibration. Figure 43 shows the altimeters

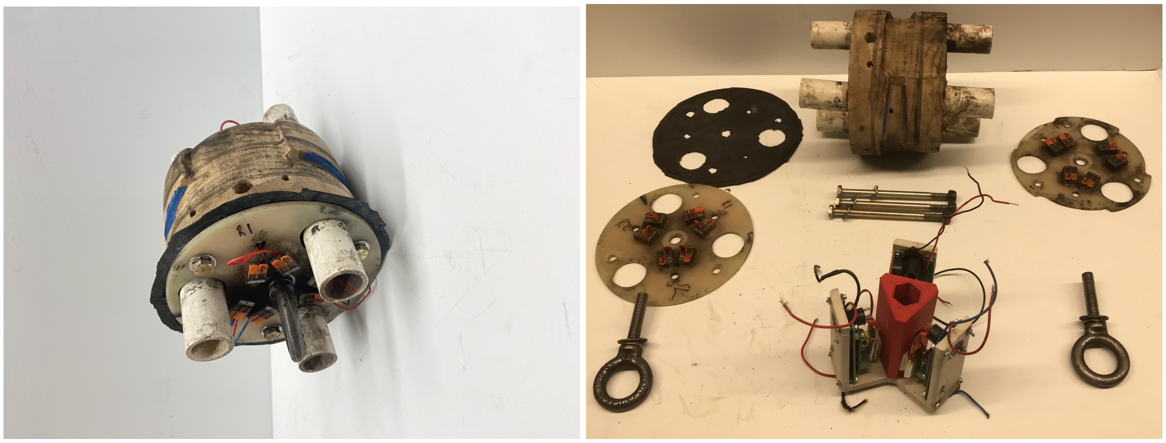


(a) Raven3 (b) Stratologger

Figure 43: Mounted Altimeter Boards

3.6.4 Structural Elements

The altimeters that control ejection charge deployment, as well as the associated batteries and switches, are contained in the Compact Removable Avionics Module, or CRAM. The primary feature of the CRAM is a twist-to-lock retainment system that allows for robust mounting inside the vehicle while still being easily removable for data retrieval and replacement of ejection charges. Figure 44 shows the fully assembled and constructed CRAM and all the CRAM components.



(a) Fully Assembled CRAM (b) Disassembled CRAM

Figure 44: CRAM

The CRAM core is the central component of the CRAM to which the altimeters and other electronics are mounted. The CRAM core is be 3D printed from PLA due to its availability and ease of manufacturing. The low strength of 3D printed PLA is not a detriment in this application, as the CRAM core is entirely non-load bearing. The core is be printed in two sections, a top and bottom, and joined by press-fit steel pins. The altimeters and soldered breadboards are secured to the core by 4 #2-56 screws and nuts each, while the rotary switch is be epoxied into its mounting hole. The batteries are secured to the core via command strips. The CRAM eyebolts are secured to the steel coupling nut in the CRAM core. Figure 45 shows the assembled CRAM core, with electronics mounted.

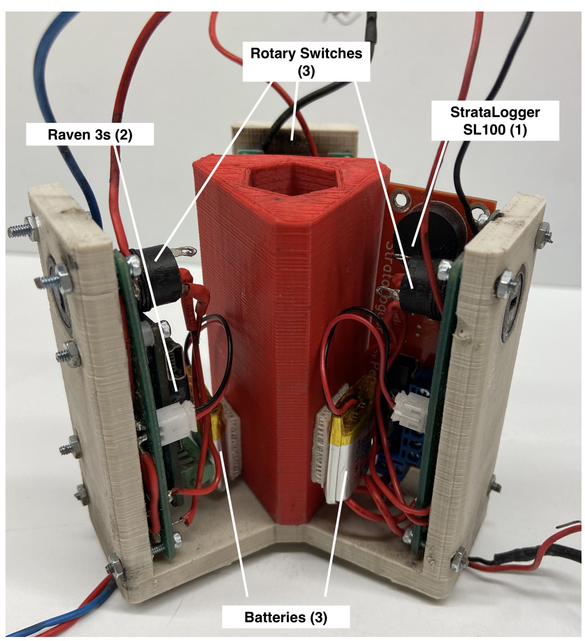


Figure 45: Assembled and Labelled CRAM Core

Bulkheads on either side of the CRAM distribute the loads from parachute deployment and keep the CRAM core inside the body. The 1/8 in. bulkheads feature multiple holes to allow for the PVC charge wells and space for wires to run from the CRAM to the charge wells. The bulkheads have been CNC routed from 1/8th in Garolite G10 fiberglass stock. Three 4.5 in. long, 1/4-20 bolts with nylon-insert locknuts are used to secure the bulkheads to the CRAM body and retain the core. Figure 46 shows both the top and bottom bulkheads of the CRAM.

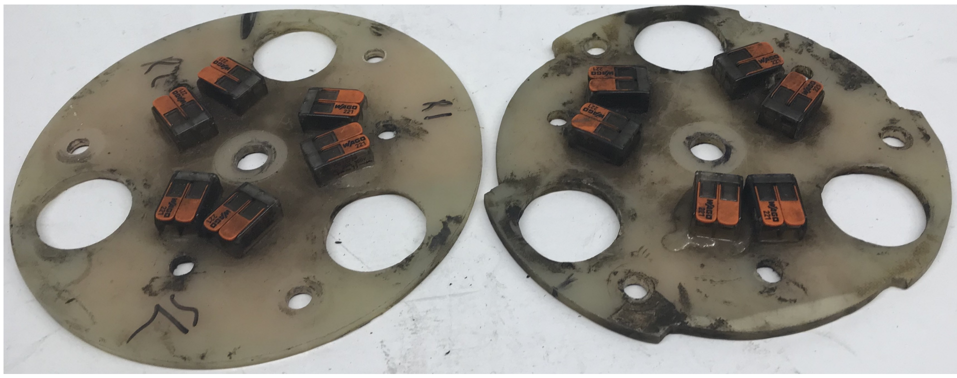


Figure 46: Top and Bottom CRAM Bulkheads

The CRAM body retains the ejection charges and transfers load from the CRAM bulkheads to the ring adapter and the recovery tube. The tapered cutouts on the exterior of the CRAM interface with a ring adapter mounted in the recovery tube, allowing the whole CRAM to be secured into the body tube with a 60 degree twist. Hardwood screws inserted from the outside of the body tube keep the CRAM body from twisting free in flight. 1/2 in. holes the exterior of the body allow for access to the altimeter arming switches, and 3/16 in. holes allow for free airflow to the altimeters. These holes match holes drilled in the vehicle body tube. On the top and bottom of the CRAM are 1 in. diameter, 2.5 in. long PVC pipes that function as charge wells, holding the black powder ejection charges in place during launch. The CRAM body has been CNC milled from 3/4 in. oak common board in four pieces, with 2 laser-cut 1/8th in. MDF spacers. The pieces were permanently assembled using wood glue. Figure 47 shows the constructed CRAM body.

Figure 47: Constructed CRAM Body

To protect the altimeters and other electrical components of the recovery system from electromagnetic interference, electromagnetic shielding in the form of copper foil tape has been added to the interior of the CRAM body and the altimeter-facing sides of the CRAM bulkheads. The pieces of copper tape overlap when the CRAM is fully assembled, forming a contiguous Faraday cage to protect from electromagnetic signals.

The ring adapter that connects the CRAM to the vehicle's body tube is a 1/4 in. thick ring with internal protrusions that match the external cutouts of the CRAM body. The adapter has been machined from 3/4 in. oak board in two pieces and wood-glued together, in a manner similar to the CRAM body. The adapter is permanently epoxied into the recovery tube, 6 in. forward of the aft end of the tube. Figure 48 shows the CRAM ring adapter epoxied into the recovery tube.

Figure 48: CRAM Tube Adapter

3.6.5 Redundancies

Redundancy in the recovery system is crucial to the success of the mission. A vehicle flight cannot be considered successful without the successful operation of the recovery system. Increasing the safety factor of the recovery system through redundancies is important to ensure a safe recovery of the vehicle.

A total of three altimeters will be used for both the drogue and main parachute deployments. The main altimeter will first deploy a drogue at detected apogee. The backup altimeter will deploy the drogue parachute 1 seconds after detected apogee. The second backup altimeter will deploy the drogue parachute 2 seconds after detected apogee. Similarly, the three altimeters will also control the release of the main parachute. The first altimeter will deploy the main parachute at 650 ft. The second altimeter will deploy the main parachute at 550 ft. The third altimeter will deploy the main parachute at 500 ft. Each altimeter is connected to one battery. As a result, the failure of one battery or one altimeter will not result in an unsuccessful recovery. Each altimeter will set off a black powder charge to deploy each parachute through an E-match. Optimally, all three altimeters will set off a block powder charge, with the first charge deploying the main parachute and the backup altimeters setting off black powder charges without affecting the deployment. The addition of two backup altimeters results in a much safer system that is not dependent on the success of one battery, altimeter, or E-match.

The CRAM, where important recovery electronics are housed, is susceptible to shear and removal from the vehicle body. A twist-to-lock system has been designed on the outer surface of the CRAM with a corresponding insert in the recovery tube. Additionally, screws the length of the entire CRAM are inserted to keep the CRAM together. By using three screws and three separate twist-to-lock cutouts on the outside of the CRAM, the factor of safety of the CRAM is increased. Removal of the CRAM from the recovery tube or separation of the CRAM structure would be detrimental to mission success. By including screws and a twist-to-lock system, the likelihood of CRAM structural failure is greatly reduced.

3.6.6 Telemetry

In order to track the position and status of the launch vehicle in real time during its flight, a telemetry system has been designed. The telemetry system gathers data during flight, packetizes it, transmits it to a relay station, and receives it at a ground station where the position and status of the vehicle are displayed. The portion of the telemetry system onboard the launch vehicle is located in the nose cone, and transmits at 250 mW of power and a frequency of 433 MHz using a dipole antenna. The main function of the telemetry system is transmission of GPS data; however, the transmission of pressure and acceleration data will also be included to communicate the launch vehicle's status and give data capable of calculating a more accurate estimation of the vehicle's position. For an illustration of the overall system design, see Figure 49.

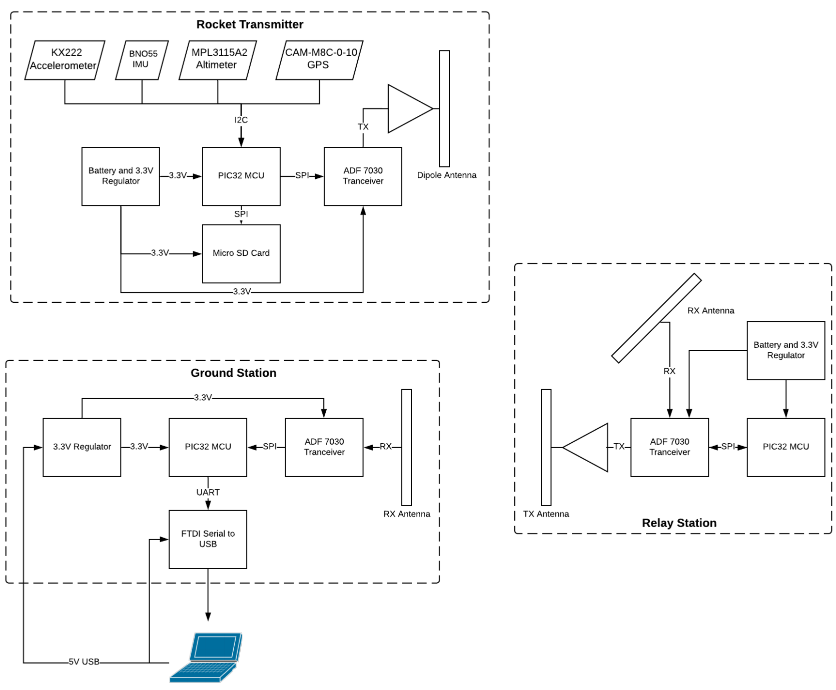


Figure 49: Telemetry System Block Diagram

3.6.6.1 Vehicle Hardware

The telemetry system features a transceiver, transceiver control board, and sensor board that gather and transmit launch vehicle location data from onboard the launch vehicle.

3.6.6.1.1 Transceiver

The transceiver module selected for use in the design is the ADF7030 from Analog Devices, which is capable of operating between 426 MHz and 470 MHz. Because of the data rate requirement of the system, an operating frequency in the 433 MHz band was selected to decrease path losses and increase effective range. In addition, none of the other transmitters located in the payload of the vehicle operate in the 433 MHz band, ensuring that the launch vehicle transceiver will not interfere.

The launch vehicle transceiver is capable of transmitting 250 mW of radiated power. The ADF7030 is capable of outputting −20 dBm to 17 dBm (0.01 mW to 50 mW) of power from its transmit ports. For this reason, a MAAM-009560 20 dB power amplifier is placed on the output of the ADF7030, and the tunable output power of the transceiver is adjusted so that the radiated power of the antenna is in the range of 23 dBm to 24 dBm. The ADF7030 is capable of operating with either a 2FSK or 4FSK modulation scheme. Because high data rates are not required, 2FSK was selected in order to maximize possible range. When transmitting with the 2FSK modulation scheme, the maximum data rate of the ADF7030 is 150 kbps, which meets the requirement of 67.5 kbps.

The relay station will be placed approximately 2,500 ft from the launch site, at competition, so the line-of-site distance from vehicle transceiver to relay receiver is approximately 5,500 ft. The connection from launch vehicle to relay station has been verified in a test flight, as described in a later subsection.

In order to guarantee that the transceiver is able to maintain a connection to the relay station throughout the entire duration of the vehicle's flight, a half-wave dipole antenna has been selected for the design: the Ready Made RC Dipole Antenna, designed for use in the 433 MHz band. This allows the antenna an approximate worse case scenario gain of −5 dBi when oriented vertically at the apogee, corresponding to a transmission angle of 63°.

3.6.6.1.2 Sensors

The telemetry system has a GPS, accelerometer, and barometric altimeter onboard the vehicle. Each sensor is sampled at a minimum frequency by a microcontroller in order to maintain an optimal resolution for the data that is being gathered so that it is accurate enough to be considered nominally correct. The sensors were selected because they possess desired characteristics needed for system performance, shown in Table 13.

Table 13: Vehicle Sensor Specifications

Sensor	Product Name	Max. Sampling Freq. (Hz)	Max. Operating Altitude (ft)	Interface
GPS	CAM-M8C-0-10	10	50,000	I2C
IMU	BNO055	100	N/A	I2C
Accelerometer	KX222-1054	25.6 (kHz)	N/A	I2C
Altimeter	MPL3115A2	160	11,775	I2C

Two accelerometers, the BNO055 and KX222-1054, are integrated into the telemetry system to serve different functions. The BNO055 has a fusion mode that performs sensor fusion calculations on measurements from the accelerometer, gyroscope, and magnetometer to obtain an absolute orientation measurement. While in fusion mode, the BNO055 clips at an acceleration of 129 ft/s^2 and is therefore not a reliable accelerometer. To compensate for this, the BNO055 serves exclusively as an orientation sensor, whereas the KX222-1054, capable of operating at accelerations up to 1029 ft/s^2, serves as the accelerometer of the telemetry system. The KX222-1054 is useful because of its high maximum sampling rate. While it is possible to derive acceleration from GPS measurements, the low sampling rate of the CAM-M8C-0-10 does not provide the desired resolution for acceleration data. Conversely, with a maximum sampling rate of 25.6 kHz, the KX222-1054 can achieve the minimum sampling requirement of 800 Hz.

The GPS sensor must be sampled at a minimum of 10 Hz, as this frequency is a standard for GPS readings and provides a minimum resolution of 59 ft. In order to achieve a resolution of approximately 6 ft, the altimeter is sampled at a minimum rate of 100 Hz. The data rates of each sensor are shown in Table 14.

Table 14: Calculated Sensor Data Rates

Device Type	Device	# Measurements	# Bits	Frequency (Hz)	Data Rate (bits/s)
Altimeter	MPL3115A2	1	24	160	3840
GPS	CAM-M8C-0-10	3	32	10	960
Accelerometer	KX222-1054	3	16	800	38400
Accelerometer	BNO055	N/A	243	100	24300
				Total	**67500**

Managing this system of sensors requires the use of a microcontroller that can accommodate four I2C interfaces to read from each device. The PIC32 MCU family from Microchip is suitable for this requirement given the number of I/O ports that are available to support the necessary interfaces. Since this family of microcontrollers requires a 3.3 V input, a voltage regulator, such as the LD1117, is required to downconvert the 3.7 V-4.2 V range from the battery. Additionally, the sensor readings are performed using timer interrupts due to the sampling frequency requirements. In order to ensure a sufficient timing accuracy, an external oscillator is used by the microcontroller.

To store each data packet locally, the microcontroller must write data to an SD card. The SanDisk Ultra microSDXC is a suitable option due to its memory capacity of 128 GB and ease of removal for analysis.

3.6.6.1.3 Battery Selection

Because the MAAM-009560 amplifier requires 5 V DC bias, a 2S lithium polymer 1000 mAh battery, the Admiral 1000 mAh 2S 30C LiPo battery powers the transmitter module. Table 15 shows the module's estimated current draw.

Table 15: Estimated Power Budget

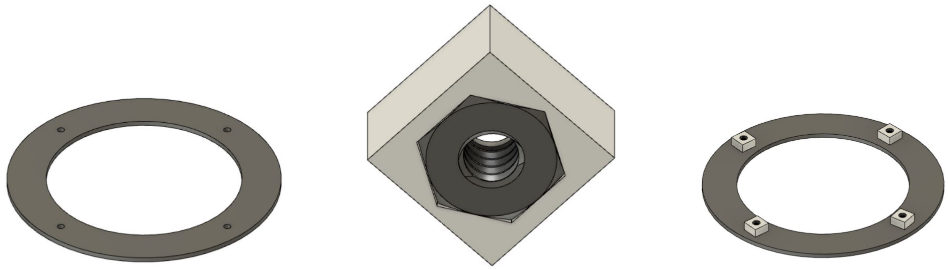
Device/ State	ADF7030	GPS	Accel. (KX222)	IMU (BNO055)	Altimeter	PIC	Power Amp	Total Current
Current Draw (mA)	65	71	0.145	12.3	2	100	250	**500.445**
							Capacity (mAh)	1000
.							**Run Time (hr)**	1.99822

Based on this estimated current draw, the onboard telemetry module should be operational for 2 hours with a fully charged Admiral 1000mAh 2S 30C LiPo battery.

3.6.6.2 Housing and Retention

The vehicle hardware described in Section 3.6.6.1 was housed in the nose cone of the launch vehicle. As outlined in CDR, the telemetry system was originally set to be retained in the nose cone using an additively manufactured, ABS plastic twist-to-lock system. Due to weight concerns, this system was changed to a bulkhead and receiving ring system made from 0.125 in G10 Garolite.

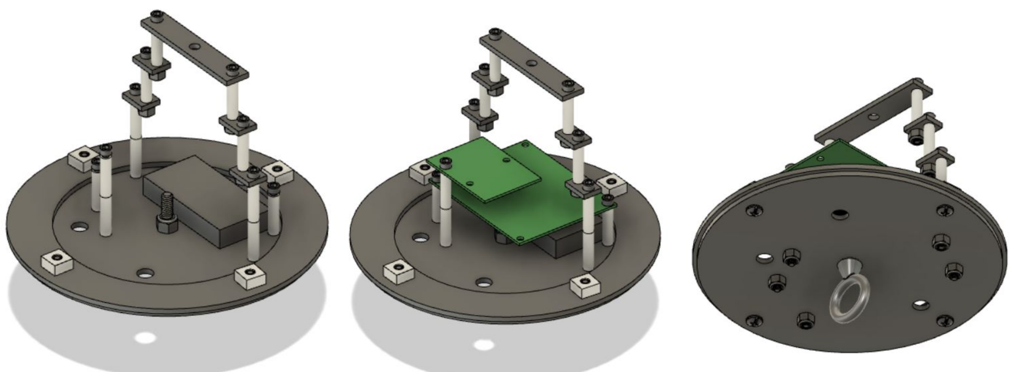
The retention ring has four equally spaced bolt holes around its radius for 10-24 screws. On the fore side of the retention ring are 4 locknuts that are positioned above each bolt hole. In order to hold the locknuts in place above the bolt holes and resist the torque applied by the retention bolts, there are 4 bolt retainers that are epoxied onto the fore side of the retention ring. This is shown in Figure 50.



(a) Retention Ring (b) Locknut and Nut Retainer (c) Retention Ring Assembly

Figure 50: Renderings of retention ring, locknut, nut retainer, and full assembly of these components.

A G10 Garolite bulkhead has 4 bolt holes corresponding to to those on the retention ring, 5 bolt holes for mounting the hardware described in Section 3.6.6.1, 1 bolt hole for mounting a 0.25 in steel eye bolt, and 3 0.375 in holes for rubber pressure tubes that give atmospheric pressure. The bulkhead is mounted to the retention ring via 4 10-24, 0.5 in long bolts mounted from the aft side of the bulkhead, through the corresponding bolt holes of the retention ring and bulkhead, and fastened with the locknuts on the fore side of the retention ring. This is shown in Figure 51



(a) Mounting hardware only (b) Mounted circuit boards (c) Eyebolt view

Figure 51: Renderings of fully assembled telemetry retention system. First picture demonstrates the retention system without electronics, second demonstrates retention system with mockup circuit boards, third picture shows eyebolt mounted to aft side of retention bulkhead.

The steel eyebolt is attached to the retention bulkhead in order to ensure that when the nose cone is ejected from the payload bay (discussed in Section 4.5.2), the telemetry system and nose cone will remain tethered to the launch vehicle by a 0.125 in thick kevlar chord attached to the eyebolt. Additionally, to facilitate the ejection of the nose cone, the cavity aft of the telemetry bulkhead is airtight. The telemetry system is sealed from the blast cavity by sealing clay.

In order to allow the telemetry system to measure atmospheric pressure, 3 rubber tubes of 0.375 in outer diameter and 0.06 in thick walls run from the bulkhead's pressure tube holes to corresponding pressure tube holes through the walls of the nose cone coupler and the payload bay. The pressure tubes are permanently epoxied to the telemetry bulkhead, but are removable from the walls of the nose cone coupler. In order to maintain the airtight seal of the blast cavity, sealing clay surrounds the site of the interface between the nose cone coupler wall and the pressure tube.

The dipole transceiver antenna is mounted by a nut attached to the transceiver cable connection through the G10 garolite platform and bolt assembly attached to the bulkhead. Both the battery and lowpass filter are adhered directly to the bulkhead by high strength adhesive tape. Both the battery and filter are positioned underneath the main circuit board.

An example of the fully assembled telemetry bulkhead in its flight configuration, with the pressure tubes and all electronic hardware mounted to it, is shown in Figure 52 below.

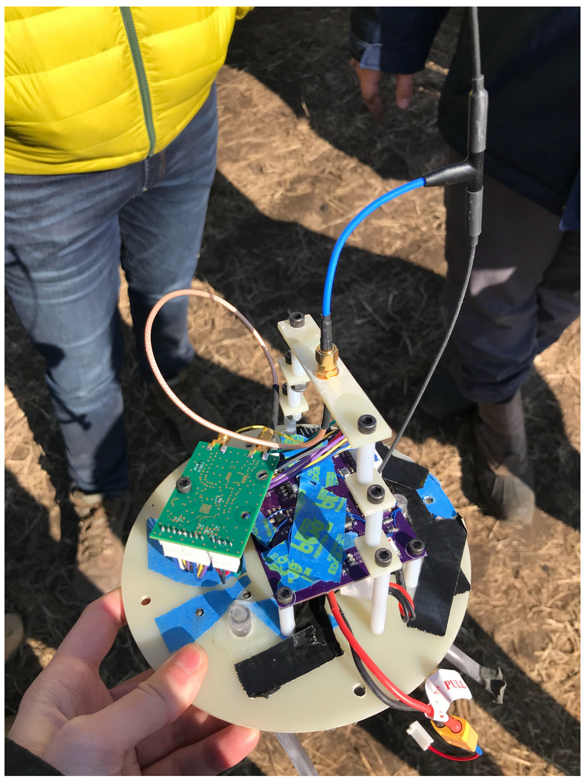


Figure 52: Fully assembled flight configuration of telemetry system and telemetry bulkhead

3.6.6.3 Relay Station

As described earlier, the relay station is set on the ground 2,500 ft away from the launch site in order to achieve acceptable antenna gain from the vertically oriented transmitting dipole antenna onboard the launch vehicle. In order to achieve an acceptable receive antenna gain without concern with regard to transmitter polarization on the launch vehicle, a circularly polarized patch antenna is used for receiving at the relay station. The radiation pattern of this antenna captures the position of the vehicle throughout its flight. The transmission to the ground station is achieved with a quarter wave monopole antenna set to transmit. An ADF7030 transceiver is used to both receive data from the vehicle and transmit data to the ground station. A PIC32 microcontroller controls this radio chip via an SPI interface by sending timed radio commands.

3.6.6.4 Ground Station

The ground station is set a few hundred feet from the launch site, where live telemetry data is recorded and displayed on a laptop. The transmission from the relay station is received with a quarter wave monopole antenna and an ADF7030 transceiver.

Since the ground station UI must report data from four different sensors in near-real time, this data must be presented clearly and intuitively. This means that instead of reporting purely numerical values, figures and plots are also utilized. For example, the GPS readings will be plotted on a map to provide a visual interpretation of where the vehicle is located. Measurements from the orientation sensor, accelerometer, and altimeter are plotted continuously to demonstrate the trajectory and altitude of the vehicle respectively throughout the flight. Following the conclusion of the test, these figures and plots can be saved locally for future analysis and reporting.

3.6.6.5 Test Flight Results

The full scale test flight of the launch vehicle confirmed that the telemetry system was able to successfully transmit all data with a nominal data package drop rate. The results of the full scale test launch can be found in Section 7.1.2.

The telemetry system was successfully retained in the the nose cone of the launch vehicle, and was able to withstand the forces of the nose cone being ejected from the payload bay by a charge at a 100 ft altitude as discussed in Section 4.5.2. The successful ejection of the nosecone as well as the data gathered by the barometer demonstrates that the pressure sealing described in Section 3.6.6.2 were effective. Additionally, the successful retention of the nose cone and telemetry system throughout the vehicle flight and nose cone ejection demonstrate the effectiveness of the retention system described in Section 3.6.6.2.

3.7 Mission Performance Predictions

In the following sections the vehicle's performance predictions will be described. Static stability margin, simulation methodology and flight profiles were analyzed prior to flight to have benchmark expected values to refer to during testing.

3.7.1 Static Stability Margin

In order to predict how the launch vehicle would react to flight conditions, the static stability margin was calculated. The stability of the vehicle is based on the ratio of the distance between the center of pressure and the center of gravity and the body tube diameter. The static stability margin was calculated by Equation 9.

$$\text{Static Stability Margin} = \frac{X_{CP} - X_{CG}}{d} \tag{9}$$

Symbol	Description	Units
X_{CP}	Nose Cone to CP Distance	in.
X_{CG}	Nose Cone to CG Distance	in.
d	Body Tube Diameter	in.

Based on this equation, the center of pressure must be located aft of the center of gravity to prevent the aerodynamic forces from creating a destabilizing moment. Because the launch vehicle has two diameters, the stability was calculated for the larger diameter which represents the minimum vehicle stability margin. The Open Rocket simulated locations of the center of pressure and center of gravity are shown in Figures 53 which yielded a stability margin of 2.79 calibers.

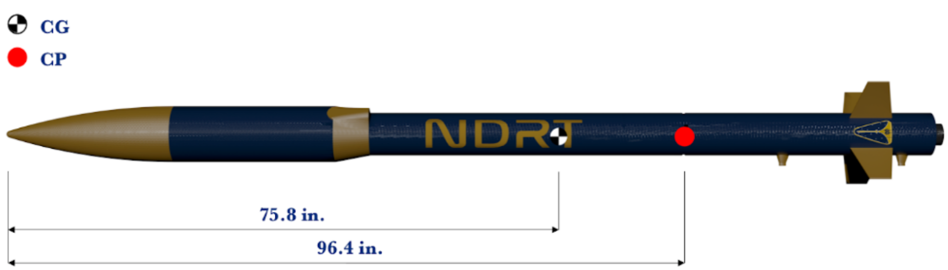


Figure 53: Simulated Loaded Static Stability Margin

Prior to the two full-scale vehicle launches, the location of the center of gravity on the built and loaded vehicle was verified by balancing the rocket on a 1/4 in. stand. The static stability margin was then calculated as 2.75 calibers at the first launch and 2.875 calibers at the second launch, both well above the minimum of 2 calibers enumerated in NASA Requirement 2.14 and within the Team Derived Requirement V.10 range of 2-3 calibers.

3.7.2 Simulation Methodology

Flight simulations were conducted using two main methods, OpenRocket and a proprietary MATLAB code employing a 4th order Runge-Kutta approximation. For each method, simulations were run at various rail cants between 5° and 10° and wind speeds between 0 and

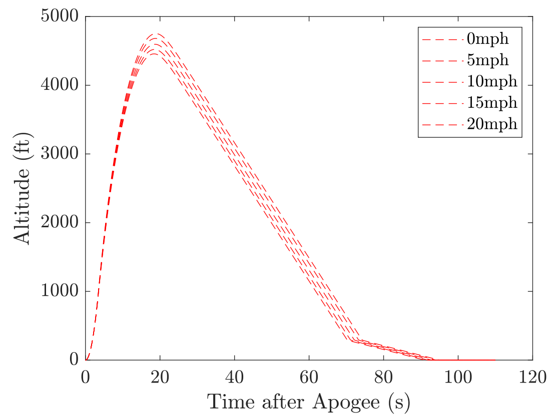


Figure 54: Flight simulations for various conditions

20 mph. The simulated apogees at each condition for both methods are listed below in Table 16.

Table 16: Simulated Apogees using OpenRocket and Matlab

Scenario	Apogee from OpenRocket (ft)	Apogee from Matlab (ft)
5°Rail Cant, 0 mph Winds	4900	4899
5°Rail Cant, 20 mph Winds	4530	4613
10°Rail Cant, 0 mph Winds	4781	4832
10°Rail Cant, 15 mph Winds	4600	4611
10°Rail Cant, 20 mph Winds	4354	4464

As shown, the simulations are consistent with the launches already performed. All conditions besides 10 degree rail cant and 20 mph winds allow the launch vehicle to reach the target apogee of 4444ft. Based on an analysis of weather conditions in Huntsville during the time of the launch, the team does not expect to have to launch in 20mph winds, and will endeavor to adjust rail cant when needed. For flight paths that are expected to overshoot the target apogee, the ABS is capable of reducing apogee by up to 500ft, which is more than needed to hit the required target for any predicted apogee. Data on Huntsville weather was gathered from https://weather.msfc.nasa.gov/wxstn/. A plot of predicted flight paths for various wind conditions is shown in Figure 54.

3.7.3 Descent Times

The main parachute is meant to deploy at 600ft AGL. Given the drogue descent velocity of 83.82ft/s and the main parachute descent time of 13.97ft/s, the total estimated descent time for the launch vehicle is 88.8s, which is within the 90s limit.

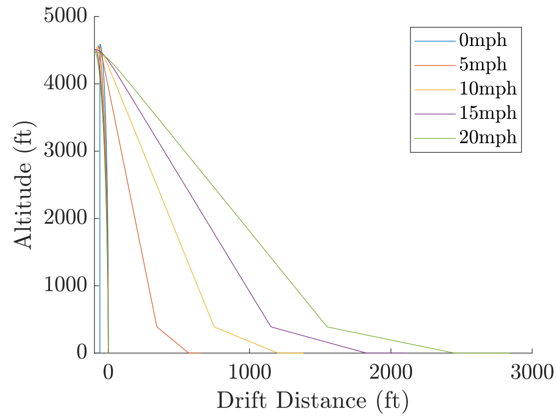


Figure 55: Predicted drift for various launch conditions

3.7.4 Drift

Drift is calculated assuming a worst-case where the launch vehicle travels at the wind speed until landing. The maximum predicted drift distance in 20mph winds is 2301 ft, which is less than the required drift radius of 2500ft. A plot of predicted drift for a variety of wind speeds is shown in Figure 55.

3.7.5 Kinetic Energy

The kinetic energy of at landing is estimated based on the heaviest section of the rocket, which has a weight of 333.4oz. Under the 12ft diameter parachute, the expected descent velocity of the launch vehicle is 13.9708ft/s. This provides a kinetic energy at landing of 63.2ft-lb, which is less than the limit of 75ft-lb. The team does not anticipate kinetic energy at landing to be impacted by wind or launch conditions, and is expected to be consistent for all launches.

4 Payload Criteria

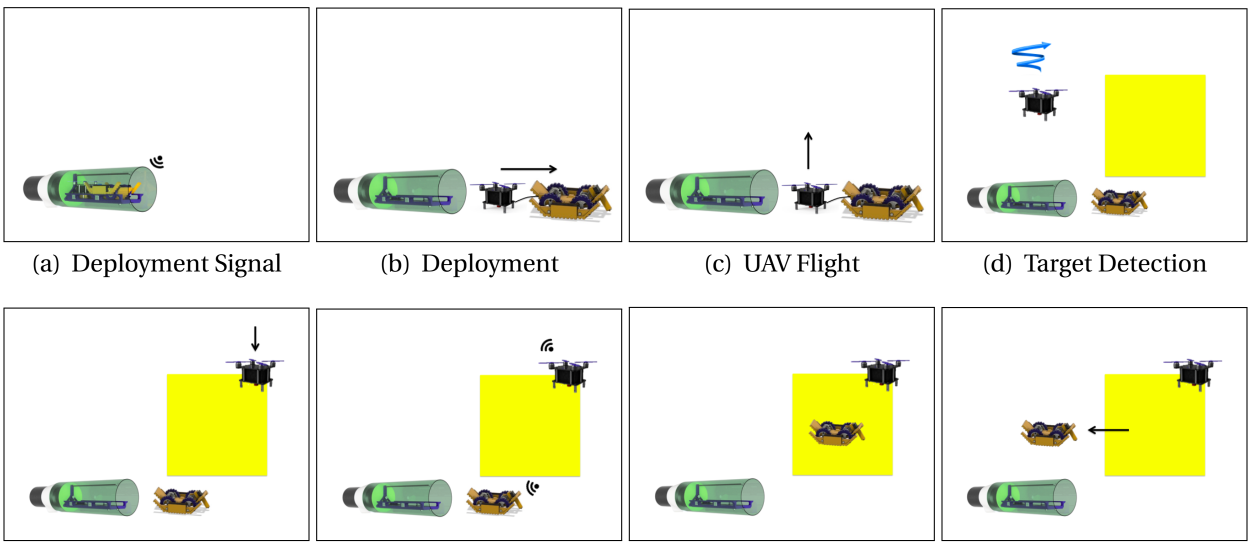
4.1 System Overview

The scoring payload this year is the Lunar Sample Retrieval System (LSRS). The LSRS consists of three interconnected systems: the Retention, Orientation, and Deployment (ROD) System, a UAV with target detection capabilities, and an eccentric-crank Rover capable of retrieving Lunar Ice samples. A visual overview of the LSRS mission can be seen in Figure 56.

The ROD system is responsible for securing the LSRS during flight and orienting the LSRS before deployment, and it interfaces with the sled and rail assembly used for vehicle integration. The bolt securing the rail platform is threaded through a bearing press-fit in the aft-bulkhead, allowing free rotation of LSRS for orientation. Four solenoids attached to the sled extend into the Rover body and UAV sled to secure the LSRS during flight. Upon successful recovery, the solenoids retract and enable the Rover to translate out of the payload bay and tow the UAV in the UAV-sled behind it.

The UAV fitted with a target detection system will then search for and locate the nearest CFEA. Target detection is accomplished by transmitting a live video feed from the UAV to a ground station. Image processing is done on the ground station and commands are sent back to the UAV. Once a CFEA is located, the UAV will land in the corner furthest from the Rover and will transmit its coordinates to the Rover.

Upon receiving coordinates transmitted from the UAV, the Rover will begin to travel to the coordinates of the UAV. Once the Rover has translated to the CFEA, the sample retrieval system will initiate. An Archimedes screw will extend from the Rover body into the the sample and collect a 10 mL sample of simulated lunar ice. After the sample has been collected, the Rover will translate 10 linear ft away from the CFEA and conclude the LSRS mission.



(a) Deployment Signal (b) Deployment (c) UAV Flight (d) Target Detection

(e) UAV Landing (f) Signal Transmission (g) Sample Retrieval (h) Traverse 10 ft

Figure 56: LSRS Mission Overview

4.2 Mission Success Criteria

The payload must accomplish 8 main tasks: (1) withstand forces experienced during vehicle flight and recovery, (2) activate remotely via a signal from the ground station, (3) orient and deploy, (4) locate the closest Competition Future Excursion Area (CFEA), (5) transmit the coordinates of the closest CFEA, (6) traverse to the sample area, (7) retrieve and secure a 10 mL lunar sample, and (8) transport the sample 10 ft away.

The mission will be considered successful if it meets all Payload and Safety Requirements outlined in the 2020 NASA Student Launch Handbook and the following criteria:

P.MS.1 The payload shall be powered off until the launch vehicle has safely landed and has been approved for remote-activation by the RSO.

P.MS.2 The payload shall remain retained inside the vehicle during vehicle flight and recovery.

P.MS.3 The payload shall self orient to within 5°of its upright position for deployment.
P.MS.4 The payload shall deploy from inside the launch vehicle from a position on the ground.
P.MS.5 The UAV shall locate, fly to, and land at the closest FEA.
P.MS.6 The UAV shall send its coordinates to the Rover and activate the Rover.
P.MS.7 The Rover shall traverse to the UAV coordinates and locate the sample area.
P.MS.8 The Rover shall recover and secure a 10 mL lunar ice sample.
P.MS.9 The Rover shall move 10 linear ft away from the sample area.

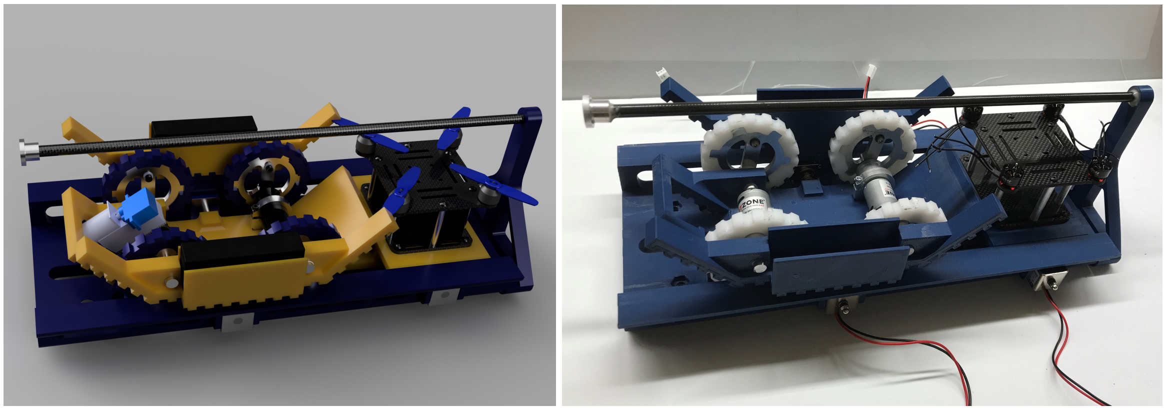
4.3 Changes Since CDR

Since CDR, a few minor changes have been made to the scoring payload. A standoff has been integrated to the sliding platform to keep the LSRS from cocking inside the Payload Bay. In addition to this standoff, two bearings will be integrated with the standoff to ensure frictionless rotation of the LSRS and proper orientation. The rails on the rail platform were manufactured out of Nylon 6 using a laser cutter and epoxied to the rail platform. This is different than 3-D printing the rails on the platform as discussed in CDR and the change was made due to cheaper manufacturing costs. The final change since CDR is the addition of a tread around the Rover wheels. This design change was required to prevent the links from cocking in a dead position of the mechanism. All changes are minor and do not affect the performance of the retention of the LSRS during flight.

4.4 Layout

4.4.1 Full Assembly

The LSRS is located in the fore section of the launch vehicle. Figure 57 shows a comparison of the rendered LSRS to the as-built LSRS. The as-built LSRS is 16.6875 in. long including the thicknesses of the fore and aft bulkheads. The fore bulkhead separates the payload bay from the inner chamber of the nosecone which is pressurized using black-powder charges and jettisoned from the payload bay. The LSRS is secured to the aft-bulkhead using a 1/2"-20 bolt and lock nut. The bolt is threaded through a flanged bearing which enables the entire assembly to rotate freely within the payload bay. The UAV is secured in the UAV Sled and is located aft of the Rover so that the Rover can tow the UAV out of the payload bay during deployment. The as-built system weighs a total of 121.9 oz and Table 17 shows a break down of the weights of different components in the LSRS.



(a) Render (b) As-built

Figure 57: LSRS Full Assembly

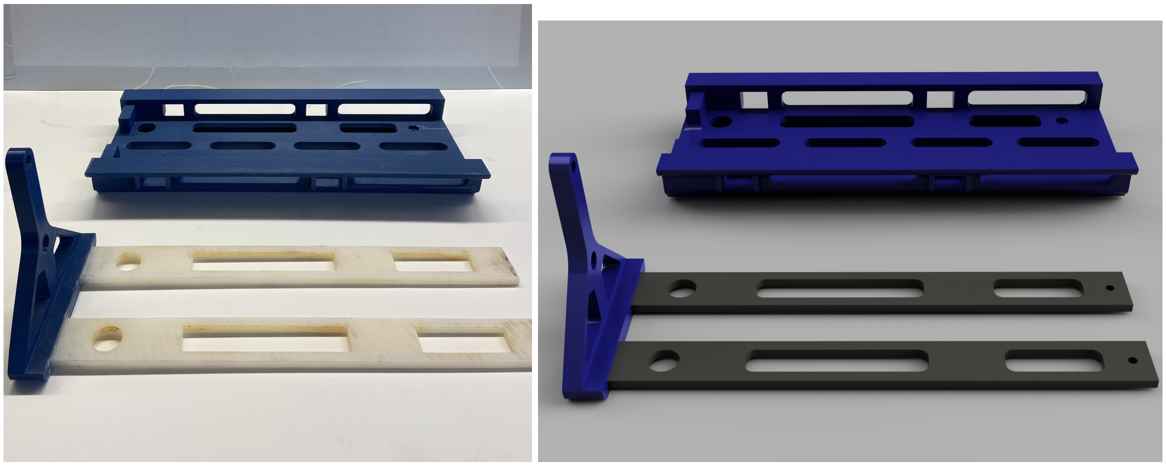
Table 17: Summary of LSRS Subsystem Weight

System	Weight	
	Simulated	As-built
UAV	17 oz	19.5 oz
Rover	41 oz	34.4 oz
Sample Retrieval	2 oz	1.4 oz
Deployment	31.2 oz	47.2 oz
Bulkheads	17.8 oz	19.4 oz
Total	109 oz	121.9 oz

4.4.2 Launch Vehicle Integration

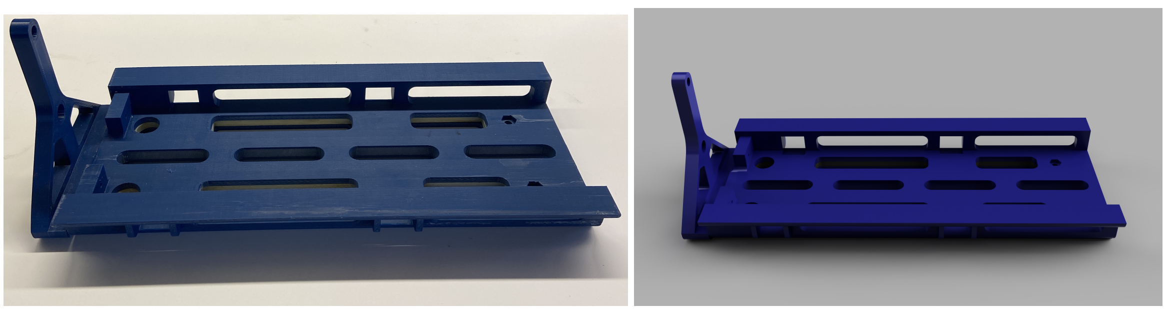
The LSRS is integrated into the launch vehicle using a rail and sled system to satisfy NASA Requirement 4.2. The system is comprised of two platforms: the rail platform and the sliding platform. This grants easy access to the payload and ensures the proper placement of the UAV and Rover into the ROD system. The rail platform is permanently attached to the aft-bulkhead using a lock-nut and bolt. The sliding platform attaches to the rail platform by inserting the two “rails" of the stationary platform into the respective slots on the sliding platform. When the sliding platform is fully placed on the rail platform, two nuts and bolts are placed in the fore section of the platforms to secure them together.

The manufactured rail and sliding platforms are shown next to the respective CAD models in Figures 58 and 59. The platforms were manufactured with a combination of 3-D printing and laser cutting. The sliding platform and the base of the rail platform were manufactured using a StrataSys F107 3-D printer with ASA filament. The rails of the rail platform were manufactured using a laser printer and were cut from a solid piece of Nylon-6. The rails were then permanently secured to the base using RocketPoxy.



(a) As-built (b) Render

Figure 58: Sliding and Rail platforms

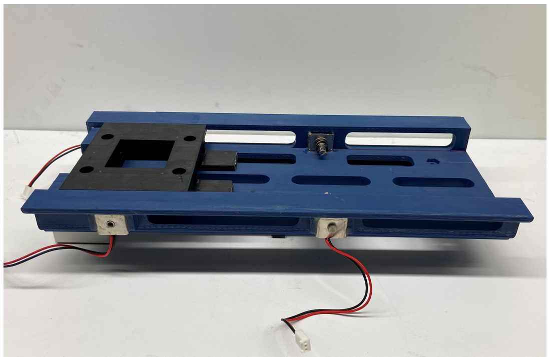


(a) As-built (b) Render

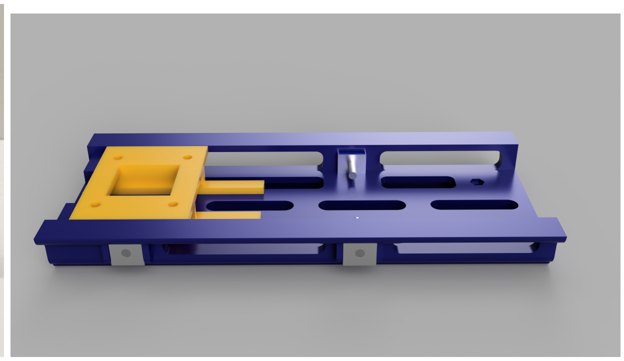
Figure 59: Platforms integrated

4.5 ROD System

The Retention, Orientation, and Deployment (ROD) System is a critical component for the success of the LSRS payload. The ROD System combines retention, orientation, and deployment in one mechanism to efficiently use the space within the payload bay and to create a simple, elegant system that fulfills multiple requirements. The system is integrated with the sled and rail platform system and is shown in Figure 60. All testing and verification of the ROD System is discussed in Section 7.1.3.



(a) As-built



(b) Render

Figure 60: Platforms integrated

4.5.1 Payload Retention

Retention of the LSRS during flight is achieved using four solenoids that are epoxied into the sliding platform. The sliding platform itself is then secured to the rail platform by two lock-nuts and bolts in the fore section of the platform. The two solenoids in the fore section of the platform slide into pin-holes in the Rover body and secure the Rover during flight. Motion of the Rover links is restricted by the nature of the eccentric crank mechanism design. The two solenoids in the aft section of the platform slide into pin-holes in the UAV-Sled. The UAV rests on the UAV-Sled by threading the UAV landing struts through four holes on the UAV-Sled. The two landing struts in the aft side of the sled have through holes which allow two epoxied pins in the aft section of the sliding platform to freely slide into the struts and securely hold the UAV in the UAV-Sled during flight.

Figures 61 and 62 show the manufactured components responsible for retention of the LSRS during flight. The sliding platform serves as a housing for the LSRS and the retention components. The team purchased four Adafruit Medium Push-Pull solenoids as discussed in CDR. As seen in figure 61, the four solenoids are placed in the respective slots of the sliding platform as well as the two UAV retaining pins. While all four solenoids are press-fit into the housing slots, 5-minute epoxy was used to ensure that the solenoids are secured during flight. The retaining pins were manufactured out of a 1/4 in. Aluminum 6061 rod using a Manual Lathe in the Student Fabrication Lab and were attached to the sliding sled using RocketPoxy. The UAV-Sled shown in Figure 62 was 3-D printed on a Statasys F107 at the Notre Dame Idea Center and the sled was printed using ASA filament.

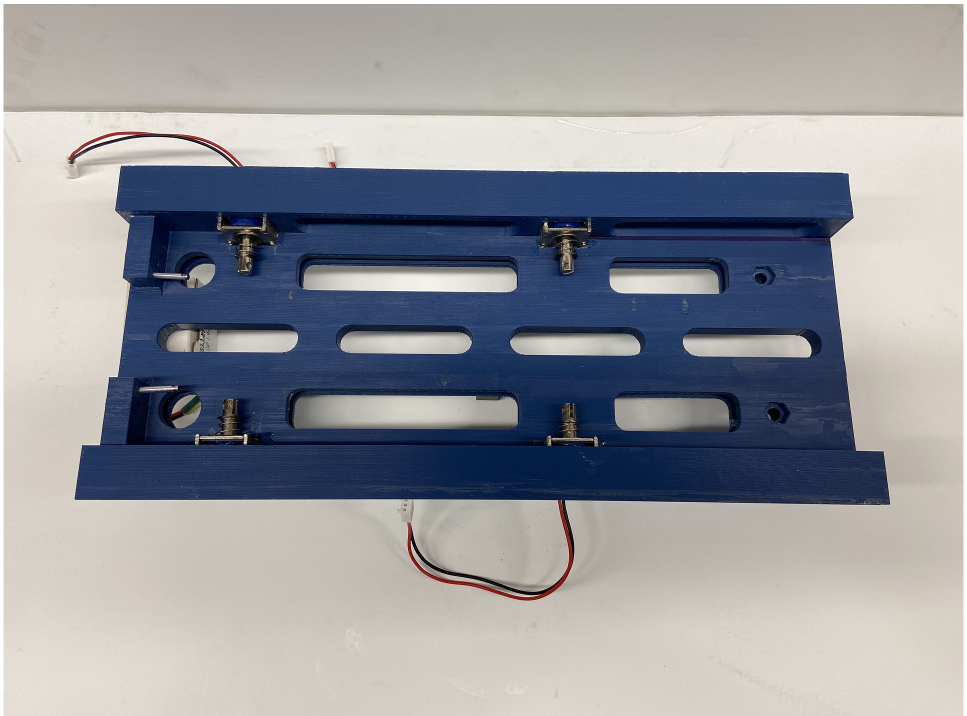
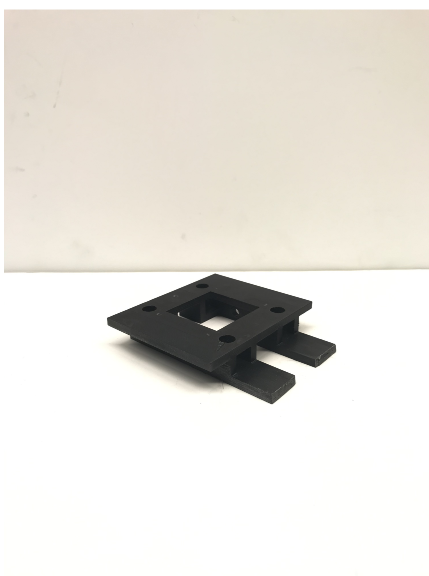


Figure 61: Solenoid Placement in ROD Platform



(a) Top

(b) Bottom

Figure 62: As-Built UAV-Sled

4.5.1.1 Retention Electronics

The retention electronics consists of an Adafruit Itsy Bitsy controller which will receive the trigger signal from the rover controller to actuate the solenoids and allow the rover and uav to exit the launch vehicle. The solenoids are powered by a 7.4V LiPo battery with power delivered to the solenoids through a MOSFET transistor. The MOSFET gates are controlled by the Adafruit controller and act as a switch to deliver power to the solenoids. Additionally, a diode across each solenoid provides a circuit for transient current to dissipate following the solenoids turning off to avoid damage to the solenoids. The solenoids are connected via a 3 pin rectangular molex connector. The assembled retention control PCB is shown in figure 63.

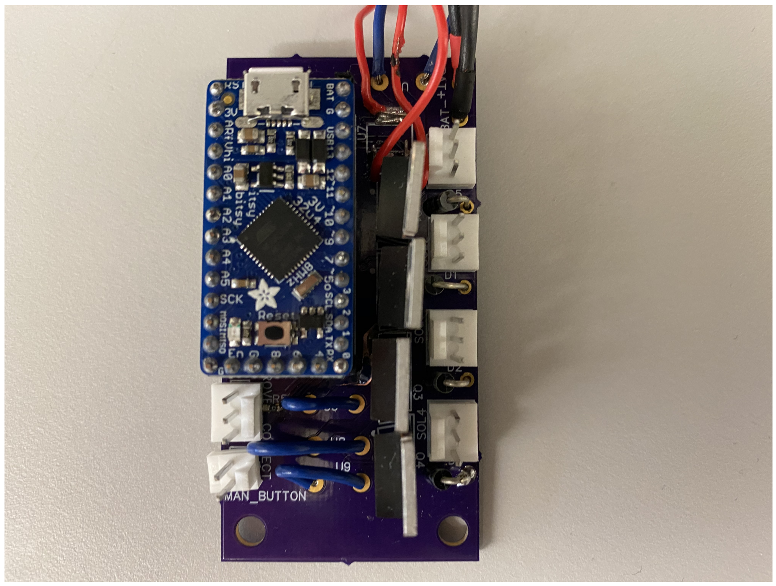
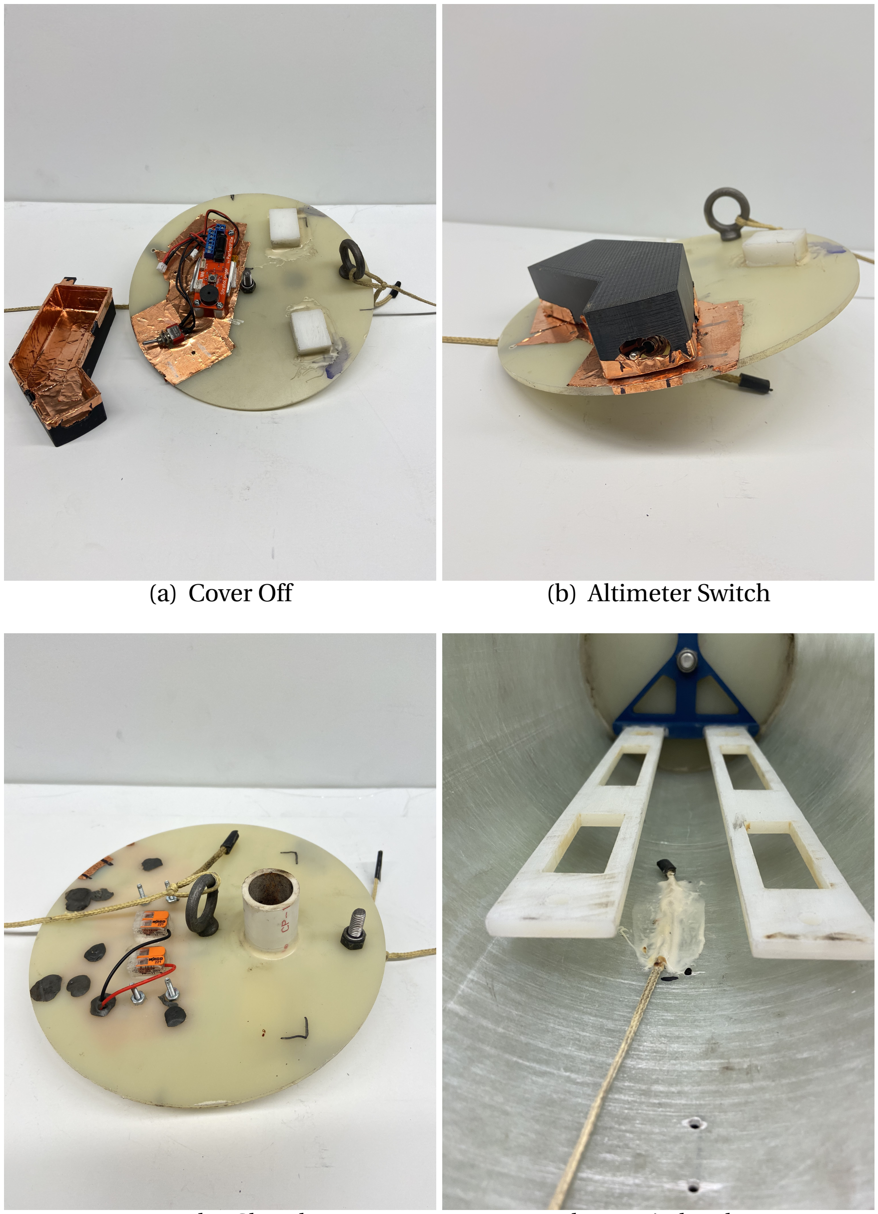


Figure 63: ROD Electronics PCB

4.5.2 Nose Cone Ejection

In order for the LSRS to deploy from the launch vehicle, the nosecone of the launch vehicle must be jettisoned during vehicle recovery after the main parachute has been deployed. This is accomplished by creating a pressure chamber inside the nosecone and separating the nosecone from the payload bay with a removable bulkhead. The bulkhead is loosely press-fit into the nosecone such that it minimizes the space between the inner diameter of the nosecone and the outer diameter of the bulkhead but is able to freely slide into place. The sliding platform and a stability rod secured to the rail platform keep the bulkhead level in the fore section of the payload bay. A ring on the inside of the nosecone lies flush with the bulkhead when the nosecone is placed on the launch vehicle. This secures the bulkhead during flight and seals the pressure chamber in the nosecone from the payload bay. When the launch vehicle has reached 400 ft after deploying the main parachute, the black-powder will ignite and jettison the nosecone from the launch vehicle.

The nosecone ejection system is shown in Figure 64 and is mounted to the removable bulkhead. The bulkhead itself was manufactured out of Garolite-G10 stock using a Techno Router. A PerfectFlite Stratologger SL100 altimeter is mounted the aft-side of the bulkhead using four M4 bolts that free fit through the bulkhead and are secured using nuts. Spacers around the bolts raise the altimeter 1/2 in. from the bulkhead to provide space for a 3.7 V LiPo battery to fit underneath the altimeter. The battery is secured to the bulkhead using velcro tape. To protect the altimeter, a cover was printed using a Stratasys Fortus F170 printer out of ABS filament. Copper tape was the applied to the interior of the casing and the bulkhead to create a Faraday cage to prevent signal interference. A lever switch is epoxied to the bulkhead near the altimeter to turn the altimeter on and off at the launch pad and a hole cutout was made in the casing to allow for easy access to the switch. Ignition wires are threaded through the bulkhead and connected to junctions epoxied on the fore side of the bulkhead. The e-match wires are correspondingly connected to the other terminal in the junctions. The e-match, with 1.5 g of black-powder, is then secured into the PVC pipe using blue-painters tape. Two 1/4"-20 eye-bolts are secured to the bulkhead using lock-nuts. 1/8 in. Kevlar chord is tied to the eye-bolts and tether the nosecone to the payload bay with. The tether attaches to another eye-bolt in the nosecone and is secured to the payload bay by epoxying 3 in. of the tether to the interior of the payload bay using RocketPoxy. The stability rod was cut from a 5/16 in. diameter carbon fiber tube using a band saw in the Student Fabrication Lab. The Stopper was manufactured out of Aluminum 6061 using a manual lathe. The stopper was epoxied to the carbon fiber rod using RocketPoxy and then the complete stability rod was epoxied to the Rail Platform using RocketPoxy.



(a) Cover Off (b) Altimeter Switch (c) Powder Chamber (d) Epoxied Tether

Figure 64: Nosecone Ejection System

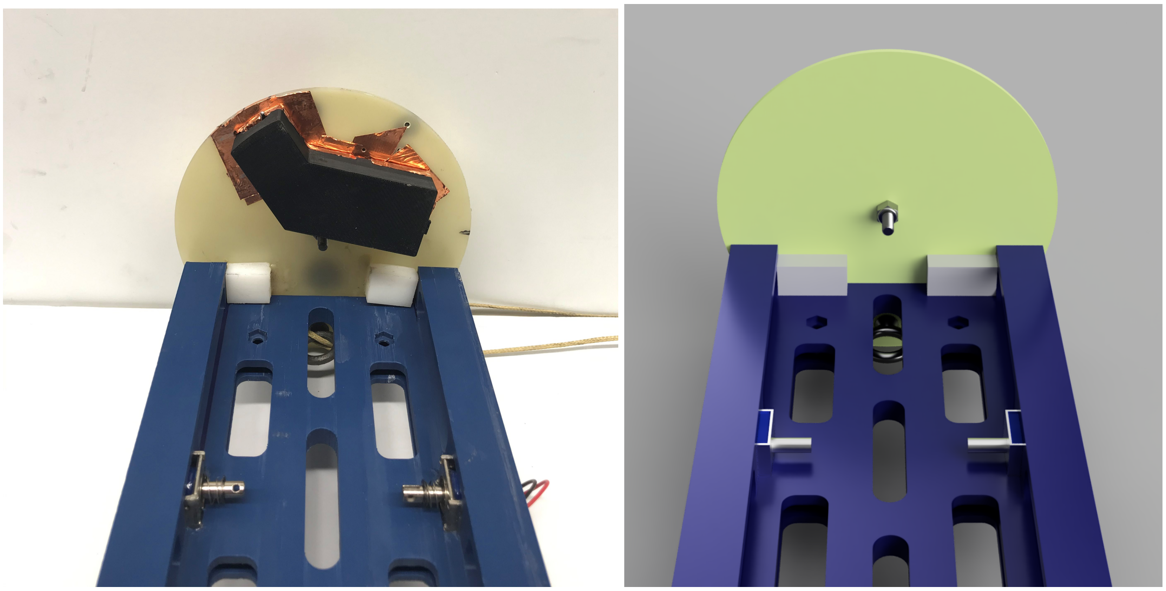
4.5.3 Orientation

Orientation of the LSRS is critical to mission to success. To reliably orient the LSRS after successful launch vehicle recovery, a system was designed using a flanged bearing in the aft-bulkhead and utilizing the gravitational force on the LSRS with an off-center center of gravity. During flight, the sled is prevented from rotating by two rectangular cubes epoxied to the fore-bulkhead which fit into the corners of the sliding platform. When the nosecone is jettisoned from the launch vehicle, the platform is able to freely rotate during the last 400 ft of recovery descent. The off-center center of gravity will cause the LSRS to self-orient so that the center of gravity is closest to the ground.

The orientation system is shown in Figure 65 The aft-bulkhead was manufactured out of Garolite-G10 stock using a Techno Router similar to how the fore-bulkhead was manufactured. A tight tolerance was placed on the center hole in the bulkhead for a tight press-fit for the orientation bearing. After the bulkhead was manufactured, a flanged ball bearing was press-fit into the bulkhead. With the bearing in place, a 1/2"-20 steel nut was threaded through the aft-side of the bulkhead and through the rail sled on the fore-side of the bulkhead. A nylon lock-nut was then threaded onto the bolt to tightly secure the rail sled to the bulkhead. The rectangular cubes used to lock the orientation of the LSRS during flight were cut from 1/2 in. thick HDPE and were epoxied to the fore-bulkhead using RocketPoxy. Figure 66 shows the fore-bulkhead with the epoxied stoppers positioned in the corners of the sliding sled. This is the placement of the fore-bulkhead during vehicle flight.

(a) Press-fit (b) Integrated

Figure 65: LSRS Orientation System



(a) As-Built (b) Render

Figure 66: Orientation Lock

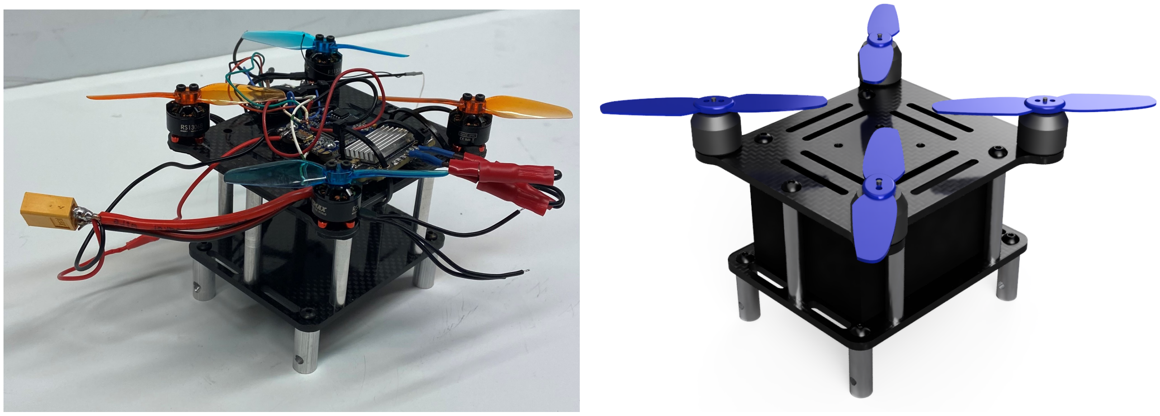
4.5.4 UAV and Rover Deployment

After receiving approval from the RSO to begin the LSRS mission, a signal will be transmitted to the ROD system electronics which will initiate deployment of the LSRS. The four solenoids will simultaneously retract and allow the Rover and UAV-Sled to translate out of the payload bay. The UAV-Sled is attached to the rear end of the Rover by a tether. This will allow the UAV-Sled to be towed out of the payload bay by the Rover. Once the Rover has traveled 10 ft from the payload bay, the Rover will detach the tether to the UAV-Sled by actuating a servo and the UAV will receive a signal to begin searching for the nearest CFEA.

4.6 UAV

4.6.1 Mechanical Design

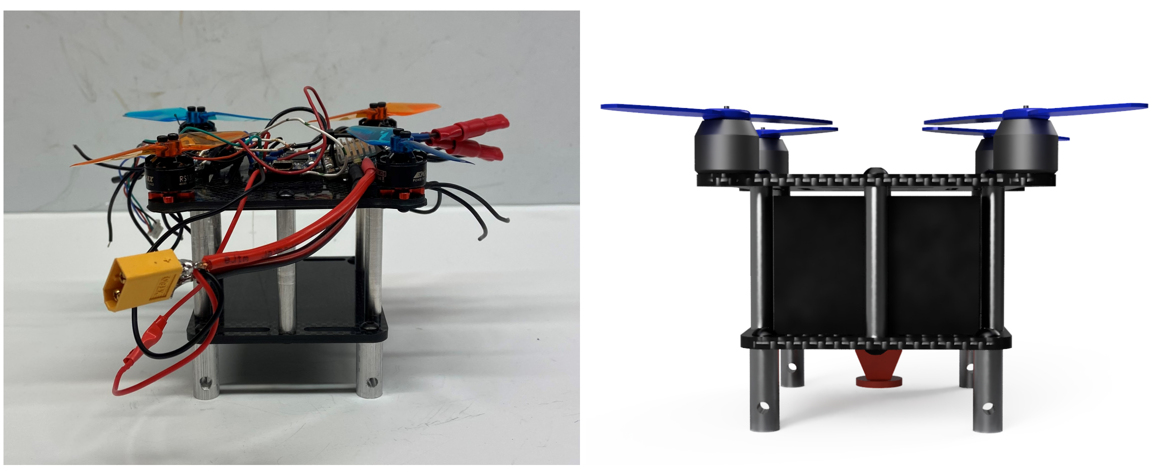
The UAV's frame comprises a pair of carbon fiber decks and a series of aluminum struts to hold the decks together. The lower deck holds the batteries and the camera, while the upper deck is where the other electronics, including the flight controller, the ESC, and the motors, are mounted. The power switch is also secured to the upper deck with epoxy. Because of the addition of a second radio transceiver, a carbon fiber plate was added to the front of the upper deck to increase the area available to mount electronic components. The plate forms a butt joint with the main deck and is epoxied in place with reinforcement from a thin aluminum strip screwed into both the main deck and the extension plate. This reinforcement significantly increases the structural integrity of the joint while only marginally increasing the UAV's weight.



(a) As-Built (b) Render

Figure 67: UAV Assembly

The UAV's carbon fiber decks were machined using a CNC router and holes for mounting electronics were drilled using a drill press. The aluminum struts and landing gear were machined using a band saw, a manual lathe, and an end mill.



(a) As-Built (b) Render

Figure 68: Retaining pin holes

4.6.2 Electrical Design

The UAV electronics can be seen in Figure 69 attached to the top platform of the UAV.

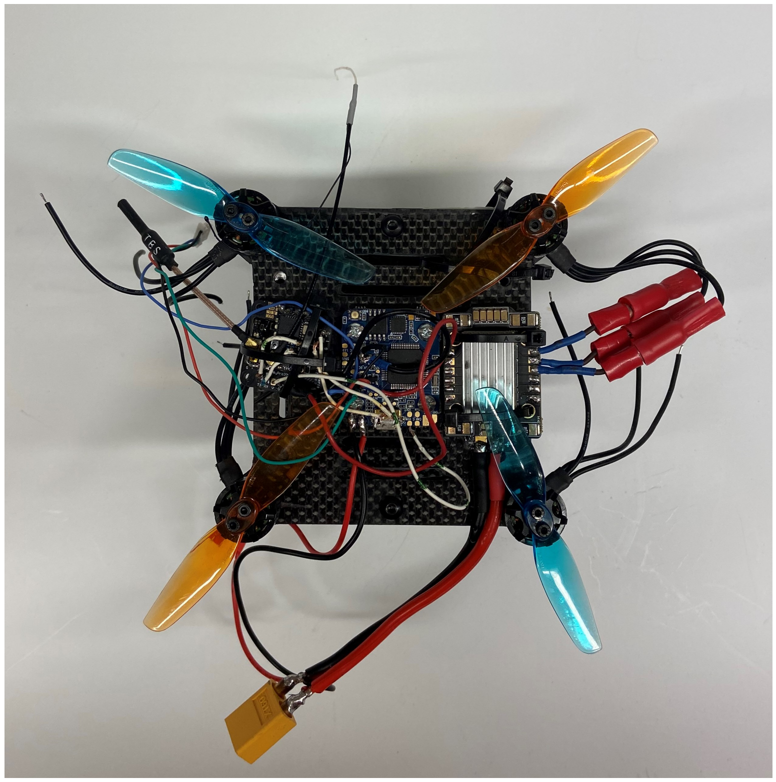


Figure 69: UAV Electronics

The UAV will use a TBS Crossfire Nano Rx transceiver to communicate with a manual controller and a Holybro 915MHz radio to communicate with the ground station for autonomous control and GPS transmission for the rover. The TBS receiver will interface with the flight controller via SBUS, a single-wire serial protocol developed for hobby radio applications, and utilize the proprietary Crossfire protocol to communicate with the manual controller's radio transceiver. The Holybro radio will interface with the flight controller via UART and will communicate with the ground station's radio transceiver using the Micro Air Vehicle Link (MAVLink) protocol.

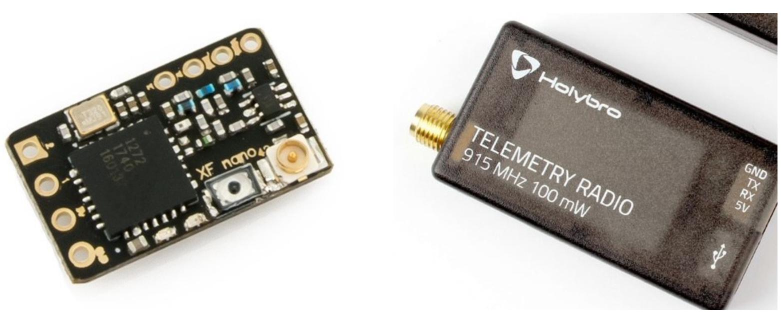


Figure 70: From the left, TBS Crossfire Nano, Holybro Transceiver

The UAV will be controlled by an Airbot Omnibus F4 Nano V6 flight controller and the motors will be controlled by an Airbot Ori32 4-in-1 Electronic Speed Controller (ESC). The UAV's position and heading data will be measured by a Matek M8Q-5883 GPS Module with an integrated compass. The compass uses I2C to interface with the flight controller and the GPS module uses UART. The UAV's video feed from its onboard Caddx EOS2 Turbo camera is transmitted to the ground station by a TBS Unify Pro32 5.8GHz radio transmitter.

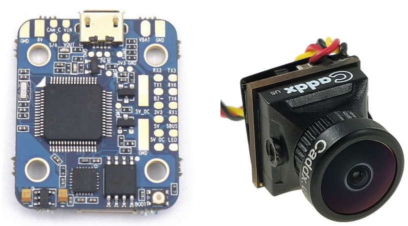


Figure 71: From the left, Airbot Omnibus flight controller and Caddx EOS2 camera

Because of supply shortages, the UAV will no longer be powered by a Lumenier 11.1V 5000mAh Li-Ion battery. Instead, it will be powered by a pair of TURPOW 11.V 2000mAh batteries wired in parallel to increase flight time. These batteries are designed for the Parrot Ar.Drone 2.0 but they will also function as needed in this application due to their compact size and high discharge rate (40A per battery).

4.6.3 Target Detection

4.6.3.1 Detection Algorithm

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 are being taken to create the optimal binary mask of the image. The team has been creating a dataset by manually annotating object masks (representing the location of the FEA in the image) over target images. These manual masks are then compared against any computer-generated masks using an objective function called Intersect over Union, shown in Equation 10:

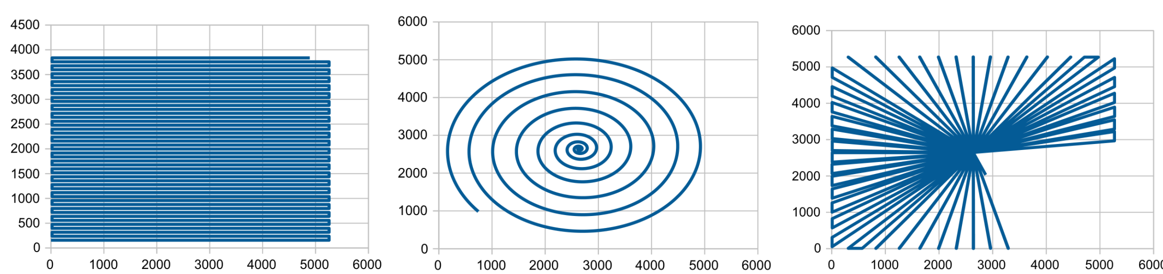
$$E = \frac{|A \cap I|}{|A \cup I|} \tag{10}$$

Symbol	Description
E	Error
A	Manually Annotated Mask
I	Comupter Annotated Mask

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. The team will continue to refine its analysis as new opportunities to collect training data present themselves. With the current dataset, the team has concluded that the HLS color spectrum, combined with the dilation, closing, and erosion morphological operations, gives 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 the table below, an excerpt from a larger 393 row table.

4.6.3.2 Search Algorithm

The UAV will follow an algorithmic search procedure to traverse the area surrounding the launch vehicle's landing site and identify a CFEA. To determine the optimal path for this search, a Monte Carlo simulation was created. This simulation modeled three pre-defined flight paths with five randomly placed targets on a 1 mi^2 field. The first path is a linear sweep of the field, making horizontal passes back and forth across the length until the entire field has been scanned. The second path is a spiral proceeding outwards from the center of the field. The final path is a series of "pie slices," proceeding from the center of the field to its edge and back. All three approaches are illustrated in Figure 76, and the results of the simulation are summarized in Table 18.



(a) Linear (b) Outward Spiral (c) Pie Sweep

Figure 72: Simulated Flight Paths

Table 18: Summary of Monte Carlo simulation results

Path	Success Rate	Mean Steps	Median Steps	Max Steps	Standard Deviation
Linear Sweep	0.9918	19386.0	15164	69712	15540.0
Outward Spiral	0.5174	8256.3	7287	35920	6203.2
Pie Sweep	0.9052	22019.3	19547.5	122911	16915.8

The Outward Spiral method showed the most promise, since it had the shortest path length of 7,000 to 8,500 steps on average, and the 50% success rate improves by shortening the gaps between spirals. However, each "step" is 5 feet long, so even this method requires approximately 40,000 feet or 8 miles of flight distance to find a target. With only 10 minutes of flight time, this requires a sustained flight speed of 45 mph or 67 ft/s. This speed is not within the capabilities of the UAV.

To remedy this issue, an informed search algorithm was developed. This algorithm designates a limited area of the field as a search space to minimize the time necessary for the UAV to identify an FEA. A satellite photograph of the launch site taken from Google Maps was used to create the search area, shown in Figure 26.

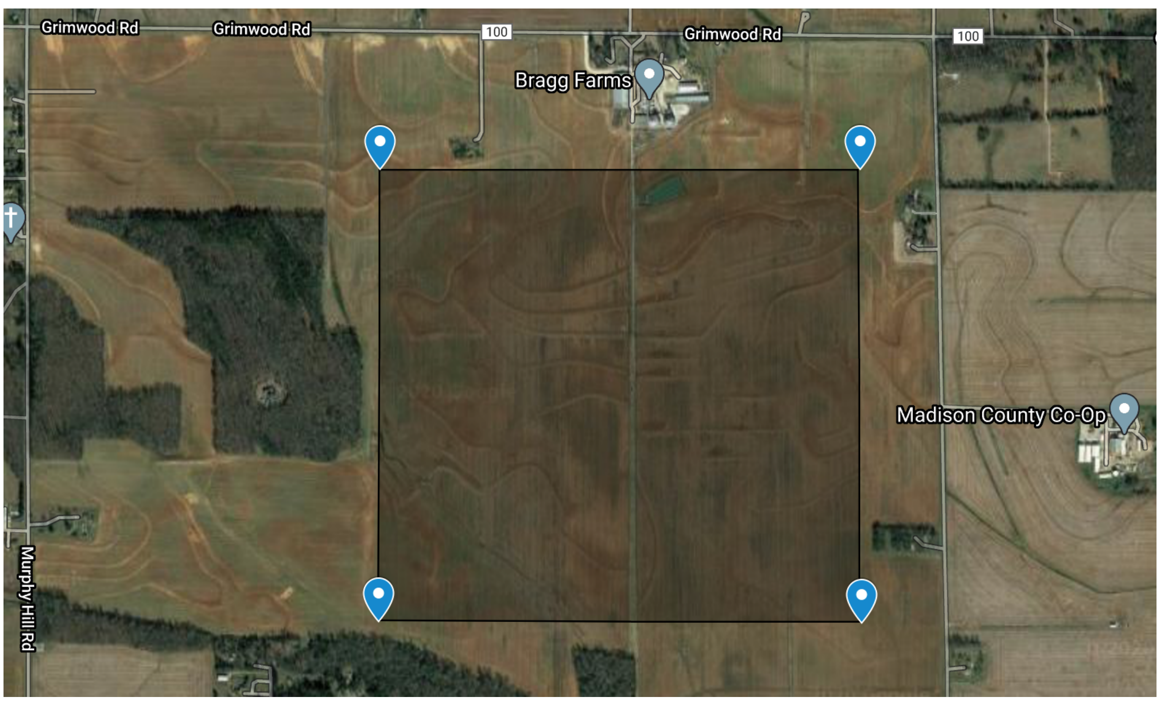


Figure 73: Location of the search area around the launch site.

The four pins indicate four GPS coordinates which have been used to define a search area for the UAV. This region was chosen to maximize open field space while avoiding forested or developed areas which will not contain CFEAs. In order to maximize search efficiency, the UAV will traverse into this region as directly as possible, and then spiral inwards towards the center. This will give the UAV the greatest likelihood of identifying a CFEA within the projected 10 minute flight window.

4.6.3.3 Ground Station Relay

The ground station relay is a command center for both the UAV and the rover, governing both autonomous and manual operations. It is centered on two Raspberry Pi 3s, one primarily communicating with the UAV and the other communicating with the rover. The full ground station assembly can be seen in Figure 61.

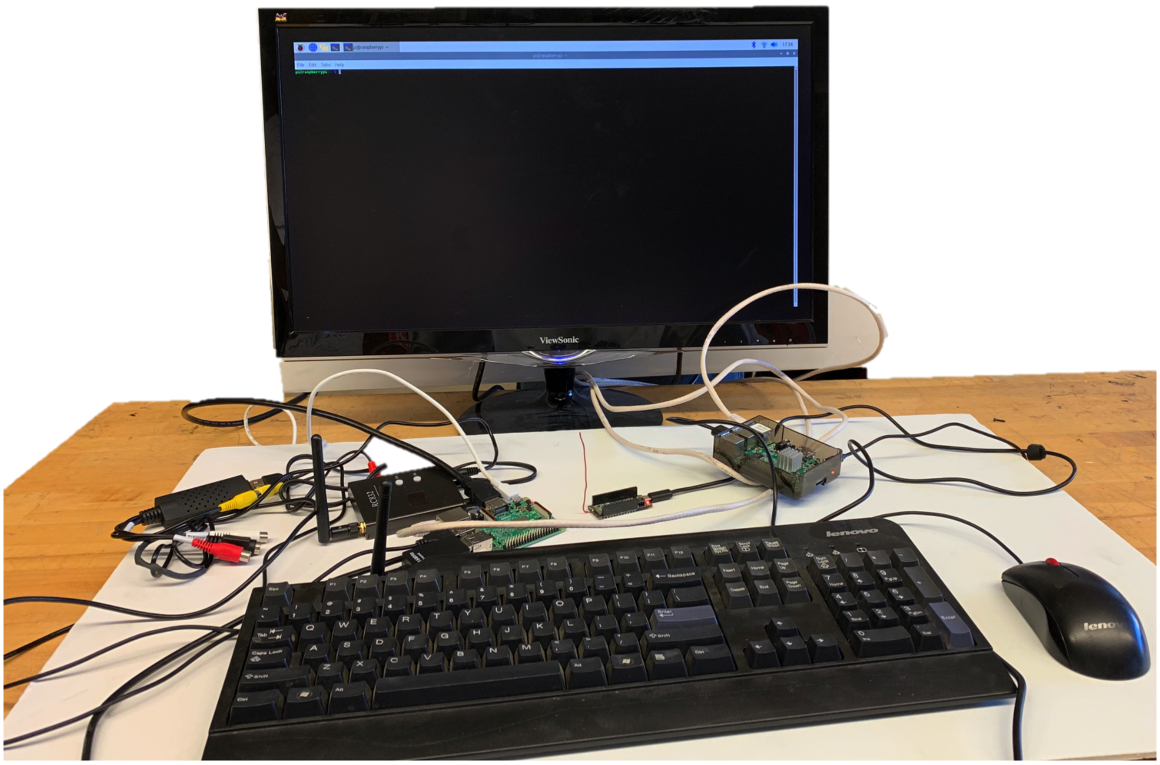


Figure 74: Full ground station assembly.

The primary Raspberry Pi handles communication with the UAV, along with data display and user input. It connects to a Holybro 915 MHz radio transceiver via USB, which sends commands and receives telemetry from the UAV using the MAVlink communication protocol. Additionally, it connects to an RC832 Audio/Video receiver over USB, which receives a live video feed from the UAV. In order to display this data, along with information about the status of the UAV and rover, this Pi is connected to an HDMI monitor, which displays live video along with the GPS coordinates of both vehicles. In case of software errors or other unexpected scenarios, this Pi will also be attached to a USB keyboard and mouse, which can be used to interface with the device in order to diagnose errors and reboot the ground station code if needed. This portion of the ground station is shown in Figure 62.

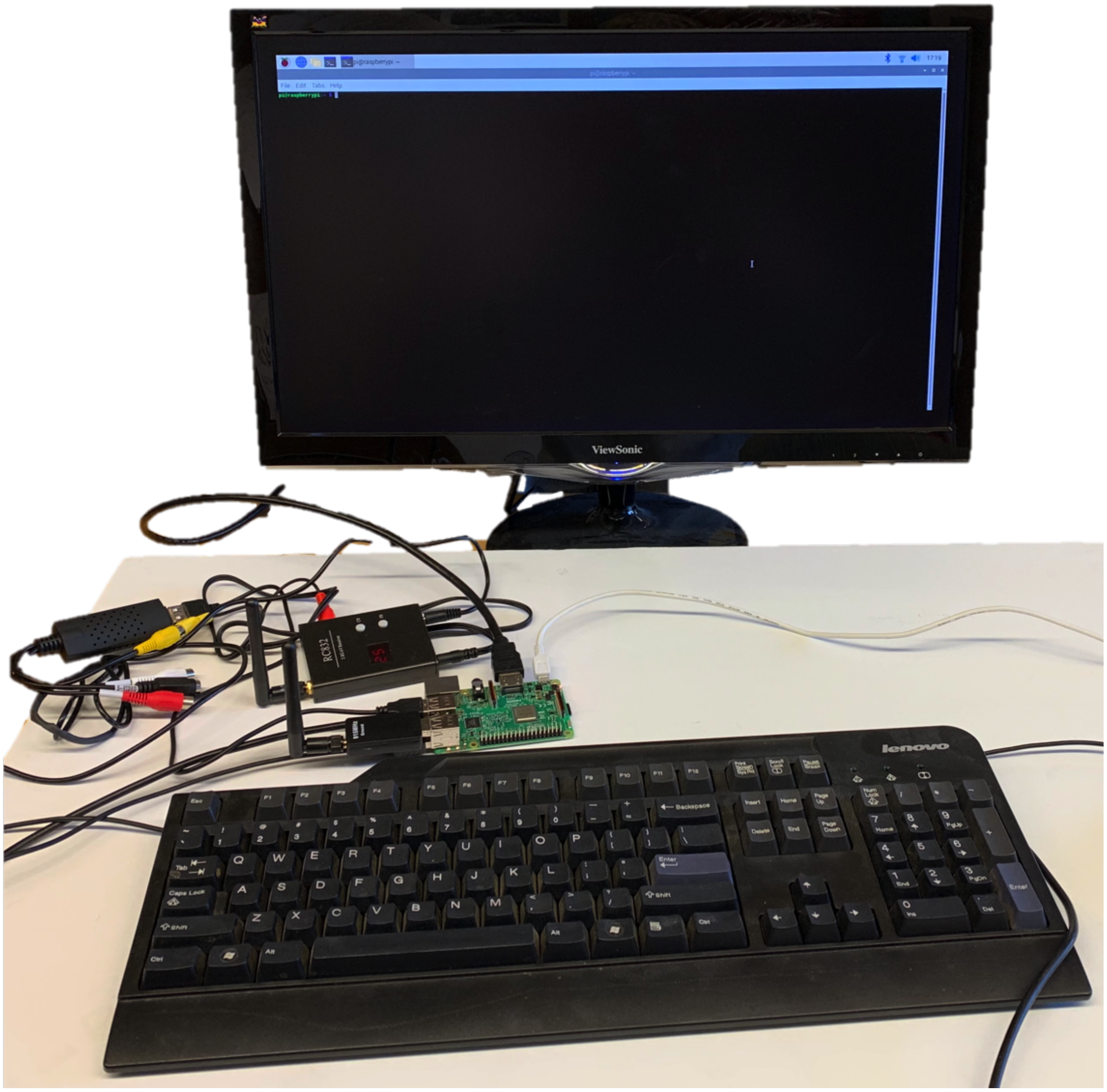


Figure 75: Primary ground station Raspberry Pi and connected hardware.

Both the target detection and search algorithms, detailed in Sections 4.5.3.1 and 4.5.3.2, respectively, run on the primary Pi. Images from the UAV camera are processed by the target detection algorithm, and the output is used by the search algorithm to determine whether to continue searching or land on the far corner of the identified target.

While the ground station directs the UAV autonomously, manual control is accomplished via an independent FrSky Taranis X9D Plus RC remote. This remote connects to a TBS Crossfire transmitter, which links to an independent receiver on the UAV. Pressing an "emergency stop" button on the keyboard will cause the ground station to cede control to this manual remote. Once the emergency stop command is sent, the UAV will cease moving and hover in place until it receives a signal from the manual controller.

The secondary Raspberry Pi handles communication with the rover, and it is connected to the primary Pi over Ethernet. This Pi is also attached via serial bus to an Adafruit Feather M0 with

Long Range 915 MHz Radio, which serves as a slave device directly handling communications with the rover. The RFM95 radio chip built into the Feather M0 could be connected to the Pi directly, but since its software library is designed to be interrupt-driven, the ground station could miss incoming packets if it is doing anything other than listening to the radio. Therefore, the Feather M0 serves as a constant listener that merely passes messages from the Pi to the radio and from the radio to the Pi. This secondary Pi will also be attached to an Xbox One USB gaming controller, which serves as a manual input source for the rover.

The secondary Pi and its two attachments are fully detachable from the primary Pi, altogether making up the Rover Control Module (RCM). It is designed to allow a manual operator to control the rover from a proximate location, with visual confirmation that the rover completes its sample retrieval task successfully. The two Pis have separate power supplies, only being connected by a signal cable. Detaching this cable activates manual control mode, and on the day of launch the operator will thereby be able to take the RCM out into the field to immediately supervise the rover's behavior. The RCM is depicted in Figure 63.

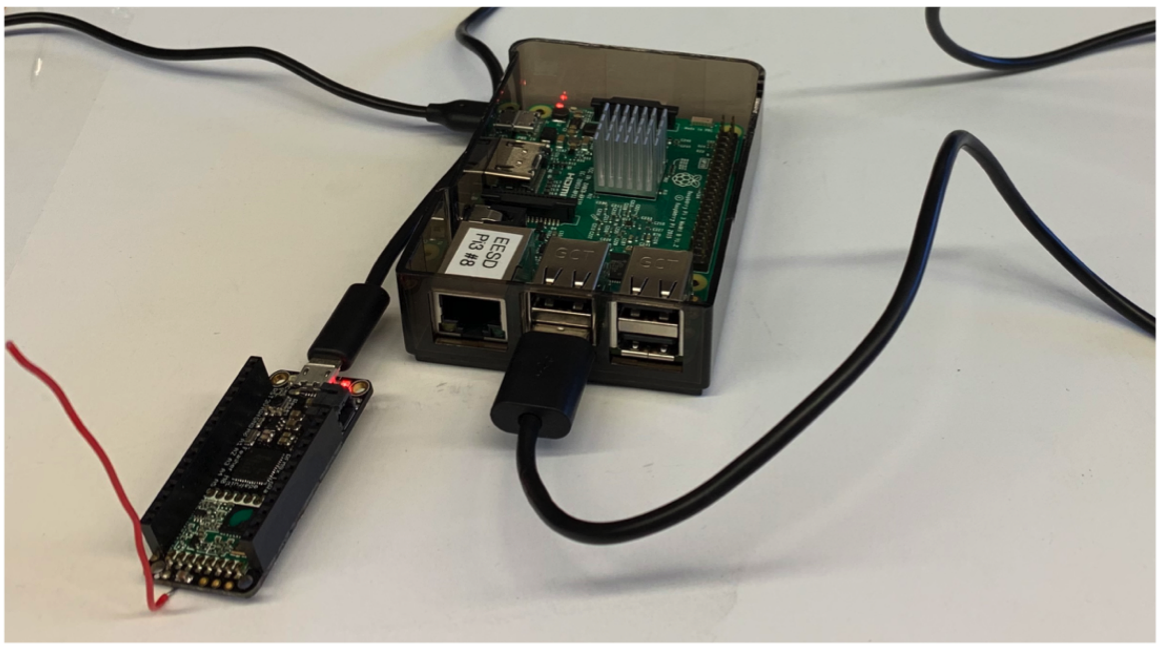
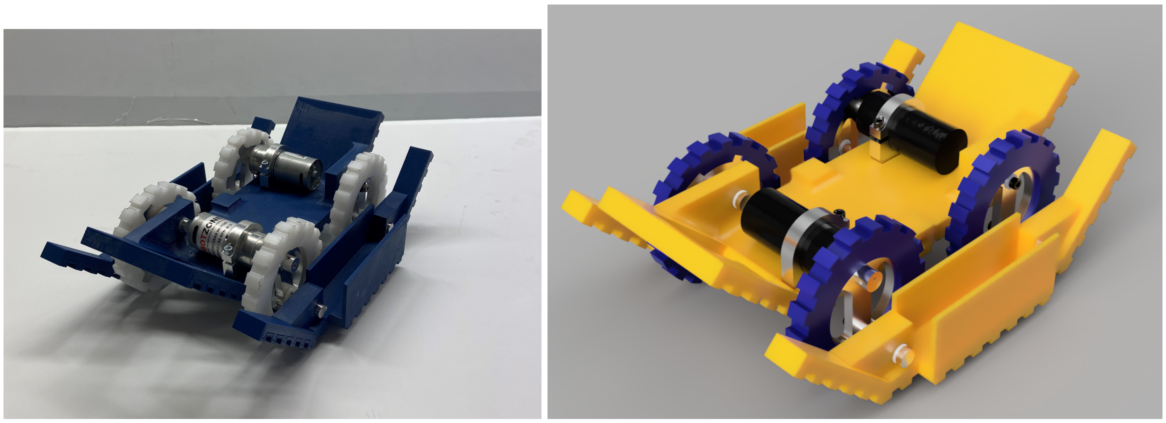


Figure 76: Rover Control Module Raspberry Pi and connected hardware

4.7 Rover

4.7.1 Mechanical Design

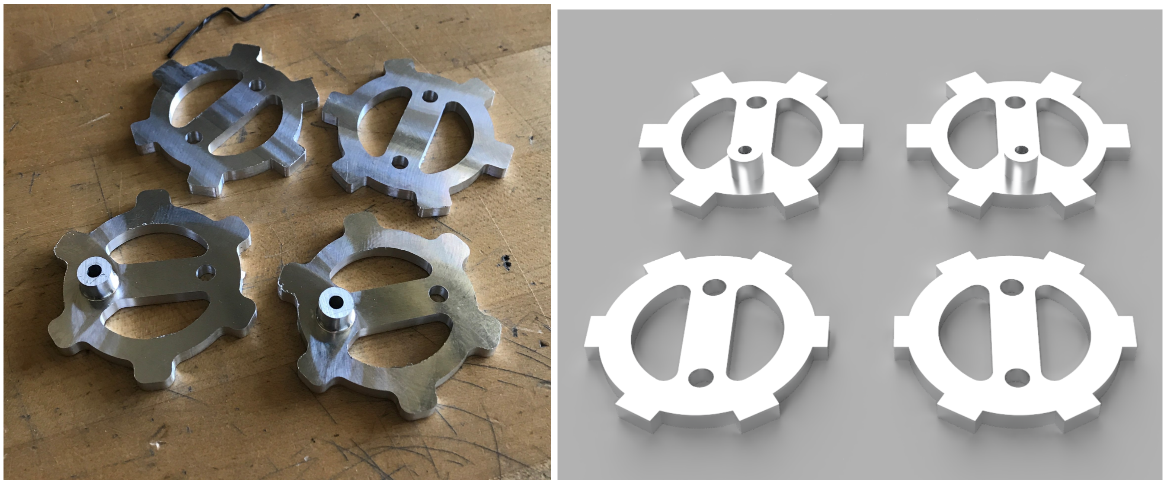
The manufactured rover is shown in Figure 77 next to the CAD model render. The rover was mechanically designed to maximize the strength of the system while minimizing weight. The body and links are printed from ASA plastic in order to save weight and provide ease of manufacturing since the complex geometry of the body and links make it difficult to machine. ASA plastic has higher strength characteristics when compared to other 3D printed thermoplastics such as PLA or ABS. The rover body and links were 3-D printed out of ASA filament at the Idea Center. Both the rover body and links have PTFE journal bearings that lower the friction between the axles and the rover body and links. The links have slots for two batteries for powering the motors that are secured using zip ties and the slots will protect the batteries from debris while the rover is traversing. Both the rover body and links have treads designed into them to improve traction of the rover.



(a) As-Built (b) Render

Figure 77: Rover Assembly

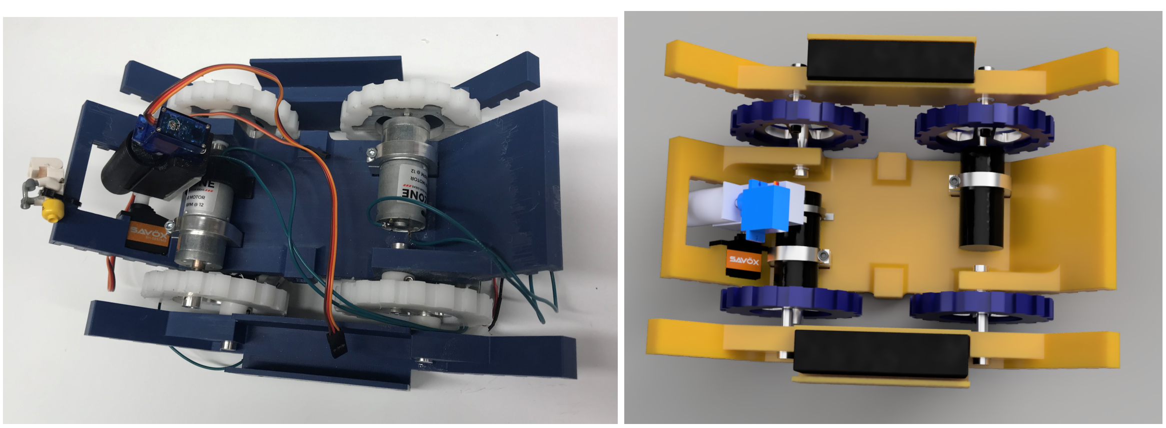
The wheel assembly is composed of an outer HDPE wheel, an aluminum hub, with two aluminum axles. The hub and axles were machined out of aluminum due to the sensitivity to the system to deflection and the hubs are shown in Figure 78. Any plastic deformation of the axles would most likely prevent the rover from properly traversing. ASA plastic would deform too easily for it to be a suitable material. The aluminum hub is press fit into the HDPE wheel to secure it. There are also splines machined into the hub and wheel to allow the transmission of torque. The aluminum axles have shoulders on both ends to properly secure them, along with a 6-32 tapped hole on one end. A 6-32 screw and washer lock the axle in place to the aluminum hub. The shoulders prevent any motion of the links and wheels along the axis of the axle. This design of the axles allows for the rover to travel with relative ease while still being able to handle all environmental conditions presented to it. For the aluminum hubs attached to the two motors a 4-40 set screw is screwed down to the flat of the motor shaft. Thread locker is used on the screw to ensure that it does not back off of the flat of motor shaft during flight or travel.



(a) As-Built (b) Render

Figure 78: Aluminum Hubs

The cutout for the sample retrieval system can be seen on one angled portion of the rover body in Figure 79. The two motors and motor mounts can also be seen. These are secured from the bottom of the rover body with 6-32 screws. Both the rover body and links have PTFE journal bearings that lower the friction between the axles and rover body and links. The links have slots for two batteries for powering the motors that are secured with zip ties. The slots will protect the batteries from debris while the rover is traversing. Both the rover body and links have treads designed into them to improve traction of the rover.



(a) As-Built (b) Render

Figure 79: Sample Retrieval Cutout

4.7.2 Electrical Design

The rover payload electronics integrates the system inputs and outputs for control of the payload. The major components consist of: an MCU, an RF transceiver, a GPS module, an

IMU, a motor controller and two drive motors, two sample retrieval servo motors, and a servo motor for releasing the UAV sled from the rover following deployment.

4.7.2.1 Microcontroller

The Microchip PIC32MX795F512H is the microcontroller for the rover system. The PIC32 interfaces with one UART module for the GPS, one SPI module for the radio, one I2C module for the IMU, 5 PWM pins for standard servo motor control, and a number of GPIO pins for LEDs and other debugging devices. The PIC32 is configured using PICKIT3 programming modules available to the team through the Notre Dame Electrical Engineering design labs and programmed in C using Microchip's free MPLABX software.

4.7.2.2 RF Transceiver

The rover receives commands through a Hope RF RFM95W radio module. This module was chosen based on its long range (LoRa) module with a range of 1.25 miles. The radio operates on the license-free ISM 915 MHz band with a 100mW power rating meeting requirement 2.22.9 and communicates to the PIC32 over SPI. One module is integrated into the design of the rover electronics board, and another module is used to send signals from the ground station for manual control and delivering the GPS coordinates of the UAV to the Rover. The radio is shown below in figure 80. The manual control of the rover will be sent over this radio transceiver from the ground station. As described in the ground station section, an Xbox One controller will be used as the manual controller for the rover with each button being assigned to control setting a specific motor in the forward or reverse position.

4.7.2.3 Rover GPS

The MTK3339 GPS module from GlobalTop Technology provides location information for the rover. This module has built-in ceramic antenna for tracking from GPS satellites with automatic switching capability and a -165 dBm sensitivity to maintain connection. The standard 1 Hz refresh rate will be sufficient for the speed of the rover and the 70mW power rating will allow for longer operation. The GPS module is shown below in figure 80.

4.7.2.4 Rover IMU

The Bosch BNO055 inertial measurement unit (IMU) is used to collect acceleration and magnetometer measurements in order to determine a compass heading for the rover in order to correct the orientation and head in the direction of the UAV transmitted GPS coordinate. A strong benefit of this package is that it is designed to perform data fusion of the acceleration and magnetometer data, allowing it to provide tilt-compensated compass data. An external 32kHz oscillator is used to provide more accurate performance from the BNO055. The BNO055 integrated circuit packaging is shown below in figure 80.

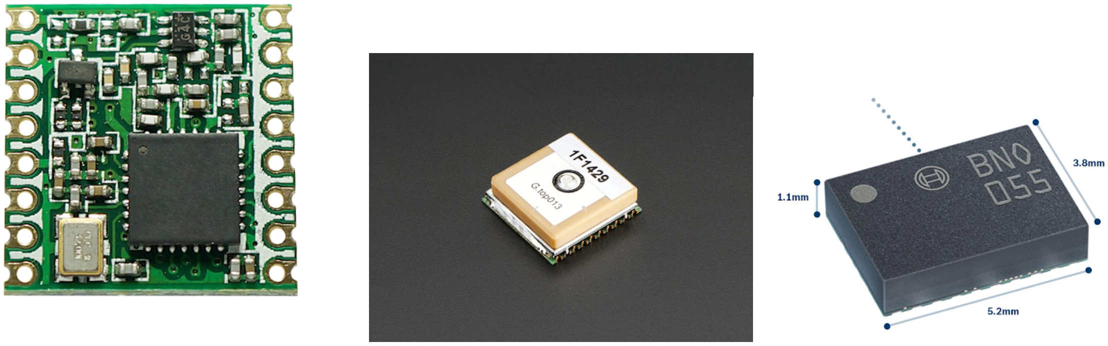


Figure 80: From the left, RFM95W Radio Module, MTK3339 GPS Module, BNO055 IMU

4.7.2.5 Rover Drive Motors and Motor Controller

The Actobotics 98 RPM Econ Gear Motor provides actuation for the drivetrain of the rover. These motors provide a high torque to size ratio with 524 oz-in at stall while weighing only 0.2 pounds. The motor draws a mere 0.10 A at no load and 3.8 A at stall. The Sabertooth 2x5 Motor Controller was selected to control the Econ Gear Motors. The Sabertooth 2x5 motor controller provides up to 5 amps of continuous current and 10 amps of peak current to each of two motor channels. The Sabertooth will be controlled using two standard servo pulse width modulation signals between 1-2 ms with a period of 20 ms while operating the Sabertooth in its “RC” mode. The Sabertooth incorporates circuit protections to avoid operation while overheating or drawing too much current.

Since CDR, it was identified that all motors and the Sabertooth motor controller operate correctly with 3.3V control signals, so the logic shifter for those signals previously included in the design has been removed.

4.7.2.6 Rover Power System

The rover is powered by two ProTek RC 11.4 V 1800 mAh LiPo batteries. The switch to these batteries was made due to a size issue with the previous selection. The battery has a high current rating of 90C well above the combined maximum current draw of all components. The D24V50F5 buck converter provides a 5V line off of the 11.4 V batteries with a high efficiency of approximately 90% and a maximum current of 5A which is sufficient for the current draw of the PIC32 circuit and small servo motors for sample retrieval. The LD1117 linear voltage regulator is used to provide 3.3V off of the buck converter’s 5V to the PIC32 and other 3.3V logic components.

4.7.2.7 Circuit Integration

A custom PCB has been designed and fabricated in order to integrate the various components of the rover electronics into a compact system. The board was designed using the online design software EasyEDA. The boards were fabricated by OSH Park and assembled by members of NDRT using soldering equipment and PPE available in Notre Dame's electronics labs. A rendering of the board and the external connections are shown in figure 81. The soldering station used by the team can be seen in figure 82.

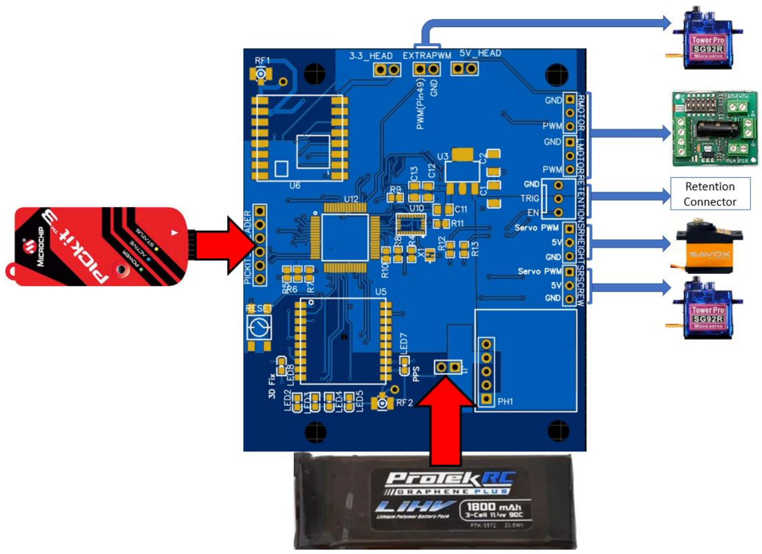


Figure 81: Rover Board Connections

Figure 82: NDRT Soldering Station

The board handles all sensor and MCU communications. Output signals to the motors on the rover are connected via rectangular Molex connectors. A set of header pins are used to connect a PicKit3 for programming, and sets of 2 pin connectors provide test points for the voltage rails on the board. XT90 connectors are used to connect the batteries to the board. The assembled board can be seen below in figure 83.

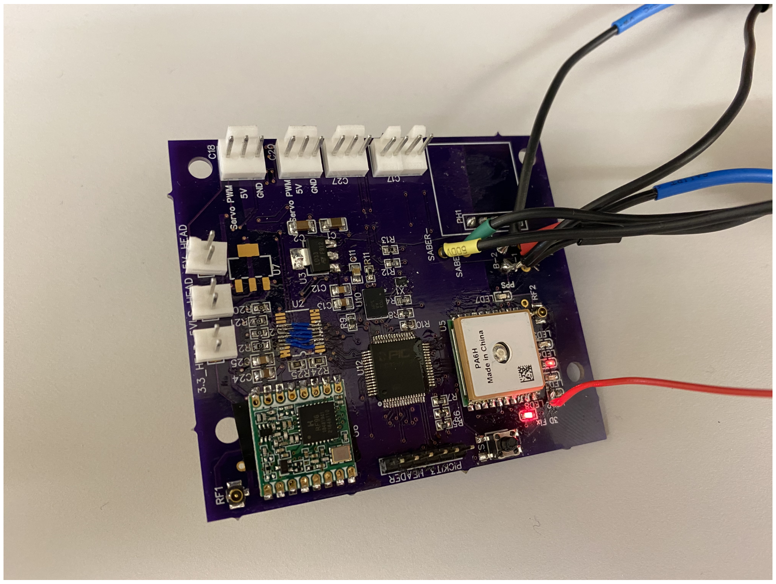


Figure 83: Rover Custom Circuit Board

4.7.3 Sample Retrieval System

The aggregate Sample Retrieval System consists of the Archimedes Screw, the screw case, and the collection bin which were 3D printed using ABS plastic on a Fortus 250mc printer. In addition to the printed parts, an FS90R continuous servo and a 20-degree pressure angle rack with a pitch of 48 were purchased and added to the system. This system, as shown in Figure 84, is deployed using a 20-degree pressure angle plastic gear attached to a Savox SH-0257 that transforms the rotational movement of the pinion to the translational movement of the rack.

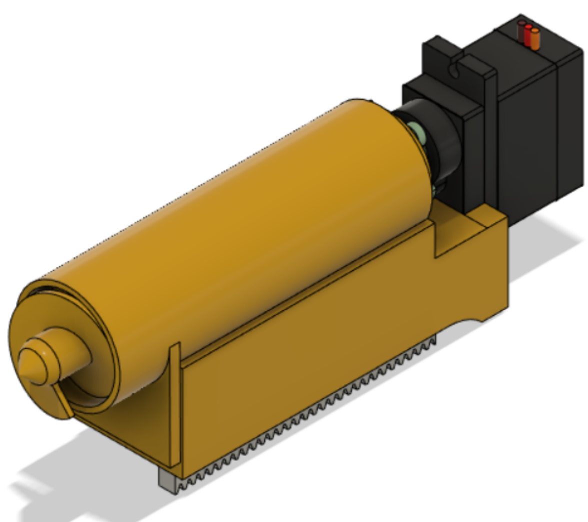


Figure 84: Sample Retrieval Design

4.7.3.1 Archimedes Screw

The screw is epoxied with RocketPoxy to a horn attached to the FS90 servo. As a result, the screw is able to freely rotate as the servo activates. The case enclosing the screw ensures that the sample is contained as it travels up the screw, but there is a slot that allows the sample to fall into the collection bin. The case is screwed into the collection bin by the front tab, so the sample can be retrieved by unscrewing the case and sliding it off. The FS90 servo is screwed into the back of the collection bin as shown in Figure 85. The sample collection bin encloses a volume of 10.26 mL^3, exceeding the 10 mL^3 minimum required for mission success according to NASA Requirement 4.3.3 and Team Derived Requirement P.15.

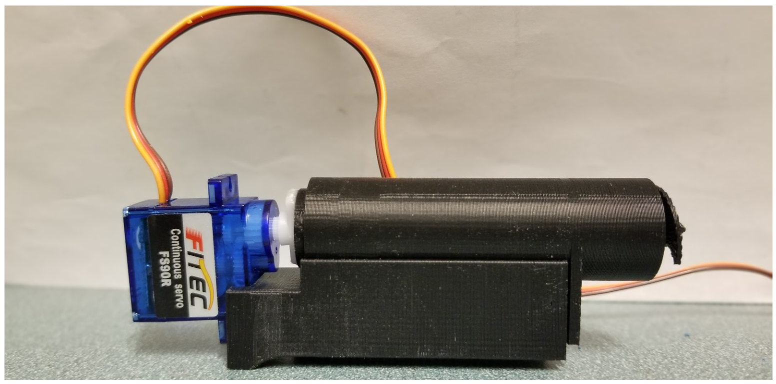
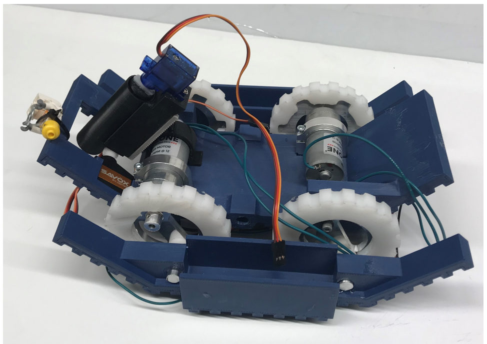


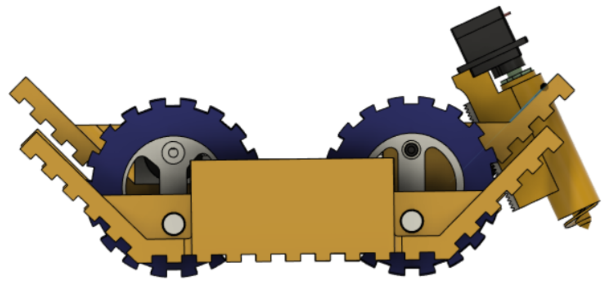
Figure 85: Assembled Sample Retrieval Screw

4.7.3.2 Rover Integration and Operation

The Sample Retrieval System is integrated with the Rover through a rack and pinion deployment system as shown in Figure 86. The screw is mounted on the rover at a 65-degree angle to ensure that it reaches the sample site in the 170-degree rotation of the servo. It is supported by a structure similar to a motor mount with two supporting angled rods. The rods hold the system upright as it moves since the case has two indentations that slide along the supporting rods. As the Savox motor turns the pinion, the rack attached to the bottom of the case moves down into the sample site, then the FS90R motor turns the screw which forces the sample to travel up and into the collection box. Once the sample is collected, the pinion will rotate in the opposite direction to retract the screw. The Archimedes Screw will remain retracted when the Rover is in transit.



(a) As-Built



(b) Render

Figure 86: Sample Retrieval Integration

Two tests were performed with the sample retrieval system. One test was performed to ensure the security of the sample in the collection bin and the other test was to measure the time it would take to collect the necessary amount of sample. After conducting two trials, we were able to validate the security of the collection bin because no sample was lost as the Screw picked up the sample. Additionally, the removal of the sample was successful since we were able to easily remove the screw that attached the case and the bin together. During the timed trials, we were able to collect an average of 107 individual sample beads in 20.6 seconds. We learned from these timed trials that in order for the screw to work optimally, the sample has to have enough movement and fluidity in the pit to easily replace what has already been picked up. We will be performing additional tests in the following weeks to test the deployment system's balance and the combined rover and screw movement.

4.7.4 Rover Software

Software for the rover is hosted on the PIC32 processor controlling the rover. The software is written and compiled in the C language using Microchip's MPLABX program designed to interface with PIC processors. A PICkit3 in-circuit debugger is used to program the PIC32 and debug the software during testing.

4.7.4.1 Rover Control

The rover goes through a few different stages during the mission. Initially, the rover will be in an idle state, secured in the launch vehicle by the retention system and listening on the radio for a deployment signal from the ground station. This results in a signal from the rover's PIC32 to the retention electronic system's Itsy Bitsy processor initiating deployment by retracting the retention solenoids and allowing the rover and UAV to drive out of the launch vehicle. As the vehicle departs the launch vehicle, header connectors that attach the rover to the retention electronics are pulled apart by the rover departing the launch vehicle, allowing it to leave unobstructed.

After departing the launch vehicle, the UAV begins its mission sequence. During that time, the Rover initiates and confirms sensor readings function nominally. If sensors are nominal, the rover awaits a confirmation signal from the ground station with GPS coordinates of the UAV at the sample area. Once the GPS coordinates are retrieved, the rover software calculates the necessary heading needed for the rover to reach the target area. A simple proportional-integral controller responds to the error between the current heading measured by the BNO055 and the needed heading. The rover begins traveling toward the sample area until GPS indicates the rover has reached the sample area where it initiates the sample retrieval process. Once complete, the rover will drive until GPS indicates the rover has traveled outside the area.

Ongoing testing is being conducted to verify the operation of each electrical system component before moving to testing of full mission software. Testing was delayed due to supplier issues globally but plans to be completed in the coming weeks.

4.7.4.2 Rover Compass Heading Calculation

Using the GPS coordinates provided by the UAV and the ones recorded by the GPS module on board the rover, the rover software will calculate the necessary bearing using the formula in equation 11.

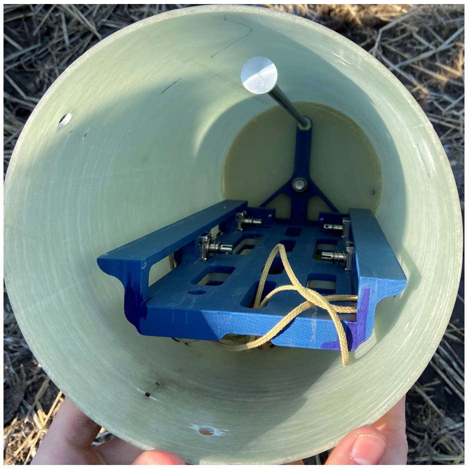
$$\theta = \text{atan2}(\sin(\Delta\lambda) * \cos(\phi_2), \cos(\phi_1) * \sin(\phi_2) - \sin(\phi_1) * \cos(\phi_2) * \cos(\Delta\lambda)) \tag{11}$$

Where ϕ_1,λ_1 is the start point, ϕ_2,λ_2 the end point, and $\Delta\lambda$ is the difference in longitude. The on board BNO055 inertial measurement unit will be used to calculate the current heading of the rover. The BNO055 shall be configured and calibrated in the COMPASS mode as outlined in section 3.3 of its datasheet. This will allow the BNO055 to fuse data from the magnetometer and accelerometer to provide tilt compensated compass data for calculating heading by taking the inverse tangent of the X and Y components of the magnetometer data.

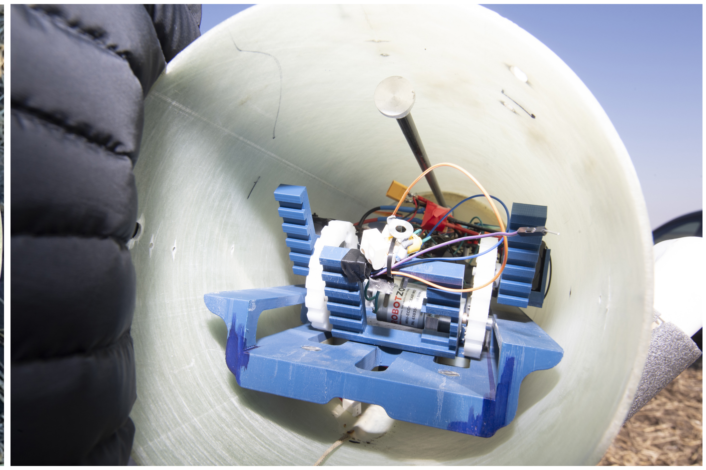
4.8 Demonstration Flight

4.8.1 Overview

A Payload Demonstration Flight occurred on February 22, 2020 at 12:04 P.M. in Three Oaks, Michigan. During this flight, the fully manufactured LSRS was flown inside the Payload Bay and was secured using the ROD System as outlined in Section 4.5.1. The purpose of this demonstration flight was to verify the ability of the ROD System to successfully retain and orient the LSRS and jettison the nosecone. Figure 87 shows the completely built payload in the launch vehicle.



(a) Testing sled fit



(b) Loading retained UAV and Rover

(c) Bulkhead Secured

Figure 87: LSRS Launch Vehicle Placement

4.8.2 Results

A summary of the performance of the LSRS during the Payload Demonstration Flight is shown in Table 25 in Section 5.4.1.

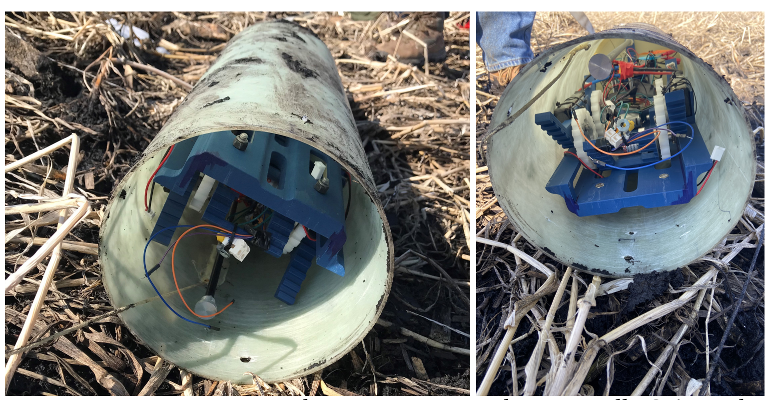
4.8.3 ROD System Performance Analysis

The ROD System demonstrated successful retention of the LSRS during flight and successfully jettisoned the nose cone after main had deployed at an altitude of 400 ft AGL. This can be seen in Figure 88.

(a) Nose Cone Separation (b) After Recovery

Figure 88: Successful Nose Cone Deployment

The ROD System did fail to orient the LSRS after vehicle recovery as seen in Figure 89. This was due to an increase in friction on the interior of the Payload Bay. A proposed solution is to integrate two bearings onto the standoff supporting the sliding platform to ensure free rotation of the LSRS. This is discussed further in Section 5.4.1.



(a) As Found (b) Manually Oriented

Figure 89: Full-Scale Orientation

5 Demonstration Flights

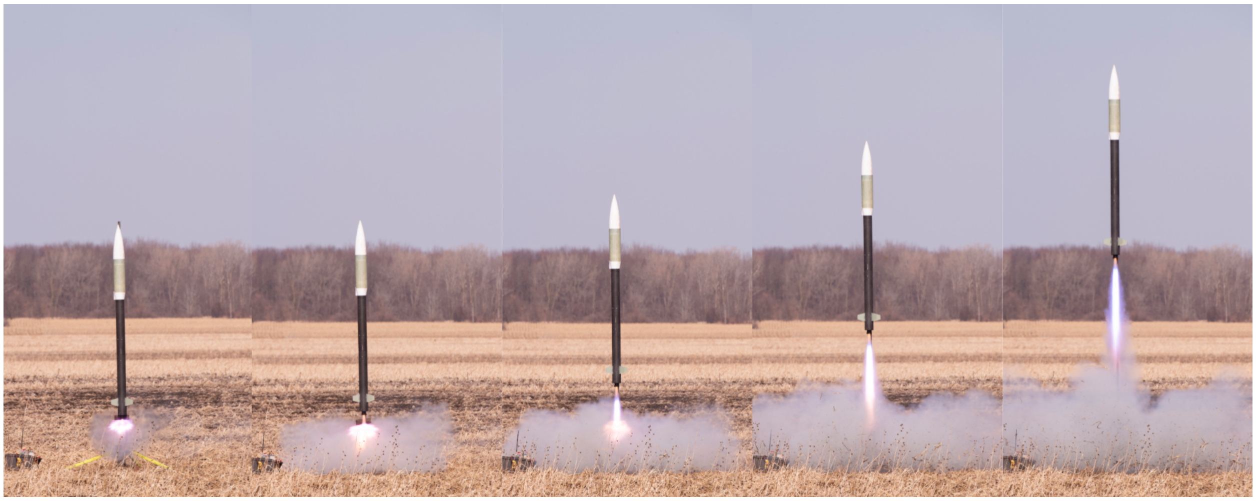


Figure 90: Payload Demonstration Flight on February 23, 2020

5.1 Verification Summary

Table 19: Flight 1 Verifications Summary

Req. ID	Item Tested	Value	Verification Status	Adjustments
V.4	Apogee of 4,444 ft	5,032 ft	Partially Verified	The launch vehicle came within 588 ft of the target apogee.
V.10	Stability margin of the vehicle with the motor must be between 2-3 calibers.	2.45 cal	Verified	Simulations updated to provide accurate Cp.
V.11	Apogee overshoot to enable ABS deployment	588 ft	Verified	Ballast added in addition to extra payload weight to reduce apogee, making it a more feasible target for ABS.
2.1	Apogee between 3,000 and 6,000 ft	5,032 ft	Verified	None.
2.4	Launch vehicle recoverable and reusable.	Fully recovered	Verified	None.
2.6	Launch vehicle prepared for flight within 2 hrs of FAA flight waiver opening.	2 hrs	Verified	Prep time decreased for next flight due to practiced procedures.
2.16	Launch vehicle accelerates to a minimum velocity of 52 fps at rail exit	62.38 fps	Verified	None.
2.18.1.1	Vehicle and recovery system function as designed	Full function	Verified	None.
2.18.1.4	Systems that change external surfaces of the rocket active during the Demonstration Flight	ABS Inactive	Not Verified	ABS Software debugged and further ground testing completed for next launch.
R.3	Altimeter bay removable and rocket apogee/flight data quickly retrieved after successful recovery	Achieved	Verified	None.
3.1.1	The main parachute deployed at or above 500 ft	534 ft	Verified	None.
3.7	Each recovery arming switch capable of being locked in the ON position for launch	Successful lock	Verified	None.
3.10	The recovery area limited to a 2,500 ft. radius from the launch pads.	Approx. 1,300 ft	Verified	None.
3.11	Descent time limited to 90 s	83 s	Verified	None.
3.12	Electronic tracking device transmits the position of the tethered vehicle to a ground receiver	Telemetry Inactive	Not Verified	Telemetry operational second test flight. Back up GPS options investigated.
3.13	Recovery system electronics not adversely affected by any other on-board electronic devices during flight	No interference	Verified	None.
P.21	Rover and UAV properly oriented regardless of the landing position of the vehicle.	Payload not flown	Not Verified	Payload flown second flight.
P.22	Motion of the Rover and UAV restricted in all directions until deployment sequence initiated.	Payload not flown	Not Verified	Payload flown second flight.
P.25	Nose cone ejected after main parachute deployment at 400 ft.	Nose cone not ejected	Not Verified	Nose cone ejected second flight.
4.2	Paylaod system launched in a high power rocket, landed safely, and recovered simulated lunar ice from CFEA	Payload not flown	Not Verified	Payload flown second flight. Mission accomplished separately.
4.3.7, 4.3.7.2-3	Payload fully retained until it is deployed as designed. Retention robust and fail-safe to endure flight forces.	Payload not flown	Not Verified	Payload flown second flight.

Table 20: Flight 2 Verifications Summary

Req. ID	Item Tested	Value	Verification Status	Adjustments
V.4	Apogee of 4,444 ft	4,320 ft	Verified	None.
V.10	Stability margin of the vehicle with the motor must be between 2-3 calibers.	2.68 cal	Verified	None.
V.11	Apogee overshoot to enable ABS deployment	-124 ft	Verified by ABS Activation	None.
2.1	Apogee between 3,000 and 6,000 ft	4,320 ft	Verified	None.
2.4	Launch vehicle recoverable and reusable.	Fully recovered	Verified	None.
2.6	Launch vehicle prepared for flight within 2 hrs of FAA flight waiver opening.	2 hrs	Verified	None. Prep time excluding black powder testing and telemetry assembly meets 2 hr requirement.
2.16	Launch vehicle accelerates to a minimum velocity of 52 fps at rail exit	62.34 fps	Verified	None.
2.18.1.1	Vehicle and recovery system function as designed	Full function	Verified	None.
2.18.1.4	Systems that change external surfaces of the rocket active during the Demonstration Flight	ABS Active	Verified	ABS actuated during flight
R.3	Altimeter bay removable and rocket apogee/flight data quickly retrieved after successful recovery	Achieved	Verified	None.
3.1.1	The main parachute deployed at or above 500 ft	522 ft	Verified	None.
3.7	Each recovery arming switch capable of being locked in the ON position for launch	Successful lock	Verified	None.
3.10	The recovery area limited to a 2,500 ft. radius from the launch pads.	Approx. 2,110 ft	Verified	None.
3.11	Descent time limited to 90 s	68 s	Verified	None.
3.12	Electronic tracking device transmits the position of the tethered vehicle to a ground receiver	Telemetry partially active	Not Verified	Telemetry GPS not operational at flight. Back up GPS options investigated, and telemetry GPS thoroughly tested post-flight.
3.13	Recovery system electronics not adversely affected by any other on-board electronic devices during flight	No interference	Verified	None.
P.21	Rover and UAV properly oriented regardless of the landing position of the vehicle.	Payload 180°from proper orientation at landing	Not Verified	Friction of orientation system will be mitigated with the addition of two bearings. The system was thoroughly tested after flight to verify mitigation. No retention or load bearing components were changed.
P.22	Motion of the Rover and UAV restricted in all directions until deployment sequence initiated.	Full retainment	Verified	None.
P.25	Nose cone ejected after main deployment at 400 ft.	Ejected after main	Verified	None.
4.2	Paylaod system launched in a high power rocket, landed safely, and recovered simulated lunar ice from CFEA	Full retention demonstrated	Partially Verified	Mission accomplished after flight.
4.3.7, 4.3.7.2-3	Payload fully retained until it is deployed as designed. Retention robust and fail-safe to endure flight forces.	Payload not flown	Verified	None.

5.2 Launch Day and Flight Analysis

The full scale vehicle was launched twice. The first demonstration flight took place on February 16th with the purpose of verifying that the vehicle is able to reach the predicted apogee and verify the drift and descent time. The second flight took place on February 21st with the purpose of confirming secure payload retention and orientation, and proving safe ABS actuation during flight.

A summary of the flight conditions is found in Tables 21 and 22.

Table 21: Demonstration Flight 1 Summary

Variable	Description
Flight Type	Vehicle Demonstration
Date	2/16/20
Location	Three Oaks, MI
Launch Conditions	Favorable (Sunny, 4 mph wind)
Motor Flown	Cesaroni L1395
Ballast Flown	No (0 lbs)
Measured Stability Margin	2.75 cal
Final Payload Flown	No (Simulated Payload: 112 oz)
ABS Status	Inactive
Official Target Altitude	4,444 ft
Predicted Altitude	5,067 ft
Measured Altitude	5,022 ft

Table 22: Demonstration Flight 2 Summary

Parameter	Value
Flight Type	Vehicle and Payload Demonstration
Date	2/23/20
Location	Three Oaks, MI
Launch Conditions	Windy (Sunny, 17 mph wind)
Motor Flown	Cesaroni L1395
Ballast Flown	Yes (0.875 lbs)
Measured Stability Margin	2.875 cal
Final Payload Flown	Yes
ABS Status	Active
Official Target Altitude	4,444 ft
Predicted Altitude	4,541 ft
Measured Altitude	4,320 ft

5.3 Actual Conditions Simulation

Flights were simulated for both launches with the actual flight conditions. The predicted versus actual apogees are found in Table 23.

Table 23: Predicted and Actual Apogees

	Flight 1	Flight 2
Predicted Apogee	5,067 ft	4,541 ft
Actual Apogee	5,022 ft	4,320 ft
Percent Difference	0.89 %	4.87 %

5.3.1 Altimeter flight profile data

The flight altimeter data was collected by two of the onboard altimeters, shown in Figure 91. As shown, the maximum altitude achieved was 5022ft, and the launch vehicle descended safely under both the drogue and main parachutes.

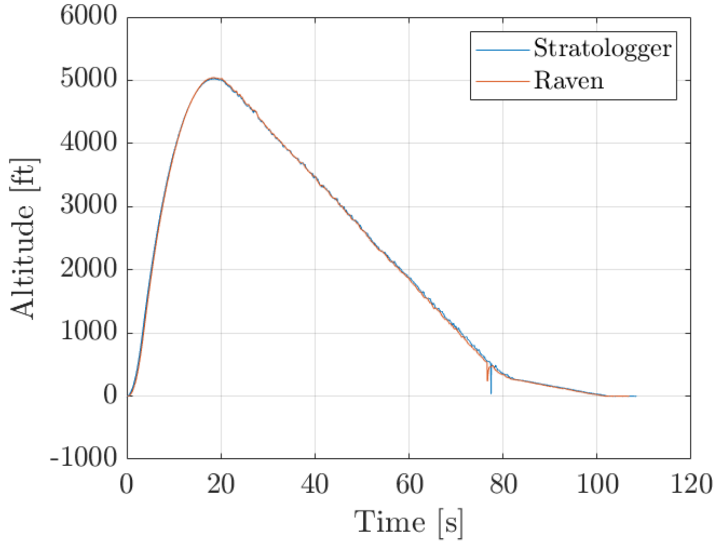


Figure 91: Flight profile data for vehicle demonstration flight

5.3.2 Comparisons to predicted flights

The vehicle demonstration flight was simulated using both OpenRocket as well as a 4th-order Runge-Kutta method. The simulations were in good agreement with one another and predicted an apogee of 5067ft and 5052ft, respectively. A plot of the simulated flight path as compared to the actual flight data is shown in Figure 92. A coefficient of drag of 0.39 was used in the simulation.

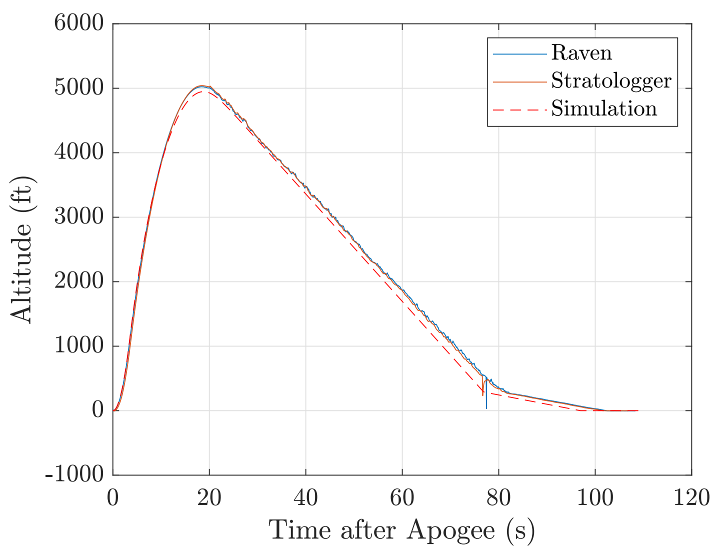


Figure 92: Simulation compared to vehicle demonstration flight

As is clear in the figure, the simulation is in good agreement with actual flight data. The predicted apogee differed from the actual apogee by less than 1.5%, and the general trajectory of the simulation is consistent with the measured flight path. The slight difference in apogee and flight path on ascent indicates that the estimated coefficient of drag value of 0.39 was too high. A new simulation was run with an estimation of 0.37, and the simulation is more in line with the actual flight data.

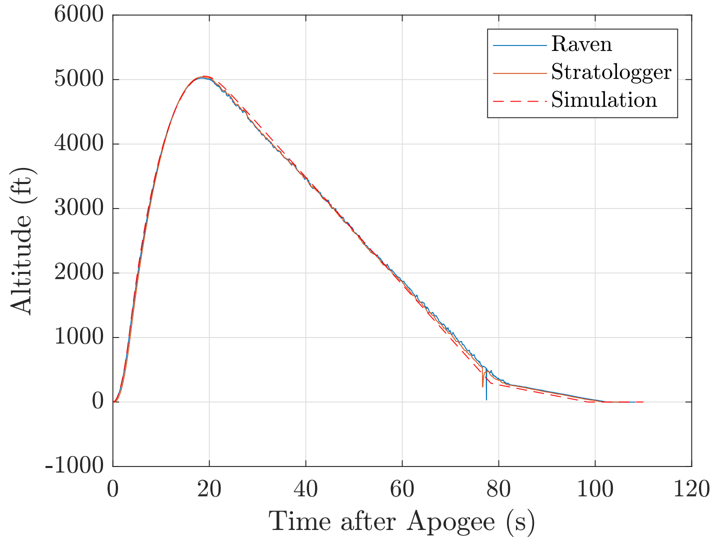


Figure 93: Updated simulation compared to vehicle demonstration flights

With the updated coefficient of drag value, the error in apogee estimation decreased to less than 0.6% and the flight path on ascent was nearly identical to the actual flight path.

The payload verification flight was also simulated with both OpenRocket and a 4th-order Runge-Kutta method. Again, the simulations were in good agreement and predicted an apogee of 4541 and 4471ft, respectively. Figure 94 shows the predicted flight path compared to the measured flight data. A coefficient of drag of 0.39 was used in the simulation.

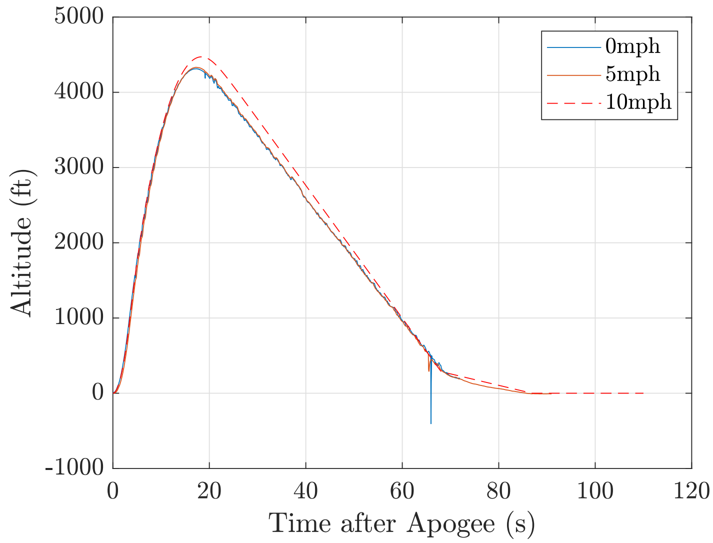


Figure 94: Simulation compared to payload verification flight

As shown, the flight trajectory is in good agreement with the predicted flight path for most of the ascent, but deviates near apogee. The error in predicted apogee was 3.3%. This can be attributed to the activation of the ABS, which reduced the velocity throughout the flight, effectively increasing the average coefficient of drag on the launch vehicle. A new simulation was run with an increased coefficient of drag of 0.43, shown in Figure 95.

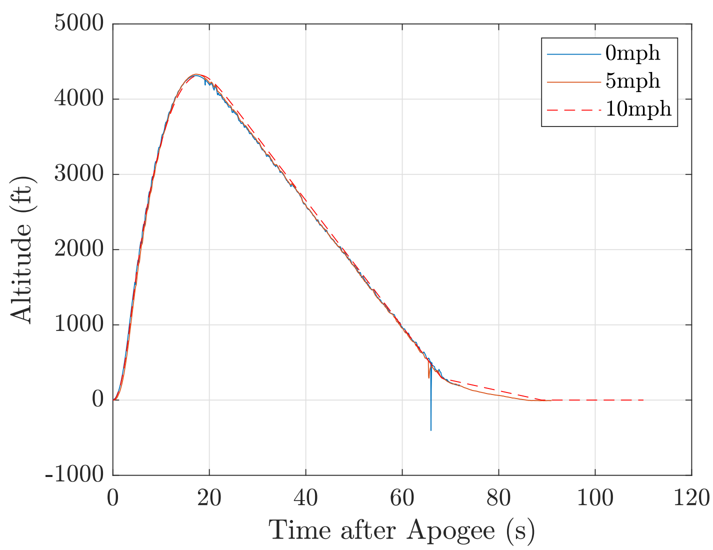


Figure 95: Updated Simulation compared to payload verification flight

While the impact of the ABS is difficult to predict with a single drag coefficient, the updated drag coefficient shows a substantially increased accuracy to the simulation. The error in apogee from the measured data was less than 0.003%.

5.3.3 Malfunctioning Hardware

During the first flight test, the secondary Raven altimeter in the recovery avionics module had a defective barometer which caused it to not deploy its black powder charges as planned. Due to system redundancy, flight performance was unaffected. Upon recovery of the landed launch vehicle, the charges were safely disarmed. For this reason, the third altimeter was not activated for the second test flight. The team has purchased a replacement altimeter to use during flight during competition.

5.3.4 Simulated Payload

Since the LSRS retention system was not ready for the first flight test, the team constructed a simulated payload to replace the mass of the payload for flight. The simulated payload consisted of two wooden bulkheads connected by two threaded rods and eye bolts. This "core" was surrounded by spare parachute shock chords in order to reach the desired mass. The final mass of the simulated payload was 112 oz.. For the second test flight, the LSRS was flown, so the simulated payload was not needed.

Figure 96: Simulated Payload Core

5.3.5 Ballast

For the second test flight, the team added 18 oz. of ballast to the launch vehicle. The team added this ballast to ensure that the launch vehicle could be flown with up to 18 oz. of ballast at the competition if needed.

5.3.6 Descent Time

The descent time was measured as the time between apogee and landing. The descent time for the vehicle demonstration flight was 84.5s. The descent time for the payload verification flight was 68.7s. Both of these values are within the required 90s of descent time.

5.3.7 Kinetic Energy

The kinetic energy at landing was calculated using the velocity at landing and the mass of the heaviest section of the launch vehicle. For the vehicle demonstration flight, the velocity at landing was 13.98ft/s, and the heaviest section of the rocket was 321.4oz, which provides a kinetic energy at landing of 61.0ft-lb. The velocity at landing of the payload verification flight was 10.9ft/s. The heaviest section of the launch vehicle was 333.4 oz. This produces a kinetic energy at landing of 38.49ft-lb. Both of these values are under the required 75ft-lb of kinetic energy.

5.3.8 Drift

For the vehicle demonstration flight, the launch vehicle experienced an estimated drift of 1300 ft. For the payload demonstration flight, the launch vehicle experienced an estimated drift velocity of 2275 ft. The higher drift for the second flight was due to high winds on launch day. Both drift values are within the acceptable radius of 2500 ft.

Table 24 shows a summary of the flight deliverables.

Table 24: Flight Deliverables

Flight	**Descent time (s)**	**Kinetic Energy (ft-lb)**	**Drift (ft)**
Vehicle Demonstration Flight	84.5	61.0	1300
Payload Verification Flight	68.7 ft	38.49	2275

5.4 Payload Analysis

5.4.1 Retention Performance Analysis

The performance of the LSRS during the PDF is summarized in Table 25.

Table 25: Payload Demonstration Flight Success Criteria

I.D.	Success Criteria	Result
PDF.MS.1	Nosecone successfully jettisons from the Launch Vehicle	Pass
PDF.MS.2	Nosecone is jettisoned from the Launch Vehicle at 400 ft after main has deployed	Pass
PDF.MS.3	Integrity of epoxy securing tether chord to the Payload Bay is not jeopardized	Pass
PDF.MS.4	LSRS is retained throughout vehicle flight and recovery	Pass
PDF.MS.5	LSRS is properly oriented after vehicle recovery	Fail
PDF.MS.6	LSRS sustains minimal to no damage during vehicle flight	Pass

From Table 25 it can be seen that the ROD System demonstrated near perfect system performance during the PDF. Only the orientation system of the LSRS failed to perform as intended. The four solenoid pins successfully retained throughout the PDF and prevented premature deployment of the Rover and UAV. Additionally, the flanged bearing and Rail platform successfully held the LSRS to the aft-bulkhead throughout flight and recovery. The nose cone was successfully jettisoned and tethered to the Launch Vehicle after main had deployed at an altitude of 400 ft AGL. The nose cone was securely tethered to the Payload Bay and no damage was sustained by the LSRS due the jettison event. Furthermore, no damage was sustained to any of the components in the ROD System, the Rover, the UAV, or the fore-bulkhead during flight.

Upon further inspection of the orientation system, it was found that dirt and dust had accumulated inside the Payload Bay which had increased the amount of friction between the standoff on the sliding platform and the interior of the Payload Bay. As a result, the LSRS was unable to rotate and orient properly for deployment. To address this failure, the team has designed a new standoff shown in Figure 18 FIGURE. This new standoff will utilize two bearings to guarantee frictionless rotation of the LSRS within the Payload Bay. Two bearings are utilized to distribute the weight of the LSRS on two contact points on the interior of the Payload Bay. This will reduce the normal force on each bearing and ensure rotation of the LSRS.

5.4.2 Payload Performance Analysis

During the PDF, the Rover and UAV were not powered as the PDF was used purely to demonstrate the abilities of the ROD System to retain and orient the LSRS. However, the structural integrity of both the Rover and the UAV was verified by successfully withstanding all flight and recovery forces. Since the team demonstrated successful retention of the LSRS during flight, further testing and verification of the LSRS mission will be conducted with ground tests. These tests are outlined in Table 42 and an overview of the payload mission can be seen in Section 4.1.

6 Safety and Procedures

6.1 Safety Analysis

Hazards are evaluated at a level of risk based on their severity and probability of occurrence. Risks will be evaluated at each subsystem level as well as the project management level. The Systems and Safety team will continue to re-evaluate the risks, mitigations, and verifications as the project continues. Probability of occurrence will be evaluated and designated with values 1 through 5, with 5 being that the event in question is almost certain to happen under present conditions, and 1 being that it is improbable the event occur. The criteria for this scoring is outlines in Table 26 below.

Table 26: Probability of Hazard Occurrence classification

Description	Value	Criteria
Improbable	1	Less than 5% chance that the event will occur
Unlikely	2	Between 5% and 20% chance that the event will occur
Moderate	3	Between 20% and 50% chance that the event will occur
Likely	4	Between 50% and 90% chance that the event will occur
Unavoidable	5	More than 90% chance that the event will occur

As mentioned, this probability is evaluated according to present conditions, meaning two assumptions were made. The first is that if the conditions change, the probability will be re-evaluated and changed accordingly. The second assumption is that all personnel involved in the activity will 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 SDS document, 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 27.

Table 27: 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 value from 1 to 20 where is lowest risk and 20 is the highest risk. 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 28, and the description of each risk level is listed in Table 29.

Table 28: Risk Assessment Matrix

Probability Level	Severity Level			
	Negligible (1)	Marginal (2)	Critical (3)	Catastrophic (4)
Improbable (1)	1	2	3	4
Unlikely (2)	2	4	6	8
Moderate (3)	3	6	9	12
Likely (4)	4	8	12	16
Unavoidable (5)	5	10	15	20

Table 29: 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.

In order to properly assess the risks 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. Each risk is assigned a risk value prior to mitigations and then a risk value after mitigations are in place.

As the mission continues, the main concern is the team's adaptability to various environments. Most of these concerns are addressed in the Environmental FMEA. The Launch Procedures have been refined through two test launches that have allowed the team to gather visual aids and warnings that will be useful in the competition.

6.1.1 Project Risk Analysis

Table 30: Project Risk Analysis

Hazard	Cause	Outcome	Probability	Severity	Mitigations	Verification
Complete destruction or loss of full scale or subscale vehicle	1. Uncontrolled descent 2. Energetics improperly contained	Team must build an entirely new vehicle causing project delays and doubling the costs of the project	Medium	High	1. All components will be tested individually prior to full-scale assembly 2. Construction procedures will be written prior to construction	1. Tests will be logged and documented; multiple sources (calculations, simulations) and trials will be used to verify the results 2. Construction procedures will be available prior to construction
Failure to conduct subscale launch by January 10th full scale launch by March 2nd	1. Weather conditions 2. Construction is incomplete 3. Failure to find a date that works with both the team and mentor	Inability to participate in competition	Medium	High	1. Multiple dates will be chosen for a possible launch 2. The team will implement a Technology Readiness Level schedule to ensure that all the subsystems are meeting each deadline 3. The team will push to meet the first available date for launch	1. The team has chosen February 1st, 15th, and 22nd in order to meet the demonstration flight deadline 2. The team has a chart to track the individual subsystems TRLs in order to identify any issues with meeting deadlines 3. The team will begin full scale construction two weeks prior to the first available launch date
Lack of funds/exceeding budget	1. Allocation of funds to a subsystem is insufficient 2. Parts are not properly sourced	Team takes on debt or funds from travel or other subsystems diminish	Medium	High	1. The allocation of funds are based off of previous years' spending and design. 2. Parts will be sourced to find the best quality at the lowest cost. Each part should be considered from at least three vendors if possible.	1. This years' budget has been set in Section 7.3 according to previous need and consultation with each design lead 2. Team members must submit their receipts and add to the budget to ensure they are tracking their spending
Delay in receiving parts/issues with vendors	1. Parts (especially custom) ordered have an anticipated arrival date that will not work with the team deadlines 2. The part shipped by a vendor is incorrect or does not meet the needs of the team	Project delays and/or mission failure	Medium	High	1. Custom parts will be ordered early in order to avoid project delays and if they are critical the team will order an additional component in the case one is damaged 2. NDRT has compiled a trusted vendor list to ensure quality of parts	1. Any custom parts will be ordered at least three weeks in advance of the start of construction and the design lead will determine whether or not multiples should be ordered 2. All team members ordering parts will consult the trusted vendor document

Team member leaves team	1. Injury or illness 2. Member has other commitments	Project delays and/or incomplete work	Medium	Medium	All tasks on the team will have multiple members assigned or at least multiple members aware of the details of the task	All designs and tests will be well documented in case someone should have to take over
Safety violations	1. Insufficient PPE 2. Insufficient training	Injury to personnel and the potential for the workshop space to be revoked	Medium	High	1. PPE will always be stocked in the workshop and a part of the Systems & Safety budget 2. All personnel that will be participating in construction must be certified in the Student Fabrication Lab according to university regulations	1. The Safety Officer will check for PPE in the workshop prior to all construction; the Safety Officer will be notified when certain PPE items are almost out of stock. 2. Students must show their certification card before entering the workshop during construction
Insufficient materials	Parts to complete the project are not ordered	Project delays	Medium	Medium	Personnel will make an itemized list of parts in their designs	Construction procedures will provide a good check to make sure all the parts need for fabrication are ordered
Violation of FAA by exceeding approved altitude	Launch site does not have proper waiver for the team's altitude requirement	Potential legal action	Low	High	The team will not use any launch sites without the proper waiver	The NDRT leadership will confirm with prospective launch sites that they have the proper waiver for NDRT's selected altitude.
Improper testing equipment	1. Test equipment is faulty 2. Inability to use University resources for more complex testing	Incorrect data could lead to faulty analyses and/or design decisions	Low	Medium	1. The team will confirm all tests with calculated results and simulations 2. The team will reach out to test facilities early to ensure lab time and comply with regulations at each facility	1. All test results will be documented and shared with the team 2. The team will reach out to test facilities at least three weeks in advance of the anticipated testing date

6.1.1.1 Construction

Table 31: Personnel Hazard Analysis-Construction Operations

Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
Skin contact with strong adhesive materials, such as epoxy or glue	Not using proper gloves necessary for safe glue/epoxy application	Severe allergic reactions, severe irritation to skin, and damage to skin	3	2	6	Mandatory safety gloves and safety training for all team members who will work with adhesives	1. All team members participating in construction are trained in the workshop according to University standards as seen in Section 6.2 2. MSDS sheets are readily available in the workshop and updated	1	2	2
Contact with the spinning bit of a portable drill or drill press	Improper technique regarding drill use	Severe damage to fingers and/or other body parts including cutting, scraping, breaking, amputation, or other injury	3	4	12	1. Mandatory safety training for all team members who will work with drills includes proper hand placement, powering off the drill and unplugging before making adjustments, and selecting proper bit and speed for a material 2. Safety Handbook includes drill use best practices	1. All team members using a hand drill will have to complete their certifications and show their safety certification card as seen in Section 6.2 2. Members will not use the drill press unless supervised by another member with the drill press certification or the NDRT Fabrication Manager	2	4	8
Loose workplace materials when drilling, sanding, or cutting	Not securing part properly with vise, clamps, or hands during machine and tool use	Blunt bodily damage, cuts, or impalement to the body	2	4	8	1. Mandatory general workshop safety training for all team members includes proper material securement techniques 6.2 2. Safety Handbook includes material security in drill, sanding, and cutting instructions	1. In order to use a hand drill, members must show their stamped Level 1 section to use the hand drill or their stamped drill press section to use the drill press according to University Standards seen in Section 6.2 2. Members will verify material security by attempting to move the piece once it is in clamps	1	4	4
Contact with the spinning bit of a dremel	Improper technique and poor hand placement	Severe damage to fingers and/or other body parts including cutting, scraping, breaking, amputation, or other injury	2	4	8	1. Mandatory safety training for all members who use the dremel includes proper hand placement, unplugging dremel before changing bits, and ensuring the switch is off before plugging in 2. Safety Handbook includes technique, hand placement, and best safety practices for dremel use	1. In order to use the dremel, members must show their stamped Level 1 certification card according to University Standards seen in Section 6.2 2. Any member dremmeling must be supervised by another Level 1 certified member or the NDRT Fabrication Manager	1	4	4

Contact with the cutting blade of a bandsaw or scroll saw	Improper sawing techniques, which includes footing, machine setup, cut speed, and hand placement	Severe damage to fingers and/or other body parts including cutting, scraping, breaking, amputation, or other injury	2	4	8	1. Mandatory safety training for all members who use the bandsaw or scroll saw includes proper footing, hand placement, etc. 2. Safety Handbook includes technique and best safety practices for bandsaw and scroll saw use	1. Team members that use the bandsaw or scroll saw must show their stamped certification card for each respective machine before use as seen in Section 6.2 2. All bandsaw and scroll saw use occurs under the supervision of the NDRT Fabrication Manager	1	4	4
Contact with the sanding surface of a belt sander or a palm sander	Improper sanding techniques such as poor hand or part placement	Damage to fingers including scraping, burning, and severe cuts	3	3	9	1. Mandatory safety training according to University standards for all members who use the sanders includes hand placement 2. Safety Handbook includes technique and best safety practices for belt/palm sander use	1. Team members will have to show their stamped belt sanding certification on their certification card in order to use any belt sanders as seen in Section 6.2 2. Members using belt sanders will be supervised by another member with belt sander certification or the NDRT Fabrication Manager	1	3	3
Projectiles, shrapnel, or other hazardous materials launched into eyes or eye contact with airborne particulates	Not wearing protective eye gear at all times in the workshop	Temporary or permanent damage to eyes which may lead to future or immediate blindness or degradation of vision	4	4	16	1. All team members in the workshop will be required to wear safety glasses at all times 2.Posted signage reminds members of this requirement	1. Team members will not be allowed to work in the workshop without proper eye protection 2. All team members participating in construction are trained in the workshop according to University standards as seen in Section 6.2	2	4	8
Inhalation of airborne particulates resulting from cutting, machining, or sanding parts	Not wearing respirator when generating harmful airborne particulates such as carbon fiber or fiberglass	Temporary or permanent damage to the lungs which could cause intense pains and long-term health issues	4	4	16	1. Team members generating potentially harmful particles will be required to wear proper protective breathing gear, such as a dust mask or respirator 2. Safety Handbook includes information on proper respiratory protection 3. Members generating airborne particulates will be required to use a vacuum as the machining, sanding, or cutting is taking place	1. Team members will be certified for proper sanding safety according to University standards as seen in Section 6.2 2. Team members will not be allowed to work in the workshop without proper breathing protection when generating harmful particles 3. MSDS sheets are readily available in the workshop	2	4	8
Extended inhalation of toxic fumes from glue, epoxy, or spray paint	Not wearing protective breathing gear when utilizing toxic chemicals	Damage to the respiratory or nervous system that could cause long or short-term health effects, including occupational asthma	4	4	16	1. Team members working with potentially harmful fumes will be required to wear proper protective breathing gear or work in a fume hood 2. Safety Handbook includes information on proper respiratory protection	1. All team members participating in construction are trained in the workshop according to University standards as seen in Section 6.2 2. MSDS sheets are readily available in the workshop	2	4	8

Baggy clothes or hair getting caught in machinery	Baggy clothing that hangs too close to machinery or long hair that is not pulled back gets caught when working on a part	Parts of the body could be pulled into machines, causing extensive bodily damage and potentially death	4	4	16	1. Mandatory general workshop safety training for all team members includes proper clothing requirements such as short sleeves, closed-toe shoes, long pants, no watches or jewelry on the hands, and hair pulled back 2. Safety Handbook includes proper workshop clothing information	1. All members participating in construction are informed of proper workshop attire according to University standards as seen in Section 6.2 2. Members must wear proper attire to enter the workshop 3. All construction in the SFL occurs under the supervision of the NDRT Fabrication Manager	2	4	8
Blunt bodily damage	Not wearing protective footwear and clothing to protect from falling objects that are blunt or sharp	Damage to the hands and feet that results in breakage or blunt damage	3	3	9	1. Mandatory general workshop safety training for all team members includes proper footwear which consists of closed toed shoes 2. Safety Handbook includes proper footwear information	1. All team members participating in construction are informed of proper workshop attire according to University standards as seen in Section 6.2 2. All members must wear closed-toe shoes to enter the workshop	1	3	3
Burns	Poor 3D printer or soldering operational procedures	Hands could receive painful burns that could lead to scarring	2	3	6	Mandatory general workshop safety training for all team members includes proper soldering and 3D printing techniques	1. All team members participating in construction are trained in the workshop according to University standards seen in Section 6.2 2. Team leads or the NDRT Fabrication Manager ensures proper hand placement and techniques for soldering during construction	1	3	3
Electric shock	Exposed wiring, static electricity build-up	Burns, electrocution potentially leading to death				1. Mandatory general workshop safety training and the Safety Handbook include information on inspection of tools and wires before use 2. Any exposed wiring is immediately reported to the Safety Officer or NDRT Fabrication Manager	1. All team members participating in construction are trained in the workshop according to University standards as seen in Section 6.2 2. All members inspect tools before use			
Hearing loss or damage	Prolonged exposure to loud machinery or construction tools	Temporary or long-term hearing loss	2	3	6	1. Earplugs will be used when using loud machinery 2. Safety Handbook includes information on hearing protection during excess noise exposure	1. The workshop contains an ear plug distribution box right next to the entry way 2. The Safety Officer and NDRT Fabrication Manager will monitor workshop noise and require earplugs if necessary	1	3	3

Tripping or slipping	Loose cords, spills	Bruising, broken bones, potential further bodily damage from pulling the cord of operating machinery	3	3	9	1. Cords are kept out of walkways whenever possible or taped to the ground if in a walkway 2. Materials will be stored properly, according to SDS sheets, and lids will be secured when material containers are not in use 3. All spills are cleaned up immediately and resulting wet spots are marked with caution signs	1. Materials have labeled cabinets where they are to be sealed and stored and MSDS sheets are readily available in the workshop 2. Notre Dame Risk Management inspects the space once a semester to verify proper storage and machinery placement	1	3	3
Fire	Overheating parts, electric components shorting, LiPo battery explosion, sparks during metal cutting, improper soldering iron placement	Burns, smoke inhalation, potentially death	3	4	12	1. Fire extinguishers are kept in the workshop and inspected regularly according to University standards 2. Mandatory general worshop training includes proper machine techniques and safety practices that prevent fire including soldering iron placement, metal cutting procedures, LiPo storage and charging procedures, etc. 3. LiPo batteries are stored in battery bags and kept inside a flammables cabinet and are monitored during charging to prevent over-charging	All team members participating in construction are trained in the workshop according to University standards as seen in Section 6.2	1	4	4

6.1.1.2 Launch Operations

Table 32: Personnel Hazard Analysis-Launch Operations

Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
CATO	Imperfections in motor	Motor explodes causing personnel injury	2	4	8	1. The Launch Manager, Dave Brunsting, will inspect all motors prior to launch 2. Dave Brunsting will install the motor prior to launch to ensure it is installed correctly.	Vehicles Pre-Flight Checklist states Dave Brunsting will be the only individual to install any motor or energetics and will obey NAR/TRA guidelines and procedures when doing so	1	4	4
Vehicle impact with personnel	1. Launch vehicles tips over towards personnel during launch sequence 2. During recovery the Launch vehicles lands on personnel	Personnel injured by launch vehicle's impact	2	4	8	1. The launch platform will be built properly and checked to ensure structural integrity 2. Stability of the vehicle off the rail is verified by simulations and testing 3. Personnel will be trained in launch proper procedures	1. All launch equipment will be verified by the Launch Manager 2. Vehicle stability simulations can be seen in Section 3.7.1 3. Vehicles Pre-Flight Checklist includes stability margin check	1	4	4
High temperature of motor when ignited	1. Motor is still hot after landing 2. Personnel are too close to launch pad	Burns	3	3	9	1. Personnel will not touch the motor after landing 2. Personnel will stand a safe distance as designated by the RSO at launch (at least 300 ft. as required by the NAR)	1. All team members attending a launch will attend a pre-launch briefing prior to any launch 2. All team members must follow instructions from the RSO 3. Vehicles Pre-Flight Checklist includes standing at a safe distance before launch	1	3	3
Pinch-points	Pinch-points created during Launch vehicles assembly	Personnel are pinched/cut on their hands	4	1	4	The team leads will enforce the use of hand PPE	The team will provide and keep hand PPE (gloves, etc) in stock	2	1	2
Excessive sunlight	Direct exposure to sun for an extended period of time	Sunburn, increased risk of skin cancer	5	2	10	The team leads will inform personnel attending the launch that they must wear proper clothes for long term exposure to inclement weather	1. Written announcements about potential weather hazards for team personnel will be sent in the full team email 2. The Safety Officer will provide a reminder during pre-launch training sessions	2	2	4
Sharp tools for system assemblies	System assemblies may require pliers, scissors, and other sharp tools	Cuts to personnel	3	2	6	1. The team leads will enforce the use of hand PPE and proper usage of all sharp tools 2. All team personnel will be trained in proper tool handling	1. The team will provide and keep hand PPE (gloves, etc) in stock 2. Leads will verify that personnel using tools have received training	1	2	2

Car accident to/from the launch site	Bad traffic/road conditions to and from the launch site	Personnel injury	2	4	8	Only drivers who are properly certified will be allowed to drive personnel	Leads will confirm driver certification before leaving for the launch	1	4	4
Extreme cold	Inclement weather conditions	Hypothermia	2	4	8	Leads will inform all those attending the launch that they must wear proper clothes for long term exposure to inclement weather	Leads will ensure that everyone leaving has proper attire	1	4	4
Payload impact	1. Payload dislodged during launch 2. UAV falls during mission	Personnel injury via impact	2	3	6	NDRT members will be attentive during the launch and trained in proper launch procedures	1. The "finger-pointing" technique will be enforced 2. Pre-launch training sessions will be conducted before each launch 3. Payload retention system thoroughly tested, see tests PDT4, PDT6, PDT8	1	3	3
Battery chemical burn	Battery for payloads malfunctions during assembly	Personnel receives chemical burn	3	3	9	1. Leads will enforce the use of proper eye and hand PPE during the handling of chemical batteries 2. All batteries not in use will be stored in a battery-safe container, per each Pre-Flight Checklist	1. NDRT will provide and keep in stock both hand and eye PPE 2. Leads will visually check to make sure all batteries are properly stored and that PPE is in use during handling	1	3	3

6.1.2 Failure Modes and Effects Analysis

6.1.2.1 Vehicles Flight Mechanics

Table 33: FMEA- Vehicles Flight Mechanics

Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
Failure of motor to ignite	1. Faulty igniters 2. Imperfections in motor 3. Faulty launch equipment	The vehicle will not takeoff	2	3	6	1. All energetics, including motor installation and inspection, will be handled by Dave Brunsting 2. After a second ignition attempt, Launch Manager approaches launch pad and replaces the igniter 3. If the ignition still fails, a second motor inspection will be done by team mentor	1. Vehicles Pre-Flight Checklist includes motor inspection by mentor 2. Ignition Failure instructions are in the Troubleshooting section	1	3	3
Vehicle fails to clear launch rail	1. Deformation of launch rail 2. Insufficient motor burn result in smaller velocity than required to clear the rail 3. Rail buttons deform or break during motor burn due to incorrect manufacturing	Overall mission failure and potential harm to vehicle or personnel	2	4	8	1. Launch rail will be inspected prior to launch 2. Motor selection is chosen based on simulations and calculations 3. Rail buttons are carefully connected to vehicle	1. The Launch Manager will verify launch equipment 2. Motor selection and predicted rail exit velocity can be seen in 3.7 3. Construction procedures will be available in workshop prior to construction	1	4	4
Failure of vehicle to reach sufficient velocity upon exiting launch rail	1. Improper motor selection 2. Excessive weight	Vehicle moves along an unintended line of motion causing potential harm to vehicle or personnel	2	4	8	1. Motor selection is chosen based on simulations and calculations 2. Weight budgets have been allocated to each subsystem	1. The Launch Manager will verify launch equipment 2. Motor selection and calculations can be seen in Section 3.7	1	4	4

Fin flutter	1. Fin material is inadequate for withstanding flight velocities 2. Vehicle velocity exceeds the expected max. velocity	Vehicle moves along an unintended line of motion causing potential harm to vehicle or personnel	1	4	4	1. Fins design and material are chosen to minimize drag and maximize strength 2. Fin flutter velocity is calculated and proven to be above expected max. vehicle velocity 3. Fin design and material are chosen based on calculations, simulations and testing to reach a static stability margin of 2.0	1. Fins will be made from 1/8 in. G10 fiberglass in an isosceles trapezoid platform shape; see Section 13 2. Fin flutter velocity is calculated to be below max. vehicle velocity, shown in Section 13 3. Expected static stability margin is above 2.0, shown in Section **??**	1	2	2

6.1.2.2 Vehicles Structures

Table 34: FMEA - Vehicles Structures

Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
Bulkhead failure	1. Improper construction 2. Insufficient adhesives to secure bulkheads 3. Material cannot withstand shear stress	1. Components are not properly retained causing damage internally to the vehicle and its components 2. Components are not protected from blasts 3. Vehicle unintentionally separates	3	3	9	1. Materials are selected carefully to withstand flight forces 2. Testing was conducted to ensure material strength is sufficient for flight	1. Material selections for bulkheads can be seen in Section 3.3.6 2. Test LVT3 describes solids testing	1	3	3
Premature nose cone detachment	1. Shear pin failure 2. Premature black power charge ignition	1. Unpredictable flight path leads to crashing and damage of vehicle components 2. Potential loss of payload components	2	4	8	1. Shake tests prove retention integrity 2. Friction fit and shear pins prevent premature separation	1. Shake tests LVT5 and PTD4 2. Press-fit instructions included in Vehicles Pre-Flight Checklist	1	4	4
Structural failure at touchdown	Improper materials are selected for vehicle body and cannot withstand impact force	1. The vehicle may be damaged or entirely destroyed upon impact 2. Potential for damage to nearby property and people	3	2	6	Materials have been chosen based on expected forces and have demonstrated functional capabilities, seen in Section 3.3	Test LVT3 describes solids testing	1	2	3
Motor explosion	1. Improper installation of motor casing 2. Imperfections within the motor	1. Vehicle and payload sustain considerable damages during flight 2. People nearby are potentially injured	2	4	8	1. The Launch Manager, Dave Brunsting, will inspect all motors prior to launch 2. Dave Brunsting will install the motor prior to launch to ensure it is installed correctly	1. Vehicles Pre-Flight Checklist includes motor inspection by mentor 2. Dave Brunsting will be the only individual to install any motor or energetics and will obey NAR/TRA guidelines and procedures when doing so	1	4	4
Fin integrity failure	Fins are improperly connected the vehicle body	Flight path becomes unpredictable and vehicle does not follow the intended trajectory	2	3	6	Proper techniques will be used when attaching fins to the fin can	1. Construction procedures are shown in Section 3.4 and were followed by all members involved in each task 2. Fin material selection can be seen in Section 3.4.4	1	3	3

Transition section separates from body	Poor construction techniques lead to the separation of centering rings from the vehicle body	Vehicle flight path becomes unpredictable, and the payload section may sustain considerable damages	2	4	8	Centering rings and adhesives are specifically chosen to meet anticipated forces	Material selections for the transition section can be seen in Section 3.3	1	4	4
Dropping vehicle	Carelessness of team members when transporting the vehicle to and from launch destinations	Potential damages to payload and vehicle components, especially exterior components such as fins or the nose cone	2	2	4	Team members will use great care when transporting the vehicle	No less than 5 team members will be involved on transporting the vehicle, and an additional member will aid in ensuring a clear path for transportation	1	4	4

6.1.2.3 Air Braking System

Table 35: FMEA- Air Braking System

Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
Power failure in electrical system	1. Broken circuits from poor construction 2. Damage from launch forces 3. Batteries are insufficiently charged	Shutdown of the electrical system and loss of control of ABS tabs causing an overshoot of target apogee	3	4	12	1. Battery, circuit connections, and electronic components are checked before launch 2. Only fully charged batteries are used	1. Procedures for properly constructing/testing circuits were created and properly adhered to by all members 2. ABS Inspection Checklist includes properly charging and checking the batteries and electronics	2	4	8
Incorrect or unavailable sensor data	1. Improper installation and programming of the sensors 2. Loss of power to the electrical system	Improper data transmission to flight computer that causes improper deployment of ABS	3	4	12	The ABS code and electrical components of the launch vehicle were tested prior to launch	See test ABT2 for electronic and software verifications	1	4	4
Improper command signals from microcontroller	1. Improper coding of the electronic system 2. Unexpected errors when computing live sensor data	ABS not fully deploying or partially deploying the tabs, causing loss of proper ABS functionality	2	4	8	The code for the system and components was tested before launch	See test ABT1 for microcontroller verification	1	4	4
Broken mechanical system	1. Material strength is insufficient 2. Improper construction techniques	The ABS gets stuck open or closed and causes the launch vehicle to not reach or pass the targeted altitude	2	4	8	1. Materials are chosen to minimize drag tab friction 2. Proper construction procedures were written prior to construction	1. Material selection and construction procedures are described in Section 3.5.2.1 2. The mechanical system was tested prior to launch in tests ABT1-ABT3 2. Construction procedures are available in the workshop prior to construction	1	4	4
Loss of structural integrity of drag tabs	1. Material strength is insufficient 2. Improper construction techniques	1. Drag tabs are unable to deploy 2. Drag tabs break off the outer casing of the launch vehicle, causing the complete loss of the ABS system and potential destabilization of the vehicle	2	4	8	1. Materials are chosen based on simulations and calculations 2. Construction procedures were written prior to construction	1. Drag tab construction can be seen in Section 3.5.2.1 2. Construction procedures were available in the workshop prior to construction 3. Drag tab structural integrity is validated in tests ABT1-ABT4	1	4	4

Shearing of screws or bulkheads that anchor the ABS within the launch vehicle	1. Material strength is insufficient 2. Improper construction techniques	The ABS fails to properly deploy and potentially shifts within the body tube of the launch vehicle, causing severe changes to the mass distribution of the launch vehicle	3	5	15	1. Materials for integration are chosen based on simulations and calculations 2. Construction procedures were written prior to construction	1. Materials chosen for integration components can be seen in Section 3.5.2.2 2. Construction procedures were available in the workshop prior to construction 3. Retention was validated in the full-scale flight test ABT4	1	5	5

6.1.2.4 Recovery

Table 36: FMEA- Recovery

Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
Vehicle separation failure at apogee or at main deployment	1. Black powder charges are insufficient for separation 2. Avionics are not turned on or malfunction	1. Vehicle impacts ground at high velocity damaging vehicle and/or personnel 2. Delayed ignition could result in large forces that could damage the vehicle	2	4	8	1. The black powder charges and altimeters are triple redundant 2. Each black powder charge and altimeter combination are independent of the other three 3. Altimeters are supplied from trusted vendors; see section **??**	1. See Section 3.6.5 for redundant charge layout 2. See test RT1 for black powder testing 3. Altimeters chosen for full-scale were verified in tests RT2, RT4, RT6 4. Black powder charge calculations are summarized in Section 3.6.2 and presented fully in Appendix B	1	4	4
Parachute fails to reduce descent velocity	1. Improperly sized parachute 2. Parachute is deployed at an improper time 3. Parachute is tangled and does not deploy correctly 4. Black powder charges damage some or all of the parachute	Vehicle impacts ground at high velocity damaging vehicle and/or injuring personnel	2	4	8	1. Calculations and simulations were performed to determine proper parachute size 2. Altimeters are trusted models and redundant 3. Parachute folding is practiced and verified by recovery lead 4. Nomex cloth and insulation is used to protect the parachute, shown in Section 3.6.1	1. Calculations and simulations for parachute size can be seen in Section 3.7 2. Altimeter selection and redundancy is in Section 3.6.5 3. Altimeters chosen for full-scale were verified in tests RT2, RT4, RT6 4. Recovery Pre-Flight Checklist includes proper parachute folding procedures	2	2	4
Parachute separation from vehicle	Component failure due to stresses	Vehicle impacts ground at high velocity damaging vehicle and/or personnel	2	4	8	1. Structural components are rated for the anticipated forces with a FOS	1. Solids testing for structural components can be seen test LVT3 2. Structural component verification was shown in the full-scale flight test, RT4	1	4	4
Vehicle drift exceeds allowed drift radius	1. Parachute deploys earlier than expected. 2. Parachute is an improper size.	1. Vehicle could encounter unexpected obstructions out of the drift radius causing personnel or property damage 2. Payload mission success is compromised.	3	2	6	1. Altimeters are from a trusted vendor 2. Parachute sizing is based on multiple calculations and simulations.	1. Altimeter selection can be seen in 3.6.3 and testing can be seen in Section 7.1.2 2. Drift calculations and simulations can be seen in Section 3.7.4	2	2	4

Vehicle separation during motor burn	1. Altimeter malfunction 2. Black powder ignites prematurely	1. Vehicle shears causing the interior components to be damaged 2. Personnel could be harmed	2	4	8	1. Altimeters are from a trusted vendor 3. Black powder and altimeters are tested	1. Altimeter selection can be seen in 3.6.3 2. Testing can be seen in Section 7.1.2	1	4	4
Twist-to-lock CRAM Shearing	Materials strength of twist-and-lock mechanism is insufficient	1. The CRAM moves within the body tube 2. Potential recovery failure, resulting in high velocity impact with ground and danger to personnel	3	3	9	1. Twist-and-lock mechanisms are carefully selected for anticipated forces 2. CRAM is manufactured from birch wood	CRAM details are described in the CRAM Construction Section 3. Past team experience has proven reliability of CRAM twist-to-lock 4. Full-scale flight test RT4 proves integrity	1	3	3

6.1.2.5 Payload Vehicles

Table 37: FMEA- Payload Vehicles

Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
Fire	1. LiPo batteries on the UAV or the Rover vibrate excessively during flight or are punctured 2. Wires within the UAV or rover systems short	Payload vehicles, nose cone, and payload bay are damaged or destroyed	2	4	8	1. Batteries will be checked prior to launch 2. Batteries will be housed so that they are unlikely to become damaged	1. LSRS Inspection Checklist include battery inspection 2. The UAV and Rover design with battery housing can be seen in Sections 4.6.1 and 4.7.1	1	4	4
UAV power failure	1. Team member fails to plug the UAV battery in or plugs it in backwards 2. Electronics failure 3. Battery insufficiently charged	UAV is not able to deploy or function, resulting in mission failure	2	4	8	1. A Pre-Launch Checklist will be followed to ensure electronics are set up properly 2. Only fully charged batteries will be used 3. A XT60 key-shaped connector prevents plugging the battery in backwards	The LSRS Inspection Checklist includes an electronics and battery charge check	1	4	4
Rover power failure	1. Team member fails to plug the Rover battery in or plugs it in backwards 2. Electronics failure 3. Battery insufficiently charged	Rover is not able to deploy or function, resulting in mission failure	2	4	8	1. A Pre-Launch Checklist will be followed to ensure electronics are set up properly 2. Only fully charged batteries will be used 3. A XT90 key-shaped connector prevents plugging the battery in backwards	1. The LSRS Inspection Checklist includes an electronics and battery charge check	1	4	4
UAV Unable to Operate	1. Weight of UAV is too great for stable flight 2. Wires on the UAV detach and disconnect the power supply 3. UAV is unable to detach from the platform	UAV is not able to fly correctly and likely results in a mission failure	3	4	12	1. Calculations were made to determine the amount of weight needed and the sustainable flight time 2. Wires will be securely attached and checked with test flights 3. UAV deployment system will be tested prior to launch	1. Weight allocation and justification can be seen in Section 4.6.1 2.LSRS Inspection Checklist includes checking proper wiring 3.Test PUT1 proves sled clearance	1	4	4
Battery failure	UAV or Rover battery is not capable of powering the respective system for the duration of the mission	The UAV or Rover cannot complete mission	2	4	8	1. Battery life was calculated to ensure the mission can be completed 2. Battery life was tested	1. Battery life calculations can be seen in Sections 4.6.2 and 3.6.3 2. Tests PUT9 and PRT9 validate battery life calculations	1	4	4

Radio transmission signal disruption	1. Transmitters are functioning at an improper frequency and are disrupted by other nearby transmitters 2. Transmitters lose signal due to a shielding material, such as carbon fiber, inhibiting signal transmissions	UAV is unable able to become beacon for Rover and the Rover will be unable to reach the target	1	4	4	1. All transmitting frequencies were carefully chosen to avoid overlap with other teams or nearby signals 2. The material selected surrounding the transmitters must be RF transparent	1. Transmitting frequencies can be seen in Section 4.6.3.3 2. The material surrounding the payload bay is fiberglass which is RF transparent, described in Section 7	1	2	2
Rover movement mechanism failure	1. Rover component breaks due to impact 2. Wires on the Rover detach	Rover is unable to function correctly	2	4	8	1. The retention system will be designed to constrain the rover in all three axes. 2. Wires will be securely fastened and checked prior to launch.	1. The testing plan for the retention system can be seen in 7.1.3 2. LSRS Inspection Checklist includes checking proper wiring	1	4	4
Sample retrieval mechanism failure	1. Sample retrieval components are damaged or break upon impact or due to a high-force event during flight	1. Sample retrieval mechanism is unable to support a sufficient load 2. System is unable to retrieve a sufficient amount of the provided sample.	2	3	6	1. The sample retrieval system will be made of robust materials. 2. Tests will be conducted to verify the maximum retrieval force of the system. 3. The UAV and Rover will have RF transparent materials for the deployment signal	1. The sample retrieval system materials and rationale can be seen in Section 4.7.3 2. The testing plan for the sample retrieval system can be seen in Section 7.1.5 .	1	2	2
Target detection failure	UAV detection algorithm does not recognize or encounter a sample site.	Rover has no target site to approach, resulting in mission failure.	2	4	8	Multiple detection algorithms will be compared to find the most efficient and successful.	The testing plan for target detection can be seen in Section 7.1.4.	1	4	4

6.1.2.6 Payload Deployment and Integration

Table 38: FMEA - Payload Deployment and Integration

Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
Nose cone removal failure	Black Powder charges do not generate sufficient force.	Vehicles are unable to exit the payload bay and consequently cannot complete the mission.	2	4	8	1. Black powder quantities are based on calculations. 2. Black powder will be tested prior to launch.	1. Black powder calculations can be seen in Appendix B. 2. Black powder test plans can be seen in 7.1.2	1	4	4
Nose cone removal partial failure	The black powder charges generate less force than required to sufficiently separate the nose cone from the vehicle body.	Vehicles are unable to fully exit the nose cone and are unable to orient to complete the task. The mission is a failure.	2	3	6	1. Black powder quantities are based on calculations. 2. Black powder will be tested prior to launch.	1. Black powder calculations can be seen in Appendix B. 2. Black powder test plans can be seen in Section 7.1.2.	1	3	3
Damage from vehicle impacting ground at high velocity	1. The vehicle descends at unintentionally high speeds. 2. Supports securing the payload do not function as intended.	1. Vehicles are unable to function as intended. 2. Vehicles may not be able to deploy.	2	4	8	1. The retention system is designed to be robust. 2. The retention system will be tested.	1. Material selection for the deployment system can be seen in Section 4.5.1 2. Testing plans for the retention system can be seen in Section 7.1.3.	1	4	4
Premature vehicle deployment	1. The securing mechanism fails to keep the vehicles from deploying at the incorrect time. 2. Bulkheads are not installed into the payload bay correctly.	Vehicles are not able to complete the mission successfully due to damages to essential components of the vehicles.	1	4	4	1. The securing mechanism will be designed to retain the vehicles in all three axes. 2. Construction procedures will be written prior to construction.	1. The mechanism design can be seen in Section **??**. 2. Construction procedures will be available in the workshop prior to construction. 3. The testing plan for the retention system can be seen in Section 7.1.3.	1	3	3
Delayed vehicle deployment	The black powder system mechanism takes more time than intended to operate.	1. Vehicles are unable to perform the mission within the established time constraints 2. The batteries powering the vehicles likely run out of power before completing the mission.	1	4	4	1. Black powder quantities are based on calculations 2. Black powder will be tested prior to launch.	1. Black powder calculations can be seen in Appendix B. 2. Black powder test plans can be seen in Section 7.1.3.	1	3	3
Orientation correction failure	1. Vehicle platform does not have sufficient room to rotate 2. The platform cannot move because of friction.	Vehicle is not properly oriented, leading to mission failure	2	4	8	1. The orientation system will be extensively tested prior to launch	1. Testing plans for the orientation system can be seen in Section 7.1.3.	1	4	4

Vehicle platform or rover becomes unconstrained	1. Pin mechanism is not properly set 2. Pin breaks	Vehicles experience more forces than expected, which could lead to damage	2	3	6	1. The pin connection from the solenoid will be checked prior to launch 2. The pin material has been selected to withstand forces during flight.	1. The payload lead will confirm pin attachments before launch as seen in the LSRS Inspection Checklist 2. The pins are made of stainless steel for its durability and strength as see in Section 4.5.4	1	3	3
UAV not properly secure to platform	Supports either break or are not attached correctly	Vehicles experience more forces than expected, which could lead to damage	2	3	6	1. Supports will be carefully constructed following construction procedures.	1. Construction procedures will be available in the workshop prior to construction. 2. Rention testing plans can be seen in Section 7.1.3.	1	3	4
UAV sled failure	1. Sled material strength is insufficient for forces 2. Sled connection cannot withstand forces during flight 3. Sled connection cannot withstand forces upon landing	The UAV vehicle is unable to exit the payload bay and is therefore unable to deploy to locate the target.	2	3	6	1. The sled is material is sufficient for its application 2. The retention will be tested	1. Sled material selection and FEA can be seen in Section 4.5.1. 2. The retention testing plans can be seen in Section 7.1.3	1	3	3

6.1.2.7 Launch Support Equipment

Table 39: FMEA- Launch Support Equipment

Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
Launch rail is at an improper angle	1. Launch equipment is improperly set up 2. Vehicle is improperly placed on launch pad	Vehicle does not reach apogee	2	3	6	1. Launch equipment will be set up according to NAR standards 2. The NDRT mentor and RSO recommendations will be followed when setting up the vehicle	1. The RSO will verify that launch equipment is properly set up in accordance to Section 9 of NAR's High Powered Rocketry Safety Code 2. The vehicle set up will be verified by the NDRT mentor before launch	1	3	3
Launch controller fails to ignite motor	1. Wire connection or controller is faulty	Motor does not ignite	2	2	4	1. NDRT will use an official Rocketry club's controllers	NDRT will ensure that the clubs the team launches with are reliable and have a consistent record of successful launches	1	2	2
Launch ignition wires are live during set up	1. Launch controller unit is faulty	Premature motor ignition may injure personnel	2	4	8	1. All launch equipment will be inspected prior to use	The NDRT mentor along with the local Rocketry club will assist in inspecting equipment prior to set up	1	4	4

6.1.3 Environmental Hazards

6.1.3.1 Environmental Hazards to Vehicle

Table 40: Environmental Hazards to Vehicle

Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
Shorting of electrical circuits, batteries, or payload electronics	High humidity, rain, or snow causing electric discharge	1. Potential recovery failure 2. Payload unable to complete mission	3	4	12	1. Electronic components are stored in re-sealable electrostatic discharge (ESD) shielding bags before launch 2. Once placed in launch vehicle, the altimeters for recovery, payload, and ABS are housed in Faraday cages 3. The team will not launch in rain or inclement weather conditions	1. Both storing procedures and weather clearances are included in the Vehicles Pre-Departure Checklist Inspection	1	5	5
Lightning	Weather patterns	1. Upright rocket could be struck while on launch rail, causing severe damage to vehicle structure and electrical components 2. Potential danger of strike while launch vehicle and components are outside	2	4	8	If lighting strikes occur within the launch area, the launch will be aborted and components will be kept inside of protective structures such as ESG bags and LiPo battery cases and immediately be placed indoors	1. Weather conditions are monitored by team members and mentor 2. Weather clearances are included in the Vehicles Pre-Departure Checklist Inspection section	1	4	4
Instability of launch vehicle during assembly	High winds knock over propped sections or cause members to drop sections	Potentially severe structural damage to launch vehicle or payload	2	3	12	1. Launch vehicle components never unattended during or before assembly 2. Several team members help carry the rocket to mitigate probability of wind-induced drops	1. Checklists will be used to keep track of items at all times 2. The Safety Officer will verify that multiple people carry the rocket from the preparation table to the launch rail	1	3	3

Weathercocking	High winds	Undesired launch trajectory	2	4	8	1. Static stability margin will be kept under 3 calibers to prevent overstability 2. Launch will be aborted if wind speeds reach 20 miles per hr or above, as listed in the Vehicles Pre-Departure Checklist Inspection section	Simulated and calculated static stability margin for demonstration flights are under 3 calibers, see Sections 3.7.1 and 5	1	4	4
Dragging after deployment of main parachute	High winds	Damage to vehicle structure or payload	3	3	9	1. Size of main parachute is minimized to reduce unnecessary dragging 2. Once the range is safe, team members recover the main parachute to prevent further dragging	1. See Section 3.6.1 for parachute size justification 2. Demonstration Flights prove structural integrity despite dragging before recovered, see Section 5. 3. The Recovery Post-flight Checklist includes instructions for recovery of main parachute after landing	1	3	3
Unexpected draining of battery charge	Cold temperatures	Loss of power to recovery, ABS, or payload electronics during flight, potentially resulting in mission failure	2	4	8	1. Batteries are stored in temperature-controlled environment such as a team vehicle until installation during assembly 2. Assemble launch vehicle efficiently to reduce exposure to cold temperatures	1. Battery testing proves factor of safety for battery life beyond the 2 hr minimum in case of cold weather, see tests RT6, PDT8-9, PUT9, PRT10 2. Each Pre-Departure Checklist ensures proper battery storage and each Checklist allows for the team to quickly and efficiently assemble the vehicle	1	4	4
Weakening of Bonding Materials	Humidity, rain, and heat	1. Bulkhead failure that leads to shifting of ABS, Payload, or other components, restricting function of shifted components or causing changes to static stability margin 2. Bulkhead failure that leads to retention or recovery failure	3	4	12	1. High strength RocketPoxy G5000 is used for bulkhead installation, which is rated for extreme temperatures 2. Structures with bonding materials such as epoxy will be kept in climate controlled environments (dry, moderate temperatures) such as vehicles until assembly	1. See section 3.4 for construction details 2. The Vehicles Pre-Departure Checklist includes inspection of bonding and storage instructions before assembly	1	4	4
Turbulent air	1. Low cloud cover 2. High winds	1. Creates undesired launch trajectory 2. Affects parachutes, possibly increasing descent time or drift	3	2	6	If low cloud cover or high winds (exceeding 20mph) occur, the launch will be aborted	1. Weather conditions are monitored by team members and mentor 2. Weather clearances are included in the Pre-Departure Checklist	1	2	2

Wetting of launch vehicle propulsion materials	High humidity, contact with swampy ground, snow, rain	Complete or partial failure to ignite motor	2	4	8	Motors are stored by the team mentor in re-sealable bags until motor integration	All energetics, including the motor, are handled by the team mentor	1	4	4
UV exposure to electronics or sensors	Little to no cloud cover over launch area	Potentially severe damage to the electronics and sensors within the launch vehicle	3	4	12	1. Before assembly, electronics are stored in ESD bags, which reflect UV rays 2. All electronics will not be exposed to direct sunlight once integrated	the Vehicles Pre-Departure Checklist requires storing electronics in ESD bags	1	4	4
Blunt force damage to vehicle	Hail	Changes to vehicle geometry that may affect launch trajectory	2	4	8	Launch is aborted if hail occurs	Weather clearances are included in the Pre-Departure Checklist	1	4	4
Local terrain and man-made structure interference	Natural and man-made structures around the launch site	1.Interference to the launch vehicle flight path 2. Destruction of the launch vehicle or payload	2	4	8	Launches occur in an open field away from trees and buildings	Team leads and the Launch Manager will inspect the launch site to confirm that it is safe to launch	1	4	4
Animal interference	Local animal population in and around the launch site	Potential structural damage to the launch vehicle	2	3	6	Closely monitoring local animal movements and local species in the launch area	Team leads and the Launch Manager will inspect the launch site to confirm that it is safe to launch	1	3	3
Components swelling	Humidity causing wood or metal components to expand	Components do not fit together properly, causing difficulty in assembly	2	2	4	Swollen parts can be sanded down for minor size adjustments if necessary	Sandpaper is in the Tools packing list for pre-departure	2	1	2
Unlevel launch pad	Soft or uneven ground under launch pad	Unexpected launch trajectory	2	3	6	1. Launch pad is set up on hard, even ground 2. A level is used to ensure even launch pad as seen in Vehicles Pre-flight Checklist	Team mentor ensures level launch pad during launch operations	1	3	3
Components blown in wind	High wind	Potential to lose or damage hardware	2	2	4	Hardware is stored in boxes and kept in cars before assembly	Team leads ensure proper storage of hardware	1	2	2
Poor visibility during flight	Low cloud cover or fog	Failure of team to track flight path, leading to potential loss of vehicle	2	3	6	Launch aborted in low cloud cover or foggy conditions	Weather clearances are included in the Pre-Departure Checklist	1	3	3
Wireless signal interference	Fog, trees, or other teams	Disrupted communication between systems	2	3	6	1. Launch does not occur in conditions of fog 2. The launch fields are far from trees	Weather clearances are included in the Pre-Departure Checklist The team has submitted the operational frequencies and will operate at a different specific frequency than other teams	1	3	3

6.1.3.2 Vehicle Hazard to Environment

Table 41: Vehicle Hazard to Environment

Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
Fiberglass particulates (styrene gas)	Sanding of bulkhead or other fiberglass materials	1. Cause skin, eye, and respiratory tract irritation to surrounding individuals 2. Emission of toxins depletes air quality	3	3	9	Quantity of styrene gas emitted has negligible effects on environment	1. All members involved in sanding will be certified prior to entering lab and will wear proper equipment 2. Sanding will be conducting in ventilated area and the workshop vacuum will be utilized	3	1	3
Excessive carbon dioxide emission	1. Motor produces CO_2 emissions when ignited 2.The black powder charges in the recovery system produces CO_2 emissions when ignited	Contribute to greenhouse effect and increase global warming	5	1	5	1. CO_2 emissions from the motor are negligible 2. CO_2 emissions from black powder charges are negligible	Motors and black powder charges will be inspected by the Launch Manager	4	1	4
Hydrogen chloride emmission	Ammonium perchlorate motor produces hydrogen chloride	HCl reacts with water to form hydrochloric acid, contaminating water	4	1	4	Launches will take place away from water sources in order to prevent contamination	1. Leads will survey the land to ensure the launchpad is placed away from water sources 2. Motors will be disposed of according to SDS and local standards	2	1	2
Components come loose from vehicle	Improper retention of components	Wildlife could potentially ingest or be harmed by materials	3	3	9	Exterior and interior of launch vehicle will be inspected prior to launch	Vehicles Pre-Launch Checklist includes launch vehicle inspection	1	3	3
Battery leakage	Defective batteries that fail to enclose the acid in its appropriate space	1. Absorption of acid contaminates soil 2. Pollution of groundwater	2	4	8	Batteries are housed in battery bag when not in use and are inspected by leads before and after each use	Batteries will be inspected by a team lead or the Safety Officer and if a defect is found, the battery will be disposed of according to the SDS and local regulation	1	4	4
Spray paint on vehicle	Use of spray paint to paint exterior of vehicle	Release of toxic emissions into the atmosphere	4	2	8	Spray painting is executed in a ventilated area to reduce concentration of air contamination	1. Members involved in spray painting will be certified prior to entering workspace and will wear proper PPE 2. Painting area will be well ventilated and only contain personnel participating in painting.	4	1	4

Plastic Waste	Plastic waste can be produced by 3D printing and other construction procedures	Wildlife could potentially ingest or be harmed by plastic	5	2	10	Disposal of plastics according to SDS and local standards	The workshop will contain a specific bin for recycling certain plastics in order to reduce waste	4	1	4
Wire Waste	Excessive wire scraps as a result of electrical component construction	Wildlife could potentially ingest or be harmed by wire waste	5	2	10	Wire will be disposed of according to SDS and local standards	The workshop will contain a specific bin for recycling certain electronic components in order to reduce waste	4	1	4
Soldering Material Waste	Excess materials improperly disposed of during the soldering of wires	Soldering releases toxic that can contaminate the air quality	4	2	8	Proper ventilation will be used to negate release of toxins into environment	Members involved in soldering will be certified. Disposal will be monitored according to SDS and local guidelines	4	1	4
Grass fire	1. Motor burnout 2. Electrical components short circuit	1. Damage to surrounding grass 2. Damage to animals' natural habitats 3. Greenhouse emissions as a result of combustion	2	3	6	1. Bring appropriate extinguishing devices on site of launch 2. Leads inspect wire connections and electronics before launch	1. A fire extinguisher must be available at each launch 2. The ABS Inspection, Recovery Inspection, LSRS Inspection all include instruction for checking wire connections .	1	3	3
Damage to nearby property	1. High wind speeds knock vehicle out of expected trajectory 2. Recovery fails to deliver vehicle safely to the ground	Damage to private property and/or damage power lines or environment	3	4	12	1. Launch equipment will be inspected Stability of the vehicle will be confirmed through simulations and testing 2. Leads ensure redundant and reliable systems for recovery	1. Simulations confirming vehicle stability can be seen in Section 3.7 2. The recovery system will employ three redundant altimeters and black powder charges that will be tested prior to launch, shown in Section 7.1.2	2	4	8
Noise Impacts	Excessive noise generation from the launch vehicle's motor on launch	Noise could harm wildlife, bystanders, and potentially vibrate structures	1	4	4	Impact will be temporary and will not exceed EPA regulations	Personnel will stand at least 300 ft. away from launch site as required by the NAR	1	2	2

6.2 Workshop Safety

As some tooling and assembly operations pose a risk to safety all team members must be certified according the University of Notre Dame's standards. This includes quizzes, demonstrations, and training to be certified. Each individual participating in construction must be certified to Level 1 which includes a basic workshop and hand tools safety quiz. It also requires a workshop walkthrough with demonstrations. After that individuals must be certified on each of the available tools in the workshop in order to use them. The certification includes a quiz and mandatory training with the Fabrication Manager. All members must re-complete certification each year to ensure competency. In order to enter the workshop and work with any tools a member must display their safety certification card to either a Team Lead or the NDRT Fabrication Manager, Will Mathis to prove they are certified on the specific tool or machine they are using. The card is shown in Figure 97.

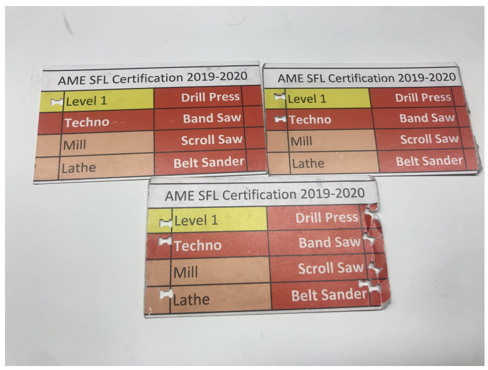


Figure 97: Safety Certification Cards with Different Levels of Certification

The link to SFL Certification Requirements and Workshop Training is:

https://sfl.nd.edu/tools-equipment

is additional instructions on how to properly use tooling in the Safety Handbook as seen on the Team's website under the following link:

https://sites.nd.edu/aiaa-club/notre-dame-rocket-team/techical-documents/

6.3 Launch Operations Procedures and Checklists

In the Launch Procedures, each task is presented next to a checkbox to ensure that members are following each task in order. In some cases not following the procedure in the exact order can result in failure of a system or a safety risk. Items that are particularly important to the success of the mission have a line for the specific lead of that system to initial to ensure that it has been validated by the lead. Items that pose an inherent safety risk are in bold and contain a warning symbol to ensure that they grab the attention of the reader. Checklists contain pictures in order to help the reader better follow the procedure by having a visual reference. All checklists must be signed off by the Safety Officer to verify the checklist has been completed and that each subsystem is fully prepared and inspected.

University of Notre Dame
NASA SLI Launch Checklist

General

Required Personnel

NAR Certified Launch Manager: Dave Brunsting
Safety Officer: Brooke Mumma
Team Captain and Vice Captains: Collette Gillaspie, Jed Cole, Eric Dollinger
Vehicles Lead: Estefy Castillo
ABS Lead: Ben Tompoles
Recovery Lead: Joe Sutton
LSRS Lead: Greg Bracht
A team member may fill in for one of these leads if approved by the Safety Officer.

Tools

- ☐ **1 hand drill, fully charged**
- ☐ **Drill bit case with standard range of bits**
- ☐ **Standard wrenches**
- ☐ **Standard Alan wrenches**
- ☐ **Screwdriver set**
- ☐ **Electrical tape**
- ☐ **Duct tape**
- ☐ **Masking tape**
- ☐ **Scissors**
- ☐ **2 folding tables**
- ☐ **Hot glue gun**
- ☐ **Garbage bags**
- ☐ **Rocket stands**
- ☐ **Rocketpoxy**
- ☐ **JB Weld**
- ☐ **Soldering iron**
- ☐ **Lead solder**
- ☐ **Digital multimeter**
- ☐ **Pens/pencils**
- ☐ **Exacto knives**
- ☐ **Metal files**
- ☐ **Assorted screws**
- ☐ **Wire cutters**
- ☐ **Wire strippers**
- ☐ **Bluntnose pliers**
- ☐ **Needlenose pliers**
- ☐ **Dial caliper**
- ☐ **Tape measure**
- ☐ **Sandpaper**
- ☐ **Epoxy applicators**
- ☐ **Level**

Personal Protective Equipment

- ☐ **Box of nitrile gloves**
- ☐ **Pair of cut resistant gloves**
- ☐ **Fire resistant battery bags**
- ☐ **First aid kit**
- ☐ **Dusk masks**
- ☐ **Pair of heat resistant gloves**
- ☐ **Safety glasses**
- ☐ **Leather gloves**

Vehicles

Vehicles Pre-Departure Checklist

Required Personnel: Vehicles Lead
Required PPE: None

Equipment

- ☐ **Nose cone**
- ☐ **Payload bay**
- ☐ **Recovery Tube**
- ☐ **Fin can**
- ☐ **Shear pins**
- ☐ **Locking screws**
- ☐ **Motor (2)**
- ☐ **Motor Casing**
- ☐ **Motor Retainer**
- ☐ **Eyebolts**
- ☐ **Camera**
- ☐ **Washers**
- ☐ **Hex nuts**

Inspection

⚠ **Failure to complete the following steps could result in an unidentified failure mode and thus a failed launch**

- ☐ Check the local weather for the following conditions. The team will not launch if the weather includes any of the following (check off if condition does not apply):
  - ☐ Winds that exceed 20 mph
  - ☐ Low cloud cover or fog
  - ☐ Rain
  - ☐ Lightning or signs of storms

⚠ **If there is high humidity, unusually high or low temperatures, or other concerning weather conditions, all components should be stored in vehicles to keep them in controlled atmospheric conditions until necessary for assembly**

- ☐ Inspect each body tube for deformations or cracks to ensure there is no damage
- ☐ Check adhesives at each connection to make sure they are strong
- ☐ Inspect fins for any cracks or deformations
- ☐ All electronics not secured to the vehicle should be placed in Electrostatic Discharge bags.

Vehicles Pre-Flight Checklist

Required Personnel: Vehicles Lead, Safety Officer, Launch Manager
Required PPE: Leather gloves, Heat resistant gloves, Safety glasses

⚠ **Failure to complete the following steps in order could result in an unidentified failure mode and thus a failed launch**

⚠ **Leather gloves should be used at any step where two components are connected in order to avoid pinch points**

- ☐ Recovery Integration (See Recovery Checklist)
  - ☐ Pack main parachute below the transition section. Ensure that the parachute is not packed so tightly that is cannot be pulled out

Figure 98: Packing the Parachute Below the Transition Section

  - ☐ Pack drogue parachute above the fin can. Ensure that the parachute is not packed so tightly that is cannot be pulled out
  - ☐ Ensure that all shock cords are attached and eye bolts are secured. **One end of the drogue shock cord should still be loose**
  - ☐ Secure the recovery tube to the payload bay with shear pins
- ☐ ABS Integration
  - ☐ Insert ABS into fincan by matching the starred hole on the side of the body tube to the starred hole around the aluminum bulkhead
  - ☐ The removable bulkhead at the top of the system is then secured using four button head screws
  - ☐ Inspect the drag tab cutouts in the fin can to ensure that the tabs are visible and have clearance to extend
  - ☐ 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
  - ☐ If the LEDs indicate a premature launched state, the system must be removed and reset.
  - ☐ Make a final inspection of the system's installation for any obvious defects or abnormalities

☐ Attach loose end of drogue shock cord to the ABS top bulkhead eyebolt

Figure 99: Attaching the Shock Cord to ABS Bulkhead

☐ Secure fin can to recovery tube using shear pins

Figure 100: Securing the Fin Can to Recovery Tube with Shear Pins

☐ Telemetry Integration

- ☐ Use twist to lock mechanism to screw telemetry system into nose cone
- ☐ Secure the lock by aligning the two eye bolts and tying them with Kevlar cord

☐ Payload Integration

- ☐ Ensure bulkhead is aligned with the blocks and the platform

⚠ **The next steps should ONLY be performed by the Launch Manager Dave Brunsting. Gloves and safety glasses should be worn.**

- ☐ Prepare nose cone ejection charge LM: ______
  - ☐ Create one ejection charge 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 switch is in the “off” position
  - ☐ Connect the loose ejection charge wire to its corresponding lever wire
  - ☐ Place the ejection charge in its corresponding PVC charge well

- ☐ Cover each charge well with painters tape to keep the charge in place
- ☐ Ensure all wire holes are plugged with sealing clay

⚠ **This concludes the steps that must be performed by the Launch Manager**

- ☐ Press fit nose cone between the sliding bulkhead and the inner diameter of the payload bay body tube. Be careful to align the shear pin holes.
- ☐ Place shear pins in holes

Figure 101: Insertion of Shear Pins in Nose Cone

- ☐ 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 recording button (button with the camera symbol).
  - ☐ If camera is flashing yellow, then the camera is recording
  - ☐ Insert the camera into the transition section slot so that the lens is facing downward
  - ☐ On the edge closest to the lens, place one 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 two 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 four steps
  - ☐ If a proper fit is achieved, tighten the lock nuts with crescent wrench
  - ☐ Perform shake test of assembly to ensure secure connection

⚠ **The next steps should ONLY be performed by the Launch Manager Dave Brunsting. Gloves and safety glasses should be worn.**

☐ **Motor Assembly** LM: ______

- ☐ 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 grains into the casing, ensuring that an O-ring is placed in between each grain

Figure 102: Installation of Each Grain

- ☐ Add an O-ring onto the forward closure

Figure 103: The O-ring around the forward enclosure

- ☐ Place the tracking smoke element inside of the forward closure, coated end first
- ☐ Screw on the nozzle holder over the nozzle. Ensure a secure fit.
- ☐ Slide the case liner inside the motor casing
- ☐ Place the forward closure inside the motor casing on the side opposite the nozzle
- ☐ Add a retaining ring on each side of the motor casing. Screw it in only until the retaining ring is exactly even with the end of the motor case - do not thread it in as far as it will go.

Figure 104: Addition of the Retaining Ring to the Forward Enclosure End of the Motor Casing

- ☐ Insert the motor into the rocket, ensuring the nozzle is facing the bottom of the fin can
- ☐ Attach the motor retainer
- ☐ Check for a secure fit

⚠**This concludes the steps that must be performed by the Launch Manager**

⚠**The Cg and stability check should be performed by the Vehicles lead**

- ☐ Center of gravity and stability check VL: ______
  - ☐ Perform center of gravity (Cg) test to ensure the center of gravity matches the simulated Cg by placing the fully assembled vehicle on a thin wooden stand so that it is cantilevered on both sides. Move the vehicle until it perfectly balances.

Figure 105: Demonstration of a CG Check

  - ☐ Mark the measured Cg and simulated Cg on the vehicle
  - ☐ Mark the simulated center of pressure (Cp) on the vehicle
  - ☐ Ensure calculated stability corresponds to predicted value
  - ☐ The simulated CP is 96.36" from the top of the nose cone
  - ☐ The simulated CG is 75" from the top of the nose cone
    - ☐ To calculate the measured stability use the distance between measured Cg and simulated Cp divided by the largest diameter
    - ☐ Simulated stability is 2.68
  - ☐ Ballast as necessary to maintain a stability margin between 2 and 3 or within 10% of predicted margin (whichever is greater)
- ☐ **Vehicle Setup and Launch Pad Preparation**
  - ☐ Register with LCO and RSO at the launch site

- ☐ Carefully carry the vehicle out to the launch pad. There should be at least three people carrying the vehicle at all times
- ☐ Check that the launch pad is fairly level with the ground with a level
- ☐ Lower the launch rail such that it is parallel to the ground

Figure 106: Lowering the Rail and Aligning the Rail Buttons

- ☐ Align the rail buttons with the rail and slide the vehicle onto the rail with the fin can towards the ground
- ☐ Set rail angle to be perpendicular to the ground with an added maximum 10 degrees into the wind
- ☐ Allow payload and subsystem teams to activate systems

⚠**The next steps should ONLY be performed by the Launch Manager Dave Brunsting. Heat resistant gloves and safety glasses should be worn.**

☐ **Igniter Installation** LM: ______

- ☐ Clear all personnel except for the Launch Manager
- ☐ Check that the ignition wires, connected to the launch control system, do not have a live voltage across them. This can be done by lightly touching the clips to each other while away from the vehicle, 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
- ☐ Clear the launch are of all personnel and maintain the distance as designated by the RSO in accordance with NAR/TRA regulations
- ☐ If motor does not ignite when planned, wait for RSO instruction to approach

Vehicles Post-Flight Checklist

Required Personnel: Vehicles Lead, Safety Officer, Launch Manager
Required PPE: Heat resistant gloves

⚠ **Team members should wait for RSO approval to approach vehicle and enter the launch field**

⚠ **After landing the motor still may be hot or batteries could catch fire. It is important to assess the landed components carefully**

- ☐ Assess the landing site and vehicle for potential hazards such as fire or smoke
- ☐ Examine recovery and payload sections for unexploded black powder charges, if any are found, see troubleshooting procedures
- ☐ Document state of vehicle with photographs before moving any part
- ☐ Disconnect quick links where possible to transport the vehicle

⚠ **The next step should ONLY be performed by the Launch Manager Dave Brunsting. Heat resistant should be worn.**

- ☐ Motor Removal LM: ______
  - ☐ Remove the motor retainer from the vehicle
- ☐ Ensure that each subsystem completes their Post-Flight Checklist

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

Safety Officer: ______________________ Date: __________

Air Braking System (ABS)

ABS Pre-Departure Checklist

Required Personnel: ABS Lead
Required PPE: Fire proof battery case

Equipment

- ☐ **Assembled ABS**
- ☐ **Assembled PCB**
- ☐ **ABS electronics toolbox**
- ☐ **Fire-proof battery case**
- ☐ **2 3.7V batteries**
- ☐ **2 7.4V batteries**
- ☐ **10-32 metal screws (4)**
- ☐ **2 Tenergy LiPo chargers**
- ☐ **Rubber cylindrical sheet**

Inspection

⚠ **Failure to complete the following steps could result in an unidentified failure mode and thus a failed launch**

- ☐ Inspect ABS for material defects. After ensuring battery is disconnected, inspect the mechanical system for loose screws and bent components, particularly the drag tabs
- ☐ With the battery disconnected from the circuit board, inspect electronics for secure connections and mounting
- ☐ All electronics not secured to the ABS system should be placed in Electrostatic Discharge bags.
- ☐ Verify batteries are fully charged based on LED status of Tenergy LiPo charger
- ☐ Ensure the proper control code has been installed on the Raspberry Pi

ABS Pre-Flight Checklist

Required Personnel: ABS Lead, Safety Officer
Required PPE: Fire proof battery case

⚠ **Failure to complete the following steps in order could result in an unidentified failure mode and thus a failed launch**

⚠ **LiPo batteries are a potential fire risk and should always be inspected for swelling to punctures before use. When not in use batteries should be housed in the fire proof battery case.**

- ☐ Ensure the SD card is inserted in the Raspberry Pi prior to powering the system
- ☐ Duct tape the 7.4V battery right next to the servo motor
- ☐ Duct tape the 3.7V battery to the wall adjacent to the PCB

☐ Plug in the 7.4V battery into the servo

☐ Plug in the 3.7V battery into the PCB

☐ Inspect the LEDs to see that the system is powered and data is being collected according to Figure 107 AL: ______

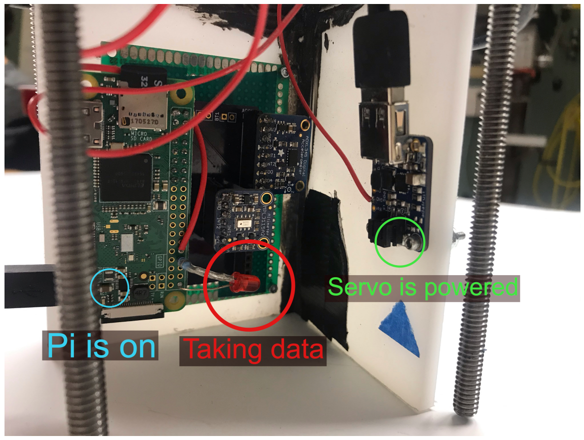


Figure 107: The LED Layout for ABS Functionality Confirmation

☐ In the event that these lights do not turn on, notify the ABS lead immediately

ABS Post-Flight Checklist

Required Personnel: ABS Lead, Safety Officer
Required PPE: Fire proof battery case

⚠ **Team members should wait for RSO approval to approach vehicle and enter the launch field**

⚠ **After landing the motor still may be hot or batteries could catch fire. It is important to assess the landed components carefully**

☐ Use a screwdriver to unscrew the button head screws from the forward bulkhead of the ABS.

☐ Check that the drag tabs are fully retracted to avoid jamming the ABS in the fin can while removing.

☐ Carefully remove the ABS from the fin can by lifting with the Recovery system eyebolt at the forward bulkhead of the ABS

☐ Inspect the batteries for damage. If damaged, place in the fire-proof battery case for safe storage

☐ Inspect the avionics system for power and status LED indication to determine if power was lost during flight or landing

☐ Unplug both batteries to power off the system

- ☐ Inspect and note any damage to the mechanical system or payload assembly
- ☐ Remove the micro SD card form the Raspberry Pi
- ☐ Insert the micro SD 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
- ☐ Store all disconnected electronics in ESG bags

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

Safety Officer: ______________________________ Date: __________

Recovery

Recovery Pre-Departure Checklist

Required Personnel: Recovery Lead, Vice Captain, Safety Officer
Required PPE: Fire proof battery case, nitrile gloves, safety glasses

Equipment

- ☐ **CRAM body**
- ☐ **CRAM core, both pieces**
- ☐ **CRAM core pins**
- ☐ **Raven3 altimeters (2)**
- ☐ **Stratologger SL100 Altimeter**
- ☐ **Fully Charged 3.7v, 170 mah Batteries (3)**
- ☐ **Assembled altimeter wiring perfboards**
- ☐ **CRAM top bulkhead**
- ☐ **CRAM bottom bulkhead**
- ☐ **4 1/2 in, 1/4-20 Grade 8 bolts (3)**
- ☐ **1/4-20 hex nuts (3)**
- ☐ **1/4 in washers (6)**
- ☐ **3/8 in washers (2)**
- ☐ **E-matches (6)**
- ☐ **Black powder (mentor, 19.5g)**
- ☐ **3/8 in Eyebolts (2)**
- ☐ **3/8 in quick links (5)**
- ☐ **3/16 in quick links (3)**
- ☐ **Slider Ring**
- ☐ **1 in Nylon shock cord (35 ft, x2)**
- ☐ **Main parachute (10 ft)**
- ☐ **Drogue parachute (2 ft)**
- ☐ **Pilot Chute (2 ft)**
- ☐ **Main Parachute Deployment Bag**
- ☐ **24 in Nomex blanket (2)**
- ☐ **Laptop with Featherweight Interface Program and Perfectflite DataCap installed**
- ☐ **Data cable for Raven altimeters**
- ☐ **Data cable for Stratologger altimeter**
- ☐ **Fire-retardant cellulose wadding**
- ☐ **Talcum powder**
- ☐ **Sealing clay**
- ☐ **Telemetry Housing Assembly**
- ☐ **Telemetry Vehicle Electronics**
- ☐ **Telemetry Relay Station**
- ☐ **Telemetry Ground Station**
- ☐ **Rubber sealing**

Inspection

⚠ **Failure to complete the following steps could result in an unidentified failure mode and thus a failed launch.**

- ☐ Inspect main parachute bulkhead (in transition section of vehicle) for fatigue or failure in bulkhead and epoxied seal.
- ☐ Inspect CRAM body for fatigue or failure
- ☐ 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 connect to quick links. Check for holes or wear.
- ☐ Check the LiPo batteries to ensure a full charge.
- ☐ Connect each altimeter to a battery through the mounted screw terminals and connect the altimeter to a laptop through the data cable. Check the programming of the altimeters to confirm proper deployment programming.
- ☐ All electronics not secured to the CRAM should be placed in Electrostatic Discharge bags.
- ☐ Ensure that 6 lever nut wire connections are properly epoxied to the upper and lower CRAM bulkhead

Recovery Pre-Flight Checklist

Required Personnel: Recovery Lead, Vice Captain (Jed Cole), Safety Officer, Launch Manager
Required PPE: Fire proof battery case, safety glasses

⚠**Failure to complete the following steps in order could result in an unidentified failure mode and thus a failed launch**

⚠**LiPo batteries are a potential fire risk and should always be inspected for swelling to punctures before use. When not in use batteries should be housed in the fire proof battery case.**

- ☐ Telemetry Activation and Uplink
  - ☐ Insert SD card into telemetry vehicle system
  - ☐ Connect power to telemetry vehicle system
  - ☐ Turn on telemetry relay system
  - ☐ Connect power to telemetry ground station
  - ☐ Activate uplink between telemetry vehicle system and relay station
  - ☐ Activate uplink between relay station and ground station
  - ☐ Ensure that ground station is properly receiving data package
  - ☐ Place relay station approximately 2500 ft away from pad
- ☐ Main Parachute Folding
  - ☐ Suspend the parachute by its shroud lines, shaking the parachute lightly to untangle the cords.
  - ☐ Line all of the shroud lines up such that they are the same length. Tape the shroud lines at this position to make folding easier. MAKE SURE TO UNTAPE THE PARACHUTE SHROUD LINES PRIOR TO INSTALLATION IN THE VEHICLE.

⚠**Failing to untape shroud lines could cause recovery failure**

Figure 108: Taping the Shroud Lines to Ensure They are Straight

- ☐ Flatten out the canopy of the parachute, such that there are an even number of gores on either side of the centerline, where the shroud lines are. Ensure all of the gores are flat, folded in an accordion-like fashion.

Figure 109: Folding the Parachute

- ☐ Fold both sides of the parachute inwards toward the center line, forming a rectangular parachute shape.
- ☐ Feed the slider ring up from the parachute bridle all the way to the beginning of the canopy.
- ☐ Quick link (3/16 in) the crown of the parachute to the deployment bag tether.
- ☐ Z-fold the deployment bag tether and insert it in the bag, pushing it all the way to the top.
- ☐ Push the canopy of the parachute into the open deployment bag, starting with the top and working down the folded canopy.
- ☐ Z-fold and lace the shroud lines of the parachute along the straps mounted to the outside of the deployment bag. Ensure that the shroud lines are capable of easily pulling out of the straps.

Figure 110: The Z-Folded Shroud Lines in Parachute Bag

- ☐ Untape the shroud lines.

⚠**Failure to untape the shroud lines could cause recovery failure**

- ☐ Quick link (3/16 in) the pilot chute to the deployment bag.
- ☐ Add a quick link (3/8 in) to the main parachute bridle.

☐ Drogue and Pilot Chute Folding

- ☐ Suspend the parachute by its shroud lines, shaking the parachute lightly to untangle the cords.
- ☐ Line all of then shroud lines up such that they are the same length.
- ☐ Flatten out the canopy of the parachute, such that there are an even number of gores on either side of the centerline, where the shroud lines are. Ensure all of the gores are flat, folded in an accordion-like fashion.

Figure 111: Folding the Drogue Chute in Accordion Fashion

- ☐ Fold one side of the parachute towards the other, forming a flat triangle with shroud lines protruding from one corner.
- ☐ Fold the parachute shroud lines upwards into the middle of the triangle, with the parachute bride sticking out the bottom.
- ☐ Fold the parachute in half longways, then Z-fold it.

- ☐ Attach a quick link (3/16 in) to the parachute bridle and loosely wrap in Nomex blanket.

Figure 112: The Folded Drogue Being Folded in the Nomex

- ☐ CRAM Assembly
  - ☐ Check to ensure all of the solder joints on the altimeter perfboards are solid, and that the board is securely screwed to the CRAM core.
  - ☐ Check the mounting screws on both the top and bottom platforms to ensure electronic components are secure
  - ☐ Secure each the altimeter to its respective perfboard with screws and ellectrically connect it using the on-board screw terminals.
  - ☐ Place the top piece that houses battery on the bottom platform that houses the altimeters
  - ☐ Plug each altimeter battery into its respective JST port on the perfboard.
  - ☐ Place the CRAM core in the CRAM body.
  - ☐ Four wires protrude from each perfboard, two upwards and two downwards. Feed the upward-facing wires through the CRAM top bulkhead and the bottom-facing wires through the CRAM bottom bulkhead. Connect them to the Wago lever nuts on the oustide face of the bulkheads.
  - ☐ Bolt the bulkheads onto the CRAM body.

Figure 113: Inserting the Bolts to Connect Bulkhead to CRAM Body

⚠**The next steps should ONLY be performed by the Launch Manager Dave Brunsting. Gloves**

and safety glasses should be worn.

- ☐ Ejection charges LM: ______
  - ☐ Create six ejection charges using e-matches 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 recovery activation 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, covering the full well with painter’s tape.
  - ☐ Ensure all wire holes in the CRAM upper bulkhead are plugged with sealing clay.

⚠**This concludes the steps that must be performed by the Launch Manager**

- ☐ CRAM Integration Preparation
  - ☐ Thread the eyebolts into place on either side of the CRAM. Make sure they are evenly threaded by turning them at the same time until they are fully in
  - ☐ Twist the CRAM into place in its adapter in the recovery tube.
  - ☐ Ensure that the switch ports and air holes in the CRAM are visible from the holes in the airframe.
  - ☐ Screw the CRAM in place from the outside to keep it from rotating.
- ☐ Parachute Installation
  - ☐ Ensure that all both the parachutes are properly connected to the shock cords and enclosed in the Nomex parachute protectors
  - ☐ Connect the main parachute shock cords to the eyebolts on the payload bulkhead and the fore end of the CRAM
  - ☐ Connect the drogue chute shock cords to the eyebolts on the ABS bulkhead in the fin can and the aft end of the CRAM
  - ☐ Fold the excess shock cord together in an z-fold and loosely tape it together with a single layer of painters tape.

Figure 114: Z-Fold of Shock Cord and Application of Painter’s Tape

  - ☐ Place several handfuls of cellulose recovery wadding in the recovery tube near the top of the CRAM

Figure 115: Insertion of Cellulose Wadding Near CRAM

  - ☐ Lightly coat the outside of the main and drogue parachutes with talcum powder
- ☐ Arming the System
  - ☐ Use a screwdriver to switch on each altimeter's (there are three).
  - ☐ Listen for each altimeter's starting sequence.
  - ☐ Listen to the continuity beeps of the altimeters to confirm both main and drogue charges are active for all three altimeters.

Recovery Post-Flight Checklist

Required Personnel: Recovery Lead, Vice Captain, Safety Officer, Launch Manager
Required PPE: Fire proof battery case

⚠**After landing the ejection charges may not have detonated or batteries could catch fire. It is important to assess the landed components carefully**

- ☐ 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
- ☐ 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, connectors, and launch vehicle for any damage sustained during the flight
- ☐ Store all disconnected electronics in ESG bags

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

Safety Officer: ______________________________ Date: ____________

LSRS

LSRS Pre-Departure Checklist

Required Personnel: LSRS Lead
Required PPE: Fire proof LiPo Bag, Nitrile Gloves, Safety Glasses

Equipment

- ☐ **2 1/8 inch kevlar chord**
- ☐ **Fore Bulkhead**
- ☐ **Stratologger SL100 Altimeter**
- ☐ **Fully Charged 3.7v, 170 mAh Battery**
- ☐ **Stationary Platform**
- ☐ **Sliding Platform**
- ☐ **UAV Sled**
- ☐ **Platform nut and bolt (2)**
- ☐ **Solenoid (4)**
- ☐ **Stability Rod and Stopper**
- ☐ **Orientation Bearing**
- ☐ **Aft Bulkhead nut and bolt**
- ☐ **Fully charged 1800 mAh, 11.1 V Battery (2)**
- ☐ **Fully assembled Rover**
- ☐ **Fully assembled UAV**
- ☐ **Fully charged 5000 mAh, 11.1 V Battery**
- ☐ **Fully assembled Sample Retrieval System**
- ☐ **Zip ties**
- ☐ **1/4-20 bolts (4)**
- ☐ **1/4-20 nuts (4)**
- ☐ **1/8 kevlar cord (20 ft)**

Inspection

⚠ **Failure to complete the following steps could result in an unidentified failure mode and thus a failed launch**

⚠ **LiPo batteries are a potential fire risk and should always be inspected for swelling to punctures before use. When not in use batteries should be housed in the fire proof battery case.**

- ☐ Ensure that all batteries are fully charged for all systems
- ☐ Check wiring connections on UAV, Rover, and ROD to ensure that all electronics are secure
- ☐ All electronics not secured to the vehicles should be placed in Electrostatic Discharge bags.
- ☐ Check UAV, Rover, and ROD ASA plastic components for cracks or defects
- ☐ Ensure that bearing is able to rotate freely when the UAV and rover are not in the payload bay

LSRS Pre-Flight Checklist

Required Personnel: LSRS Lead, Safety Officer, Launch Manager
Required PPE: Fire proof battery case, nitrile gloves, safety glasses

⚠**Failure to complete the following steps in order could result in an unidentified failure mode and thus a failed launch**

⚠**LiPo batteries are a potential fire risk and should always be inspected for swelling to punctures before use. When not in use batteries should be housed in the fire proof battery case.**

- ☐ UAV Activation
  - ☐ Place battery into UAV frame and secure with velcro
  - ☐ Plug the battery into the ESC
  - ☐ Turn the switch on at the bottom of the frame to power the UAV
  - ☐ Verify that the transmitter on the UAV is transmitting by ensuring the ground station has a camera feed
  - ☐ Turn off the switch at the bottom of the frame to deactivate the UAV
- ☐ Rover Activation
  - ☐ One battery will be placed in each of the links
  - ☐ Secure the batteries with zip ties around each link
  - ☐ Turn on the rover by plugging each battery into the PCB
  - ☐ Inspect LED on the corner of the board by the GPS to verify that the Rover is receiving power
  - ☐ Ensure connection with the Ground Station and verify motor functionality by manually inputting commands to the rover when it is outside of the launch vehicle
- ☐ Deployment Activation
  - ☐ Place battery at the bottom of the sled and plug into the microcontroller to turn on the deployment electronics
  - ☐ Ensure connection to the Ground Station by manually inputting commands to retract and extend the solenoids
  - ☐ Retract the solenoids before placing items into the payload bay
- ☐ Platform Assembly
  - ☐ Properly slide UAV into UAV Sled by orienting it so that the struts go through the holes in the sled
  - ☐ Place UAV Sled on platform such that pins go through the holes in the UAV struts
  - ☐ Ensure solenoid pins extend into UAV sled by sending a signal to the system from the Ground Station. This will lock in the UAV
  - ☐ Place Rover body onto such that the sample retrieval system is facing towards the nose cone
  - ☐ Align the holes in the rover body with the pins in the solenoids

☐ Extend the pins so that the rover is secured in the platform

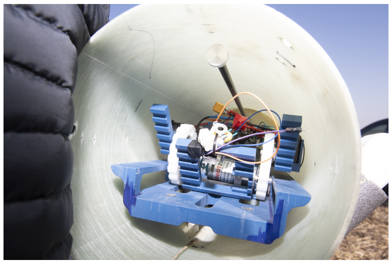


Figure 116: Retention Fully Assembled in the Vehicle

☐ Insertion into Payload Bay

☐ Insert the platform onto the guide rails fixed to the bulkhead at the back of the payload bay

☐ Insert 1/4-20 bolts and nuts through the platform to secure it to the guide rails

☐ Tie the 1/8" kevlar cord connected to the back of the payload bay to the eyebolt on the fore bulkhead in a bowline knot. Ensure these connections are completely secure.

Figure 117: Bowline Knot for Payload Bulkhead Eyebolt

☐ Tie the other unconnected piece of 1/8" kevlar cord to both the payload bulkhead eyebolt and the nosecone eyebolt on the telemetry bulkhead in a bowline knot. Ensure these connections are completely secure.

⚠**Failure to check all knots attached to the fore payload bulkhead could cause retention failure after separation**

☐ Attach the fore bulkhead by aligning the blocks to the platform

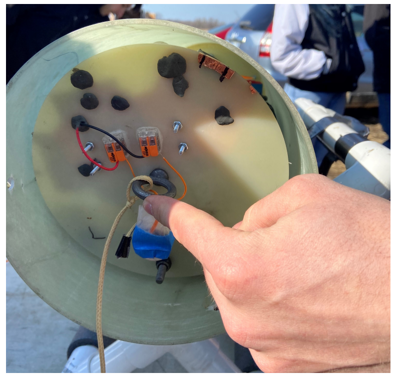


Figure 118: The Payload Fore Bulkhead Aligned in Payload Bay

LSRS Post-Flight Checklist

Required Personnel: LSRS Lead, Safety Officer
Required PPE: Fire proof battery case

⚠ **After landing the ejection charges may not have detonated or batteries could catch fire. It is important to assess the landed components carefully**

- ☐ Ensure nose cone charge has proerly fired
- ☐ Document state of LSRS with photographs
- ☐ Make any notes regarding mission success/failure
- ☐ Inspect batteries for any damage
- ☐ Inspect all systems for any damage
- ☐ Empty sample retrieval system
- ☐ Turn off the ROD solenoids and rover by disconnecting batteries
- ☐ Turn off UAV by turning off the switch and disconnecting battery
- ☐ Store all disconnected electronics in ESG bags
- ☐ Properly store LiPo batteries in LiPo battery bags

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

Safety Officer: ______________________________ Date: __________

Troubleshooting Checklist

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.
- ☐ Remove the shear pins from the rocket and separate the sections.
- ☐ Remove the parachute, Nomex protector and shock cords from the rocket.
- ☐ Separate the fin can and recovery tube
- ☐ 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.

Tight Fitting Parachute

If the folded parachute is too tight inside the parachute bay, it may not slide out upon separation, which will result in the vehicle descending much faster than normal.

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

- ☐ Remove the parachute from the vehicle
- ☐ Unfold the parachute and refold according to the procedure outlined in the Recovery Checklist.
- ☐ 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 the procedure outlined in the

Recovery Checklist. A layer of talcum powder on the parachute and coupler may also help the parachute to slide out.

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 the next step.

⚠ **The remaining steps should only be performed by the Launch Manager.**

- ☐ 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 Launch Manager for further troubleshooting.

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. Failure to do so could result in an unintentional ignition.**

⚠ **These next steps should only be performed by the Launch Manager.**

- ☐ Separate the fin can and recovery tube
- ☐ 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.

Punctured or damaged battery

Extremely dangerous, if believed to be damaged at all, battery should not be used AT ALL. While the team is still at the launch site, the battery should be housed in a fire proof battery case. The battery should then be disposed of according to University Standards upon return.

⚠ **PPE required are heat resistant gloves and safety glasses**

☐ If battery is believed to be damaged, approach with caution, as it should be considered an exploding hazard. PPE must be worn when handling the defective battery.

☐ 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

7 Project Plan

7.1 Testing

The testing plans and progress for each subsection are summarized in Table 42. Testing manuals for each test are included in Sections 7.1.1-7.1.6

Table 42: Testing Plan

System	Test	Test ID	Requirements Verified	Status
Launch Vehicle	Subscale Wind Tunnel Test	LVT1	2.17.1	Pass
	Subscale Launches	LVT2	2.17.1	Pass
	Bulkhead Solids Testing	LVT3	V.12, 2.4	Complete
	Full Scale Vehicle Test Flight	LVT4	V.4, V.11, 2.1, 2.4, 2.6, 2.16, 2.18	Complete
	Shake Test	LVT5	2.4	Complete
	Center of Gravity Test	LVT6	V.10, 2.18	Complete
Recovery	Black Powder Testing	RT1	3.2	Complete
	Altimeter Testing	RT2	3.4	Complete
	Telemetry Range and Antenna Test	RT3	R.11, R.12, 3.12	Complete
	Full Scale Recovery	RT4	R.3, 2.18, 3.1.1	Complete
	Failed Deployment Charge Safe	RT5	R.6	Complete
	Altimeter Battery Life	RT6	2.7	Complete
Payload: Deployment	Free Rotation of Platform	PDT1	P.21	Pass
	Solenoid Actuation	PDT2	P.22	Pass
	Solenoid Actuation with Signal from Rover	PDT3	P.22	In progress
	Vibration & Motion Restriction of Rover and UAV	PDT4	P.20, P.22, 4.3.7	Pass
	Deployment of Rover and UAV	PDT5	P.22	In Progress
	Full Scale	PDT6	P.20-P.22, P.25, 2.18.2, 4.3.7	Complete
	Nose Cone Ejection Ground Test	PDT7	P.25, 2.18.2, 4.3.7	Complete
	Retention Battery Life	PDT8	2.7	Complete
Payload: UAV	Manual Flight	PUT1	P.14	Complete
	Autonomous Flight	PUT2	P.13	Complete
	Manual Override	PUT3	P.23	Complete
	Transmit Video to G.S.	PUT4	P.23	In progress
	Detection of Simulated CFEA	PUT5	P.23	In Progress
	Landing Location Identification	PUT6	P.24	In Progress
	Detection of CFEA with UAV	PUT7	P.23	In Progress
	Flight Time	PUT8	P.6	In progress
Payload: Rover	Electrical Connections	PRT1	P.4	In Progress
	Manual Drive	PRT1	P.7	In Progress
	Autonomous Drive	PRT3	P.7	In Progress
	Manual Override Test	PRT4	P.7	In Progress
	Terrain Navigation	PRT5	P.2, P.3	In Progress
	Turning Capabilities	PRT6	P.2	In Progress
	Full Scale Structural Integrity	PRT7	2.18.2	Complete

System	Test	Test ID	Requirements Verified	Status
	Rover Battery Life	PRT8	P.6, 2.7	In Progress
	Sample Retention	PRT9	P.17, 4.3.4	In Progress
	Sample Retrieval Time	PRT10	P.15, 4.3.3	Inc Progress
	Sample Retrieval Deployment	PRT11	P.16, P.18, 4.3.2	In Progress
	Retrieval Deployment Calibration	PRT12	P.16, 4.3.2	In Progress
ABS	Subscale Launch	ABT1	V.4	Complete
	Mechanism and Motor Ground Testing	ABT2	V.4	Complete
	Control Structure Ground Testing	ABT3	V.4	Complete
	Electromagnetic Interference Test	ABT4	V.4	Complete
	Pre-Launch Disturbance Test	ABT5	V.4	Complete
	ABS Demonstration Flight	ABT6	2.18.1.4, V.4	Complete

7.1.1 Launch Vehicle Testing

LVT1: Subscale Wind Tunnel Testing

Objective:
To obtain an experimental drag coefficient for the launch vehicle with air braking tabs at (1) no extension, (2) half-extension, and (3) full-extension. Drag may be scaled to model full-scale vehicle flights.

Tested Items:

- Subscale vehicle with no tab extension (no actuation)
- Subscale vehicle with half tab extension (half-actuation)
- Subscale vehicle with full tab extension (full-actuation)

Motivation:

- To ensure that the subscale launch vehicle can withstand the wind conditions it may face during testing
- To calculate the airspeed around the rocket, the induced drag, the drag coefficient, and Reynold's number.

Success Criteria:

LVT1 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
2.17.1.	The subscale model should resemble and perform very similarly to the full-scale model.	Success - Dimensionless parameters, such as coefficient of drag, are consistent between wind tunnel and simulated data. Fail - Wind tunnel data is inconsistent with theoretical and subscale data.	Pass

Test Procedure:

Equipment:

- 2 ft x 2 ft x 6 ft subsonic tunnel in Hessert Laboratory with test article mount (see schematic in Figure **??**)
- Aerodynamics Lab DAQ Utility
- Sub-scale vehicle
- 3D printed ring simulating unactuated air braking tabs
- 3D printed tabs simulating air braking tab half-actuation
- 3D printed tabs simulating air braking tab full-actuation
- 3D printed bracket

Setup:

Create CAD model of bracket to mate with the test article mount inside the wind tunnel (used to suspend the launch vehicle in the subsonic wind tunnel). 3D print bracket. Epoxy bracket inside the body tube of the launch vehicle. Perform nine 10 second tests per level of actuation (no tabs, half tabs, and full tabs)

Safety Notes:

- Ensured subscale test article was completely intact via visual and shake tests for damage
- Ensured test section was clear
- Ensured wind tunnel door was sealed shut prior to running tests
- Team members stood at a safe distance from the wind tunnel when testing was underway

Procedure:

1. Attach 3D printed ring simulating unactuated air braking tabs to the subscale vehicle
2. Insert vehicle into wind tunnel, parallel to the flow
3. Connect the epoxied bracket on the launch vehicle to the test article mount inside the wind tunnel
4. Close the wind tunnel door, ensuring its seal
5. Step away from door
6. *I*ncrease wind tunnel airspeed speed to ~1.3 m/s under the supervision of NDRT graduate advisor Emma Farnan
7. Record data at given speed for 10 s
8. Continue to increase the wind tunnel airspeed under the supervision of Emma Farnan to ~3.6, 7.5, 11.6, 15.7, 20.0, 24.2, 28.6, and 32.9 m/s and record data at 10 s at each speed
9. Decrease wind tunnel airspeed to 0 m/s under supervision of NDRT graduate advisor, Emma Farnan
10. Disconnect launch vehicle from test article mount
11. Remove launch vehicle from wind tunnel
12. Attach 3D printed tabs simulating air braking tab half-actuation to subscale vehicle
13. Repeat steps 2-

14. Attach 3D printed tabs simulating air braking tab full-actuation to subscale vehicle
15. Repeat steps 2-26
16. Shut down wind tunnel under supervision of NDRT graduate advisor, Emma Farnan

Results: The tests involving tab extensions yield meaningful data. The data collected showed that the tabs had a negligible effect on drag. In some cases, the tabs reduced drag. Reasons for the discrepancy include noise and a thick boundary layer due to low speed winds (testing had a maximum airspeed of 32.9 m/s while subscale simulations had a maximum airspeed of 89.9 m/s). Data collected for the drag coefficient of the launch vehicle itself is useful because the thick boundary layer launch vehicle does not affect the rocket in its entirety.

LVT2: Subscale Launches

Objective:
Verify the stability and geometry of the launch vehicle.

Tested Items:

- Sub-scale launch with no tab extension
- Sub-scale launch with half tab extension
- Sub-scale launch with full tab extension

Motivation:

- To verify the flight characteristics of the proposed launch vehicle
- To verify the effectiveness of the ABS drag tabs

Success Criteria:

LVT2 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
2.17.1.	The subscale model should resemble and perform very similarly to the full-scale model.	Success - The subscale vehicle is launched and recovered AND is undamaged and relaunchable. Fail - Launch vehicle becomes damaged due to launch or recovery such that it cannot be launched again in the same day OR launch vehicle deviates significantly from expected launch profile.	Pass

Test Procedure:

Equipment:

- Subscale vehicle
- Launch rail

- Subscale Motor

Setup:
Attach recovery shock cord to fin can and bottom of recovery tube. Insert fire retardant, biodegradable insulation into top of fin can. Fold parachute and insert into top of fin can. Join fin can and recovery tube via coupler for a friction fit. Insert motor into motor mount and secure with motor retainer. Activate sensors and insert into top of recovery tube. Join payload tube and recovery tube via coupler and secure with set screw.

Safety Notes:

- Only launch manager can handle motor
- Listen to RSO instructions at all times

Procedure:

1. Slide rail buttons onto launch rail, and set launch rail pitch
2. Secure ignition wiring onto motor
3. Launch vehicle
4. Recover landed vehicle and retrieve flight data from sensors

Results: The subscale launch vehicle successfully launched and landed for three separate flights on December 7, 2019. Altimeter data for each sensor was collected and the vehicle followed the expected flight path. Full subscale results can be seen in Section **??**.

LVT3: Bulkhead and Centering Ring Solids Testing

Objective:
To verify bulkhead and centering ring material selection for flight stresses.

Tested Items:

- 0.1875 in. G10 fiberglass bulkhead

- 0.125 in. G10 fiberglass centering ring

Motivation:

- To guide decision on bulkhead and centering ring material and thickness selection
- To ensure that bulkheads can sustain their intended loads without damage

Success Criteria:

LVT3 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
V.12	Epoxied bulkheads are able to hold the load of drogue and main parachute deployments.	Success - Epoxied angled bulkheads must be able to hold comparable loads to straight epoxied bulkheads. Fail - Epoxied angled bulkheads do not hold comparable loads to straight epoxied bulkheads.	Complete
2.4	Vehicle must be able to be recovered without damage and relaunched in the same day.	Success - Centering rings are able to withstand the maximum thrust of the L1395 motor which is 400 lbs Fail - Centering rings are not able to withstand the maximum thrust of the L1395 motor which is 400 lbs.	Complete

Test Procedure:

Equipment:

- 6” diameter carbon fiber couplers with epoxied bulkheads
- 6” diameter carbon fiber couplers and 3” diameter motor retainer tubing with centering rings epoxied in
- 2 2” washers
- 3/8” bolt and nut
- Load frame

Setup: Bulkheads: Mix epoxy and spread out in a ring in the coupler. Slide bulkhead over ring. Fillet each side of the seam with epoxy. Make sure bulkhead is leveled or at designated angle by measuring with a level or ruler (if at angle). Leave to dry for 24 hrs. Epoxy the supports in and leave to dry another 24 hrs. Place a 2” washer on either side of the bulkhead and secure with a 3/8” bolt and nut.
Centering Rings: Mix epoxy and spread out in a ring around the motor retainer tubing. Slide the centering ring around the tube and fillet each side with epoxy. Make sure that the centering ring dries level by using a level. Once the centering ring is stiff, put a ring of epoxy around the inside of the coupler. Slide centering ring into the coupler over the ring of epoxy and fillet each side. Leave to dry for 24 hrs.

Safety Notes:

- It is unsafe to handle epoxy without gloves
- Wear safety glasses during testing in the load frame
- Stand a safe distance away from the force frame while testing is underway, as coupler and bulkhead have potential to break and components may come loose

Procedure:
Bulkhead

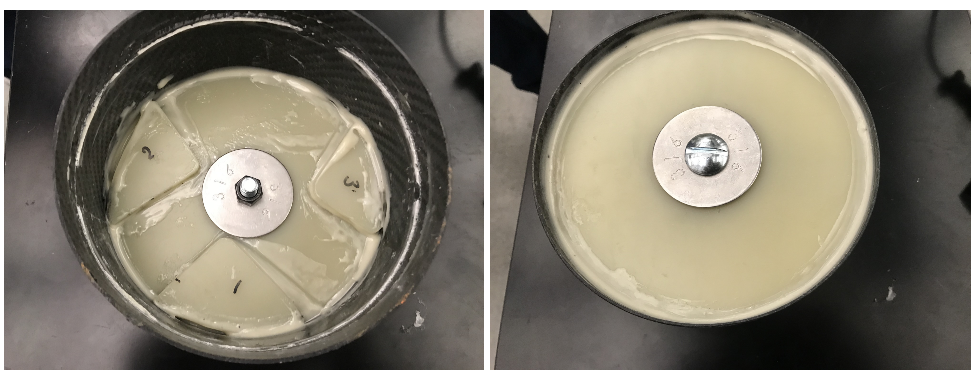
1. Make sure the head of the load cell is the cylindrical 1/4” head

2. Load coupler and bulkhead onto force frame
3. Make sure that the head is centered over the center of the bolt in the bulkhead
4. Gradually increase force upon bulkhead until signs of structural failure show, such as cracked bulkhead or separation at the epoxy seam
5. Record force at failure
6. Repeat for each bulkhead

Centering Rings

1. Load coupler and centering ring system onto force frame
2. Gradually increase force upon inner tubing until signs of structural failure show, such as cracked bulkhead or separation at the epoxy seam
3. Record force at failure
4. Repeat for each bulkhead

Results: Since the team has used similarly sized bulkheads in the past, the team was confident in the strength of the fiberglass bulkheads. However during construction, the payload bulkhead became slightly angled about 1/4" off-center inside the payload tube. Due to this, the team performed solids testing on the new slanted bulkhead to validate its strength. The bulkhead was constructed according to the same measurements as the one inside the payload bay as seen in Figure 119. In addition a straight 3/16" fiberglass bulkhead was tested and an unsupported angled bulkhead was tested.



(a) Bottom of Angled Bulkhead (b) Top of Angled Bulkhead

Figure 119: The Angled Bulkhead

In each bulkhead test, the bulkhead was centered in the machine as such. The lower crosshead moved at a slower speed. The team recognizes that this static loading will not be entirely indicative of the dynamic loading in flight, but the static loading will allow comparison to previously successful flight hardware in past years.

Figure 120: Bulkhead Testing Set-up

In this test the straight bulkhead reached a maximum load of 275 lbs. The angled bulkhead without supports reached a maximum load of 194 lbs. The angled bulkheads with supports reached a maximum load of 282 lbs. Since the supports added a significant amount of strength to the bulkhead and the team has verified this thickness and material has worked in the past when placed straight in the body tube, the team is confident that the supports add sufficient strength to the angled bulkhead to be suitable for flight. Figure 121 shows the failure mode for the angled bulkhead with supports. As seen in the image, the supports sheared off first, then followed by the epoxy around the bulkhead.

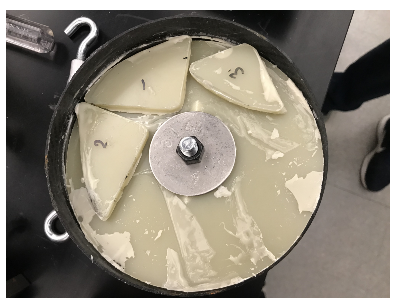


Figure 121: Angled Bulkhead with Supports Failure

For the centering rings, the centering ring system which contained one centering ring was placed on the plate in the the center and a 2.75” crosshead pushed on a 3” weight to center the force on the inner motor retainer tube seen in Figure 122.

Figure 122: Centering Ring System in Test Machine

This test resulted in a maximum force of 163 lbs. The epoxy sheared on the outer tubing and the fiberglass began to crack as seen in Figure 123. Since the fin can contains three centering rings distributing the force, this measurement exceeds the minimum threshold of a maximum of 400 lbs. This provides a worst-case factor of safety of 1.23, which is sufficient for flight.

Figure 123: Centering Ring Failure

LVT4: Full Scale Test Flight
Objective:
To validate the launch vehicle's stability, structural integrity, recovery systems, payload systems, and the team's ability to prepare the launch vehicle for flight.

Tested Items:

- Vehicle airframe performance
- ABS performance
- LSRS performance
- Telemetry module performance
- Recovery system performance
- Launch procedure streamline

Motivation:

- To ensure a successful mission with all requirements met and all subsystem designs validated

Success Criteria:

LVT4 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
V.4	The vehicle is designed to reach a 4,444 ft altitude.	Success - The vehicle reaches the target altitude. Fail - the vehicle does not reach the target altitude within a reasonable margin.	Partial Success
V.11	The motor selection must tend towards overshooting rather than undershooting the target apogee.	Success - Launch vehicle is able to overshoot target apogee. Fail - Launch vehicle is not able to reach tatget altitude with selected motor.	Success
2.1	The vehicle will deliver the payload to an apogee altitude between 3,500 and 5,500 ft AGL	Success - Payload is delivered to an altitude within the acceptable range given. Fail - Launch vehicle delivers the payload to an apogee outside the acceptable range.	Success
2.4	The launch vehicle will be designed to be recoverable and reusable.	Success - Launch vehicle can be launched more than once after only loading a new motor and resetting electronics and parachutes. Fail - Launch vehicle needs structural repair before it can be flown again.	Success
2.6	The launch vehicle will be capable of being prepared for flight at the launch site within 2 hrs of the time the FAA flight waiver opens.	Success - Launch vehicle is prepared within the acceptable time frame. Fail - Launch vehicle is not able to be prepared within the acceptable time frame.	Success
2.16	The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit.	Success - The launch vehicle meets the minimum off-rail exit velocity. Fail - The launch vehicle does not meet the minimum off-rail exit velocity.	Success
2.18	All teams will complete demonstration flights as outlined in Req. 2.18.1-2.18.2.4	Success - Launch confirms that hardware is functioning properly AND flight is stable AND no damage is sustained AND payload system accomplishes simulated mission. Fail - Hardware does not function properly OR flight is unstable OR damage is sustained OR payload is not flown OR payload does not accomplish mission successfully	Success

Test Procedure:

Equipment:

- Nose cone
- Payload bay
- Transition Section
- Recovery Tube
- Fin can
- Shear pins
- Locking screws
- Motor (2)

- Motor Casing
- Motor Retainer
- Eyebolts
- Camera
- Washers
- Nuts
- Screws
- Motor retainer

Setup:

Safety Notes:

- Only launch manager can handle motor
- Only launch manager can handle black powder
- When launch manager is handling motor or black powder, all others are to stand a safe distance away
- Everyone must listen to range officer at all times

Procedure:

1. See Section 6.3 for the full-scale test procedures and checklists

Results: Successful test flights performed on 2/16/2020 and 2/23/2020. See section 5 for full results and flight analysis.

LVT5: Shake Test

Objective:
To verify that all vehicle components are secured to the airframe properly.

Tested Items:

- Vehicle airframe components

Motivation:

- To prevent any launch vehicle components from becoming damaged in flight

Success Criteria:

LVT5 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
2.4	Launch vehicle is not damaged in flight and can be relaunched.	Success - Launch vehicle is fully assembled and no components rattle around. Fail - One or more components are rattling around.	Success

Test Procedure:

Equipment:

- NDRT Launch Vehicle

Setup:

- Assemble vehicle following the procedure described in LVT4

Safety Notes:

- Shaking launch vehicle is prone to dropping and therefore can potentially become damaged
- Anyone in general vicinity of launch vehicle can be hit by shaking vehicle

Procedure:

- Shake launch vehicle
- Listen for any rattling parts

Results: Results to be collected prior to launch.

LVT6: Center of Gravity Test

Objective:
To verify that actual vehicle stability aligns with simulated vehicle stability.

Tested Items:

- Center of gravity

Motivation:

- To prevent launch vehicle from being over or under stable during flight

Success Criteria:

LVT6 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
2.18	Vehicle must have stable flight	Success - Launch vehicle center of gravity places the stability margin between 2 and 3. Fail - Launch vehicle center of gravity places the stability margin outside of the acceptable range.	Success

Test Procedure:

Equipment:

- NDRT Launch Vehicle

- Laser cut vehicle stand

Setup:
Assemble vehicle following the procedure described in LVT4

Safety Notes:

- N/A

Procedure:

1. Place launch vehicle on stand and find the spot where the vehicle balances on the stand
2. measure distance to tip of nosecone from that location
3. calculate actual stability margin

Results: Results to be collected prior to launch.

7.1.2 Recovery Testing

RT1: Black Powder Separation Testing

Objective:
To verify that the calculated quantities of black powder are sufficient to shear the retaining shear pins and separate the vehicle sections.

Tested Items:

- Deployment of the recovery parachutes
- Nose Cone Ejection for payload deployment

Motivation:

- Ensure personnel safety during vehicle launch
- Verify accuracy of black powder calculation techniques
- Ensure success of payload deployment

Success Criteria:

RT1 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
3.2	Each team must perform a successful ground ejection test for both the drogue and main parachutes.	Success - All vehicle sections completely separate after black powder ignition and all parachutes end the test outside the vehicle. Fail - Vehicle sections do not completely separate or at least on parachute remains inside the vehicle after test conclusion.	Complete

Test Procedure:

Equipment:

- Fully constructed vehicle airframe
- # 2-56 Nylon shear pin (x10)
- ABS Removable Bulkhead and Screws
- All components of CRAM
- 3/8 in. Eyebolts (x2)
- Recovery Coupling Nut
- Wago 221 Lever Nuts (x2)
- Main Parachute
- Drogue Parachute
- Pilot Chute
- 35 ft Shock Cord (x2)
- 3/8 in. Quicklinks (x6)
- Nomex Blanket (x2)
- Deployment Bag
- Shooter's wire, approx. 45ft
- Sealing Clay
- 9V Battery

Setup:
Fold the main and drogue parachutes according to the parachute folding procedures described in Section . Fold the two shock cords according to the shock cord folding procedures described in Section . Secure the ABS removable bulkhead in the fin can using the associated screws

Safety Notes:

- This test involves the use of black powder, a potentially dangerous energetic. The team launch manager, Dave Brunsting, should prepare and install all black powder charges, as well as intitiate the charges during testing.
- During black powder ignition, a perimeter of at least 10 ft. around the vehicle must be maintained by all personnel. Larger perimeters may be established at the discretion of the launch manager.

Procedure:

1. Tape two 6 in. pairs of shooter's wire to one of the switch port cutouts on the inside of the CRAM body, such that they are both capable of being accessed from outside of the rocket after CRAM installation. Ensure that each pair of shooter's wire is twisted together at the switch port.
2. Run one pair of shooter's wire through one of the wire holes in the CRAM top bulkhead. Run the other pair through a wire hole in the CRAM bottom bulkhead.

3. Bolt the CRAM bulkheads on to the CRAM body and thread the eyebolts into the inset coupling nut.
4. Seal any holes remaining holes in the top or bottom bulkheads using clay.
5. Have the team launch manager prepare three black powder charges: a 4.5g charge for the main parachute compartment and two 1 g charges, one for the drogue compartment and one for nose cone ejection.
6. Have the team launch manager install the black powder charges in the CRAM charge wells, connecting to the fed shooter wire using the Wago lever nuts.
7. Twist the assembled CRAM into the matching adapter in the recovery tube.
8. Using quicklinks, connect both shock cords to their respective eyebolts. The drogue harness should connect between the CRAM bottom bulkhead and the ABS bulkhead, and the main harness should connect between the CRAM top bulkhead and the main parachute bulkhead, in the transition section of the vehicle.
9. Connect the folded parachutes to their respective shock cords using quicklinks.
10. Insert the parachutes into the vehicle, taking care to ensure that the parachutes are completely covered by either a Nomex blanket or deployment bag.
11. Assemble the rest of the vehicle.
12. Insert shear pins into the drilled holes in the airframe, two between the recovery tube and the fin can and four between the recovery tube and the transition section.
13. Connect two 15 ft lengths of shooter wire to the exposed wires taped to the CRAM switch ports.
14. Rest the vehicle horizontally on wood supports.
15. Establish a minimum 10 ft. perimeter around the vehicle
16. The launch manager should connect the first pair of shooter wire to a 9v battery, igniting the drogue ejection charge.
17. Repeat with the main parachute ejection charge.
18. When the team launch manager has given the all-clear, approach the vehicle to check for successful separation and main parachute deployment.
19. Repeat steps 1-18 with the Nose Cone ejection charge, taking all the same safety precautions and following the direction of the team launch manager.

Results: On the morning before the Vehicle Demonstration Flight on February 16, black powder separation tests were performed on both the main and drogue parachute compartments. On the recommendation of our launch manager, two 5g black powder charges were prepared and installed in the vehicle, with one charge installed on the main parachute side of the CRAM, and one on the drogue parachute side. The drogue parachute charge was then ignited, following test procedure. Figure 124 shows both the main and drogue charge separation, using 5 gram charges on each of the compartments.

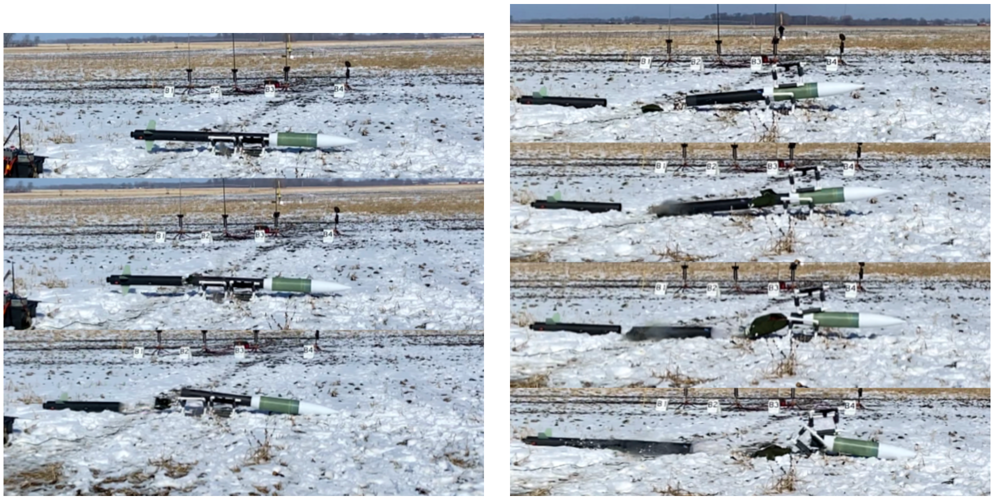


Figure 124: Black Powder Separation Testing

As both compartments fully separated during testing without damage to either the airframe or the parachute rigging, the black powder test was deemed a success and the tested 5 grams of black powder was used in flight to separate the vehicle.

RT2: Altimeter Testing

Objective:
To ensure the altimeters are properly powered and respond as expected to flight events.

Tested Items:

- Featherweight Raven3
- Perfectflite Stratologger SL100

Motivation:

- Ensure personnel safety during launch
- Verify reliability of recovery electronics

Success Criteria:

RT2 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
3.4	Both drogue and main parachute deployment must be initiated by a commercial altimeter.	Success - The both the drogue and main e-match substitutes successfully light on both altimeters. Fail - At least one e-match substitute does not light at its expected time	Complete

Test Procedure:

Equipment:

- Raven3 Altimeter
- Stratologger SL100 Altimeter
- Assembled Altimeter Perfboards w/ Attached Switches (x2)
- 3.7 V LiPo Batteries, 170 mah (x2)
- Small Incandescent Bulbs (x4)
- Stranded Wire, 6 in. (x8)
- USB-MicroUSB cord
- Stratologger Interface Adapter
- Laptop with Perfectflite DataCap software and Featherweight Iterface Software

Setup:
Ensure that the recovery switches are already installed and soldered in place on the Altimeter Perfboards, ready to accept the altimeters. Install the altimeters onto the altimeter perfobaord with the attached screw terminals. Use the stranded wire to connect each of the small incandecent bulbs to the altimeters, in the places described in the recovery circuit diagrams. These will act as e-match substitutes.

Safety Notes:

- This test involves the use of lithium-polymer batteries, which can be volatile and potentially dangerous if used incorrectly.
- Never short the leads on a LiPo battery.
- Keep the batteries in a fire-proof LiPo bag when not in use.

Procedure:

1. Plug each battery's JST connector into its associated port on both of the perfboards.
2. Power on the altimeters using the recovery activation switches.
3. Plug the Raven altimeter into the laptop using the MicroUSB cable and start the Featherweight Interface Software.
4. Begin a simulated flight using the altimeter software.
5. Watch the drogue e-match substitute. For a successful test, it should light up as the simulated vehicle passes its apogee.

6. After the simulated vehicle passes its apogee, watch the main e-match substitute. In a successful test, this should light up before the simulated vehicle reaches 500 ft. AGL.
7. Repeat steps 3-6 using the Stratologger altimeter in place of the Raven, The Stratologger Interface Adapter in place of the MicroUSB cable, and the Perfectflite DataCap software in place of the Featherweight interface software.

Results: Altimeter testing on all commercial flight altimeters used in the vehicle was performed on Saturday, February 15. In testing the primary Raven3 altimeter, the incandescent e-match substitutes successfully lit up as the false data supplied by the computer program reached apogee, and as it reached 600ft AGL, as programmed. Similarly, the secondary Raven3 and Stratologger lit the e-match substitutes at the programmed times in the simulated trajectory, successfully qualifying the programming and wiring of all the recovery altimeters.

RT3: Telemetry Range and Antenna Test

Objective:
To ensure that the telemetry system will reliably transmit data from the launch vehicle during the entirety of the mission.

Tested Items:

- Receiver module
- Receiver patch antenna
- Transmitter module prototype module
- Transmitter dipole antenna
- Receiver monopole antenna

Motivation:

- To ensure reliable transmission over the range necessary for the mission.

Success Criteria:

RT3 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
2.18.1	Demonstration flight must prove proper hardware functioning including tracking devices.	Success - At 1 mile, the transmission success rate is above 90% AND the received packet data error rate is below 10%. Fail - At 1 mile, the transmission success rate is below 90% OR the received packet data error rate is below 10%.	Complete, Pass

Test Procedure:

Equipment:

- 2 Laptops
- Receiver module
- Transmitter module
- Transmitter dipole antenna
- Receiver patch antenna
- Receiver dipole antenna

Setup:
Two transceivers will be placed at various distances and will attempt to transmit packets between the modules. Line-of-sight will be maintained between the transmitter module and receiver module to mimic the line-of-sight transmission that will occur during launch vehicle flight. Transmissions will occur at distances of 0.5 mile and one mile. The antennas for the transmitter and receiver modules will both be placed approximately 5 ft above the ground. They will be powered from the laptops that will be used to collect the data. Because path loss is higher for transmissions close to the ground, this test is expected to be a worst-case scenario in terms of operating conditions.

Safety Notes:

- All LiPo batteries must be transported in fireproof battery bags. Connections should be inspected before testing.

Procedure:

1. Take the two transceiver modules and separate them by approximately 0.5 mi with guaranteed line-of-sight.
2. Position the antennas in the upright position approximately 5 ft above the ground.
3. Attempt to transmit a packet from the transmitter prototype.
4. Check to ensure that the packet was received by the receiver.
5. Save the contents for further analysis.
6. Test transmission for a duration of 1 minute.
7. Repeat the test at 1 mi.
8. Compare the number of received packets to the number of transmitted packets to calculate a packet drop rate using Equation 12.

$$R = 1 - \frac{n}{N} \tag{12}$$

Symbol	Description	Units
R	Drop Rate	%
n	Number of Recieved Packets	packets
N	Number of Transmitted Packets	packets

Results: The results from the Range Test are shown in Figure 43. In both cases, the drop rate was less than 10%, which met the success criteria.

Table 43: Range Test Results

Distance (mi)	Packet Drop Rate
0.5	3.23%
1.00	8.33%

RT4: Full Scale Recovery

Objective:
Fully test the entire recovery system in a flight environment.

Tested Items:

- Recovery Altimeters
- Load-bearing structural connections, such as bulkheads
- Parachute Packing Methodology

Motivation:

- Demonstrate safety and reliability of recovery system
- Facilitate testing of the launch vehicle in a safe manner.

Success Criteria:

RT4 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
2.18.1	Each team must complete a full scale Vehicle Demonstration Flight prior to FRR	Success - Recovery system functions as intended, effectively deploying parachutes at appropriate altitudes to slow and recover the vehicle. Fail - Major component of the vehicle breaks during recovery, or abnormal behavior is observed that could compromise successful recovery in the future.	Complete

Test Procedure:
Check Section 6.3 for full-scale launch procedures pertaining to recovery.

Results:

Results for both the Vehicle Demonstration Flight and Payload Demonstration Flight can be found in Section 5

RT5: Failed Deployment Charge Safe

Objective:
Ensure that black powder charges can be safely and successfully removed from the vehicle in the event of a launch abort, or if unexploded black powder remains in the vehicle after landing.

Tested Items:

- Recovery Activation Switches
- Recovery Wiring

Motivation:

- To ensure team safety in the face of potentially hazardous scenarios.

Success Criteria:

RT5 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
R.6	The recovery system shall be capable of being "safed" after landing, in the event that an ejection charge has failed to deploy.	Success - The e-match substitutes do not light at any point during the test. Fail - The e-match substitutes light at any point during testing.	Complete

Test Procedure:

Equipment:

- Fully mounted and assembled recovery avionics
- Flathead Screwdriver
- Small Incandencent Bulbs

Setup:
Place the small incandescent bulbs in the places where black powder charges would go during a full scale flight. Ensure that the batteries used to power the altimeters are fully charged and the electronics are fully assembled.

Procedure:

1. With the e-match substitutes in place, power on all three recovery altimeters.
2. Listen through the start up sequence of a the altimeters, ensuring proper start up.
3. One at a time, turn off the altimeters using the screwdriver in the rotary switch, looking for the simulated e-matches to light up.

Results: During the course of the test, the e-match substitutes never ignited, indicating that the black powder charges would not be ignited and that the altimeters can be properly safed.

RT6: Altimeter Battery Life

Objective:
Ensure that the altimeter batteries have the capacity to power the altimeters during the entire 2-hour on pad time and throughout the flight.

Tested Items:

- Altimeter batteries

Motivation:

- To ensure proper recovery even in the event of an abnormally long on-pad time.

Success Criteria:

RT6 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
2.7	The launch vehicle and payload will be capable of remaining in launch-ready configuration on the pad for a minimum of 2 hrs without losing the functionality of any critical on-board components.	Success - Altimeters successfully ignite two e-matches after more than two ours in launch-ready mode. Fail - One of the altimeters exits flight-ready mode before two hours is up or fails to ignite the e-matches after the extended on-pad time.	Complete

Test Procedure:

Equipment:

- Fully Assembled Recovery Avionics
- Screwdriver
- Stopwatch
- E-matches

Setup:
Ensure all the recovery batteries are fully charged before the test.

Procedure:

1. Using a screwdriver, turn on all the altimeters. Ensure that they go through their normal

startup sequence.
2. Set a stopwatch for 2 hours.
3. After two hours have passed, perform an altimeter test using e-matches, as described in Section 7.1.2.

Results: The altimeter battery test was performed on Friday, February 14th. In accordance with procedure, the altimeters were left on for 2 hours before attempting an altimeter test. All of the recovery altimeters passed the altimeter test after 2 hours of simulated on-pad time, indicating that the batteries are of sufficient capacity.

7.1.3 Payload: Deployment Testing

PDT1: Free Rotation of Platform

Objective:
To ensure the payload platform can rotate freely with minimal friction inside the payload bay for orientation purposes.

Tested Items:

- Payload platform and bearing system

Motivation:

- To validate the orientation system design and its loaded CG

Success Criteria:

PDT1 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.21	The deployment system must be able to orient with the platform reaching equilibrium at its lowest point with respect to the ground regardless original orientation.	Success - The payload platform freely rotates AND reaches equilibrium at its lowest point. Fail - The platform cannot freely rotate OR does not reach equilibrium at its lowest point	Incomplete

Test Procedure:

Equipment:

- Payload bay tube
- Fore sliding platform
- Aft stationary platform assembly
- Ballast for UAV and Rover
- UAV
- Rover
- Clamps
- Mounting rig
- Solenoids

Setup:

This test will take place in three phases: a simulated rig with ballast, a simulated rig with the UAV and rover, and the full assembly. The setup for the simulated rig will be to have the whole configuration outside the body tube to observe the test and more easily modify it if changes are necessary. This will consist of a sturdy mount that the aft bulkhead will be securely clamped to so that it is completely immobile. The sliding platform will then be secured onto the stationary platform with bolts. Ballast will be taped to the fixture to simulate the UAV and rover. For the second trial, the ballast will be replaced with the UAV and rover. The setup for the full assembly will consist of all the parts being secure within the body tube as they would be in the full scale flight.

Safety Notes:

- Inspect batteries before use. All LiPo batteries not in use should be transported in fire proof battery bags.

Procedure:

1. The system is placed at a random orientation.
2. The platform will be released by hand.
3. When the platform reaches equilibrium, the location will be noted.
4. Repeat this with each configuration.

Results: The test will be completed from March 2-6.

PDT2: Solenoid Actuation

Objective:
To ensure that the solenoids actuate properly for deployment and retention of the Rover and UAV sled.

Tested Items:

- Adafruit Medium Push-Pull Solenoids
- UAV Sled

- Rover Body

Motivation:

- To validate the actuation mechanism of the solenoids
- To verify the solenoid properly fits into the UAV Sled and Rover Body

Success Criteria:

PDT2 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.22	The ROD system restricts motion in all directions until signalled to deploy the Rover and UAV	Success - The solenoids ALL retract out of the pin slots AND remain retracted for 30 s AND then re-extend into the pin slots. Fail - Some OR All solenoids do not retract out of the pin slots OR do not remain retracted for 30 s, OR do not re-extend into the pin slots	Incomplete

Test Procedure:

Equipment:

- Solenoids
- UAV Sled
- Rover Body
- Battery
- Microcontroller
- Clamps

Setup:

This test will have two stages: testing solenoid actuation into the Rover Body and testing solenoid actuation into the UAV sled. A simple code will be written and uploaded to a microcontroller that will retract the solenoids for 30 s and then extend to solenoids for 45 s to allow time for the solenoids to cool. The UAV Sled and Rover Body will first be clamped down and held in place. Then the solenoids will be inserted into the respective pin slots and be clamped down as well. Once the solenoids are in place, they will be connected to the microcontroller.

Safety Notes:

- Inspect batteries before use. All LiPo batteries not in use should be transported in fire proof battery bags.
- Special care will be taken towards the longevity of the solenoid retraction to prevent overheating.

Procedure:

1. The solenoids will be inserted into the pin slots.
2. The retraction program will be initiated on the microcontroller.
3. The time between retraction and extension will be timed.
4. The solenoid pin will be inspected after solenoid extension.

Results: To be completed between March 2-6.

PDT3: Solenoid Actuation with Signal from Rover

Objective:
To ensure that the Rover and Retention electronics are able to communicate properly and that the Retention electronics retract the solenoid pins upon receiving the command from the Rover.

Tested Items:

- Retention PCB
- Adafruit Medium Push-Pull Solenoids
- Rover Electronics

Motivation:

- To verify Retention electronics are able to receive signals from the Rover
- To verify that the solenoids fully retract upon receiving the signal from the Rover

Success Criteria:

PDT3 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.22	The ROD system restricts motion in all directions until signalled to deploy the Rover and UAV	Success - The Retention electronics receive the initiation signal from the Rover AND retract the solenoid pins Fail - The Retention electronics do not receive the initiation signal from the Rover OR the Retention electronics receive the initiation signal AND do not retract the solenoid pins	Incomplete

Test Procedure:

Equipment:

- Retention PCB
- Rover
- Solenoid Pins
- Batteries for electronics

Setup:
This test will have two stages: testing that the Retention electronics can receive signals from the Rover and testing that the solenoids retract when the Retention electronics receive the initiation signal from the Rover. The solenoids will be connected to the Retention PCB and all connects will be inspected that they are correct. Then the Retention PCB will be connected to the Rover using jumper wires and again connections will be inspected to verify they are correct. When all the connections are verified, the batteries that power the electronics will be connected and the electronics will be inspected that they are functioning properly.

Safety Notes:

- Inspect batteries before use. All LiPo batteries not in use should be transported in fire proof battery bags.
- Inspect all electrical connections prior to connecting batteries and verify ground connections.
- Special care will be taken towards the longevity of the solenoid retraction to prevent overheating.

Procedure:

1. A test signal will be sent from the Rover to the Retention PCB to blink a light on the PCB.
2. The PCB will be inspected for the blinking light after the command is sent.
3. The initiation signal to retract the solenoids will be sent to Retention PCB.
4. The solenoids will be inspected for full retraction.

Results: To be completed March 2-6.

PDT4: Vibration and Motion Restriction of Rover and UAV

Objective:
To validate the retention system and ensure the UAV, Rover, and all components will not move during flight.

Tested Items:

- Solenoids
- Stationary platform
- Sliding platform
- UAV sled
- Rover
- UAV
- ROD system

Motivation:

- To ensure that the full payload will be retained during launch, flight, and recovery
- To validate the mechanical fail-safe of the solenoids and that they remain stationary during launch, flight, and recovery

Success Criteria:

PDT4 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.22	The deployment system must restrict motion of the Rover and UAV in all directions until the deployment sequence is initiated.	Success - ALL of the payload components are fully retained. Fail - Some OR all of the components are not fully retained.	Pass
4.3.7	Any part of the payload or vehicle that is designed to be deployed must be fully retained until it is deployed as designed.	Success - ALL of the payload components are fully retained. Fail - Some OR all of the components are not fully retained.	Pass

Test Procedure:

Equipment:

- Solenoids
- UAV Sled
- Rover
- Sliding Platform
- Stationary Platform
- UAV
- Nuts and Bolts

Setup:

The Solenoids will be properly inserted into the slots on the sliding platform. The UAV sled with the UAV and the Rover will be placed into position on the platform and the solenoids will be inserted into the respective slots. The sliding platform will then be slide onto the stationary platform and be secured using the nuts and bolts.

Safety Notes:

- Inspect all ASA components for cracks and deformation.
- Ensure all components are connected securely.

Procedure:

1. Verify all connections and retention pins are properly placed
2. Hold the stationary platform where the bearing would be located
3. Slowly and cautiously rotate the platform
4. Verify minimal motion of the payload Shake the platform in several directions to simulate flight forces
5. Verify minimal motion of the payload and retention of all parts

Results: The test was performed on 2/12/20 and both requirements were met successfully. All parts of the payload were retained when shaken in all directions.

PDT5: Deployment of Rover and UAV

Objective:
To ensure that the Rover and UAV can successfully deploy after landing and orientation.

Tested Items:

- Rover design
- UAV sled & sled/platform interface
- Hope FR RFM95W radio module
- Rover crank mechanism

Motivation:

- To validate the deployment signal reception to initiate Rover motion
- To validate the clearance, friction, and stability of the Rover towing mechanism

Success Criteria:

PDT5 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.22	The Rover and UAV remain retained until receiving the activation signal	Success - The Rover receives the activation signal AND successfully tows the UAV out of the payload bay. Fail - The signal does not activate the Rover OR the Rover cannot successfully tow the UAV out of the payload bay	Incomplete

Test Procedure:

Equipment:

- UAV
- UAV Sled
- Rover
- Sliding Platform
- Stationary Platform
- Solenoids
- Nuts and Bolts
- Ground Station
- Batteries
- Payload Bay

Setup:

The Solenoids will be properly inserted into the slots on the sliding platform. The UAV sled with the UAV and the Rover will be placed into position on the platform and the solenoids will be inserted into the respective slots. The sliding platform will then be slide onto the stationary platform and be secured using the nuts and bolts. The Rover, UAV, and ROD systems will be connected to the respective batteries. The Ground station will be powered on and communication established with each system.

Safety Notes:

- Inspect batteries before use. All LiPo batteries not in use should be transported in fire proof battery bags.
- Special care will be taken towards the longevity of the solenoid retraction to prevent overheating.

Procedure:

1. Verify all connections and retention pins are properly placed
2. Verify proper connection between components
3. Initiate deployment sequence

Results: To be completed between March 2-6.
PDT6: Full Scale

Objective:
To ensure that the ROD System can withstand flight forces and successfully retain and orient the LSRS.

Tested Items:

- Sliding Platform
- Rail Platform
- Aft-Bulkhead
- Orientation Bearing
- Nuts and Bolts
- UAV-Sled
- UAV Frame
- Rover Mechanical Components

- Adafruit Medium Push-Pull Solenoids
- Stratologger SL100 Altimeter
- Fore-Bulkhead
- 1/8 in. Kevlar Tether

Motivation:

- To validate the strength of the 3-D printed parts, bulkheads, and solenoids during main deployment.
- To verify that the altimeter correctly ignites the blackpowder charge at 400 ft AGL after main deployment.
- To verify that the orientation system properly orients the LSRS after vehicle flight.

Success Criteria:

PDT6 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.21	The Deployment system must be able to correctly orient the Rover and UAV regardless of the landing position of the upper section of the vehicle.	Success - The LSRS is correctly oriented such that the sliding platform is parallel with the ground Fail - The LSRS is incorrectly oriented such that the Rover and UAV are incapable of deploying.	Fail
P.22	The Deployment system must restrict motion of the Rover and UAV in all directions until the deployment sequence is initiated.	Success - The Rover and UAV remain in the same position on the sliding platform throughout vehicle flight and recovery. Fail - The Rover and UAV shift during flight OR the retaining pins slip from the pin holes in the UAV-Sled or Rover body.	Pass
P.25	The nose cone must eject after main parachute deployment at 400 ft.	Success - The nose cone is jettisoned from the vehicle at 400 ft AGL AND after main has deployed. Fail - The nose cone fails to jettison OR the nose cone is jettisoned prematurely before main has deployed OR the nose cone is jettisoned lower than 400 ft AGL.	Pass
4.3.7	Any part of the payload or vehicle that is designed to be deployed, whether on the ground or in the air, must be fully retained until it is deployed as designed.	Success - The nose cone remains attached to the Launch Vehicle until after main has deployed and the Launch Vehicle is 400 ft AGL AND the LSRS is retained in the Payload Bay throughout vehicle flight and recovery Fail - The nose cone is jettisoned before main has deployed OR at an altitude lower than 300 ft AGL OR the LSRS is not retained in the Payload Bay throughout vehicle flight and recovery	Pass

Test Procedure:

Equipment:

- Nose cone
- Four 4-40 Shear Pins
- Payload Bay with integrated Rail Platform
- Sliding Platform with integrated solenoids
- Nuts and Bolts
- Rover
- UAV
- Fore-Bulkhead with attached tether chord
- Batteries for electronics

Setup:
The UAV will be placed into the UAV-Sled and integrated with the sliding platform ensuring all retaining pins and solenoids are in place. The Rover will then be placed on the sliding platform and the solenoid pins inserted into the Rover Body. The platform will be inspected to verify all retaining pins are fully inserted into the UAV and Rover. The sliding sled will then be placed into the Payload Bay using the rails of the rail platform. Bolts and lock-nuts will then secure the sliding platform to the rail platform.

Safety Notes:

- This test involves the use of black powder, a potentially dangerous energetic. The team launch manager, Dave Brunsting, should prepare and install all black powder charges, as well as intitiate the charges during testing.
- Inspect batteries before use. All LiPo batteries not in use should be transported in fire proof battery bags.

Procedure:

1. Inspect and verify that the LSRS and all components are securely retained in the Payload Bay.
2. Place the fore-bulkhead on the LSRS with the stoppers in the corners of the sliding platform.
3. Place and secure the nose cone onto the Payload Bay using four 4-40 shear pins.
4. Walk the Launch Vehicle to the launch stand.
5. Turn on the nose cone altimeter.

Results: The test was performed on 2/23/2020 and all major components performed as designed. The LSRS was successfully retained throughout vehicle flight and recovery and the nose cone was jettisoned from the vehicle after main deployment at an altitude of 400 ft AGL. The orientation system failed to correctly orient the LSRS due to an increase in friction between the platform stand off and the interior of the Payload Bay.

PDT7: Nose Cone Ejection Ground Test

Objective:
To ensure that the nose cone will be successfully jettisoned from the launch vehicle during recovery.

Tested Items:

- Nose cone
- Fore-bulkhead
- Black-powder calculations
- LSRS

Motivation:

- To verify calculated amount of black-powder will jettison the nose cone from the vehicle.
- To verify that the LSRS can withstand jettison forces.

Success Criteria:

PDT7 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.25	The nose cone must eject after main parachute deployment at 400 ft.	Success - The nose cone is successfully jettisoned from the Payload Bay when the black-powder is ignited. Fail - The nose cone does not jettison from the Payload Bay when the black-powder is ignited	Pass

Test Procedure:

Equipment:

- LSRS
- Fore-bulkhead
- Nose cone
- 3 g of black-powder
- 15 ft of wire

Setup:
The LSRS will be fully integrated and secured into the Payload Bay. 15 ft of wire will be

connected to the snap junction on the fore-bulkhead for manual ignition of the black-powder and will be threaded out of the Payload Bay. The black-powder charge with the e-match will then be placed into the PVC charge well and secured using blue painters tape.

Safety Notes:

- This test involves the use of black powder, a potentially dangerous energetic. The team launch manager, Dave Brunsting, should prepare and install all black powder charges, as well as intitiate the charges during testing.
- During black powder ignition, a perimeter of at least 10 ft around the vehicle must be maintained by all personnel. Larger perimeters may be established at the discretion of the launch manager.

Procedure:

1. Place the fore-bulkhead onto the LSRS such that the rectangular stoppers are in the corners of the sliding platform.
2. Connect the e-match wires into the snap junctions with the manual ignition wire.
3. Place the nose cone onto the Payload Bay and insert four 4-40 shear pins to secure it in place.
4. Move a minimum distance of 10 ft away from the Payload Bay and ensure nothing is in front of the nose cone.
5. Ignite the black-powder charge.

Results: The test was performed on 2/23/2020 and the success criteria was met. It was noted that 3 g of black-powder created an excessive amount of pressure needed to jettison the nose cone from the Payload Bay so the test was redone using 1.5 g and the nose cone was successfully jettisoned.

PDT8: Retention Battery Life

Objective:
To ensure that the ROD System can remain in the launch configuration for a minimum of 2 hrs on the launch pad.

Tested Items:

- Altimeter battery
- Retention battery

Motivation:

- To verify that the ROD System batteries can power the electronics for more than 2 hrs.

Success Criteria:

PDT8 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
2.7	The launch vehicle and payload will be capable of remaining in launch-ready configuration on the pad for a minimum of 2 hrs without losing the functionality of any critical on-board components.	Success - The altimeter and retention batteries supply power to the electronics for more than 2 hrs. Fail - The altimeter and retention batteries fail to power electronics for more than 2 hrs.	Incomplete

Test Procedure:

Equipment:

- Altimeter battery
- Retention battery
- Stratologger SL100
- Retention PCB
- Rover electronics
- Voltmeter

Setup:
Inspect the altimeter and retention batteries for damage and signs deterioration and ensure that both batteries are fully charged using a voltmeter. Place all electronics and batteries in a secure environment that can be monitored throughout the entire test.

Safety Notes:

- Inspect batteries before use. All LiPo batteries not in use should be transported in fire proof battery bags.

Procedure:

1. Inspect and verify all electronic connections.
2. Connect the altimeter LiPo Battery to the Strattologger and connect the Retention battery to the Retention PCB.
3. Verify that the Rover is in a low-power mode state.
4. Monitor all electronics and batteries for 2 hrs.
5. After 2 hrs disconnect the batteries from the electronics and place them in fire proof battery bags.

Results: To be completed March 2-6.

7.1.4 Payload: UAV Testing

PUT1: Manual Flight

Objective:
To ensure that the UAV manual control is functional and that successful flight can be achieved.

Tested Items:

- Flight controller
- RC transmitter
- UAV RC receiver
- UAV flight stability
- UAV flight maneuvers

Motivation:

- To validate manual control of the UAV
- To ensure the UAV flight is stable
- To validate that the desired flight maneuvers are successful

Success Criteria:

PUT1 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.14	The UAV must have a manual override switch.	Success - The UAV is manually flown and performs all desired maneuvers AND the UAV has stable flight. Fail - The UAV cannot be manually flown OR cannot perform desired flight maneuvers OR is unstable during flight.	Incomplete

Test Procedure:

Equipment:

- UAV
- Manual Controller

Setup:
Ensure that area is free of bystanders and hazards to the UAV (e.g. trees and poles). Power on UAV and ensure that the RC transmitter and receiver are connected. If they do not, follow the manufacturer's directions to bind them.

Safety Notes:

- Ensure that all nearby personnel, including the UAV operator and bystanders, maintain a safe distance from the UAV at all times.

Procedure:

1. Gradually apply throttle to UAV until it begins to lift off.
2. Continue applying constant throttle until UAV reaches an altitude of five feet, then maintain a hover for five seconds.
3. Fly the UAV ten feet in a straight line.
4. Rotate the UAV 90° in place.
5. Land the UAV safely and ensure that the motors stop rotating before approaching the UAV.

Results: To be completed March 2-7.

PUT2: Autonomous Flight

Objective:
To validate the UAV autonomous flight capabilities and ensure stable flight.

Tested Items:

- Flight controller
- UAV ground station receiver
- Ground station UAV transmitter
- UAV flight stability
- UAV flight maneuvers

Motivation:

- To validate the UAV's autonomous flight capabilities
- To ensure the UAV's flight is stable
- To validate that the desired flight maneuvers are successful

Success Criteria:

PUT2 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.13	The UAV must use a commercial flight controller	Success - The UAV receives and obeys commands from the ground station AND has a stable flight with successful flight maneuvers. Fail - The UAV does not follow ground station commands OR has unstable flight	Incomplete

Test Procedure:

Equipment:

- UAV
- Ground station
- Manual controller

Setup:

- Ensure that the test area is free of bystanders and hazards to the UAV, such as trees and poles.
- Turn on UAV and ensure that the UAV's receiver is connected to both the manual controller's transmitter and the ground station's transmitter.

Safety Notes:

- Ensure that the manual override switch is functional before testing autonomous flight. Have a manual operator on standby to take over if the autonomous control malfunctions.
- Ensure that all nearby personnel, including the ground station operator and bystanders, maintain a safe distance from the UAV at all times.

Procedure:
Program the UAV to do the following autonomously:

1. Take off from the ground
2. Ascend to an altitude of five feet
3. Hover at this altitude for five seconds
4. Travel in a straight line for ten feet
5. Rotate 90° in place
6. Continue in the same direction for ten feet
7. Land safely and shut down motors

Results: To be completed March 2-7.

PUT3: Manual Override

Objective:
To ensure the UAV autonomous to manual control handoff is functional and does not affect flight stability.

Tested Items:

- Flight controller
- UAV ground station receiver
- UAV RC receiver
- Ground station UAV transmitter
- RC transmitter
- UAV flight stability
- UAV flight maneuvers

Motivation:

- To validate the UAV's autonomous control to manual control handoff
- To ensure the UAV's flight is stable before, during, and after the handoff
- To validate that the desired flight maneuvers are successful

Success Criteria:

PUT3 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.14	The UAV must have a manual override switch.	Success - The UAV autonomous to manual control handoff is successful, the UAV performs all desired maneuvers, AND the UAV has stable flight. Fail - The UAV autonomous to manual control handoff is not achieved, OR the UAV cannot perform desired flight maneuvers OR is unstable during flight.	Incomplete

Test Procedure:

Equipment:

- UAV
- Ground Station
- Manual Controller

Setup:

- Ensure that the test area is free of bystanders and hazards to the UAV, such as trees and poles.
- Turn on UAV and ensure that the UAV's receiver is connected to both the manual controller's transmitter and the ground station's transmitter.

Safety Notes:

- Ensure that all nearby personnel, including the ground station and UAV operators and bystanders, maintain a safe distance from the UAV at all times.

Procedure:

1. Program the UAV to do the following autonomously:
   (a) Take off from the ground.
   (b) Ascend to an altitude of five feet.
   (c) Hover at this altitude for five seconds.
   (d) Begin moving 15 feet in a straight line.

2. Send a signal from the ground station to enter manual control mode while the UAV is in motion.
3. Wait for the UAV to stop moving and hover in place.
4. Land the UAV safely and ensure that the motors stop rotating before approaching the UAV.

Results: To be completed March 2-7.

PUT4: Transmit Video to Ground Station

Objective:
To ensure successful video transmission from the UAV to the ground station for target detection.

Tested Items:

- Ground station video receiver
- UAV video transmitter

Motivation:

- To ensure successful video transmission, including sensor data
- To validate target detection system

Success Criteria:

PUT4 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.23	The Target Detection system must correctly identify the closest CFEA.	Success - The UAV transmits video during flight AND the ground station successfully receives the video AND the ground station successfully reads sensor data from the UAV. Fail - The UAV cannot transmit video during flight OR the ground station cannot receive video OR ground station cannot read sensor data	Incomplete

Test Procedure:

Equipment:

- Ground station video receiver
- Ground station display
- UAV video transmitter

Setup:
Place ground station and UAV approximately 25 feet apart and power on both systems.Ensure that the ground station's video receiver connects to the UAV's video transmitter and the ground station's display is connected to the video receiver.

Safety Notes:

- Ensure that sufficient distance is between the ground station and the UAV so as to avoid overloading the video receiver.
- Because the RC transmitters for the ground station and the manual controller are powered down, the UAV is safe to approach but should still be handled with caution.

Procedure:

1. Ensure that the video feed from the UAV's camera is visible on the ground station's display.
2. Explore Ardupilot's On-Screen Display settings to ensure that the ground station is receiving sensor data from the UAV and that all sensors are connected properly and configured correctly in Ardupilot.

Results: To be completed March 2-6.

PUT5: Detection of Simulated CFEA

Objective:
To verify that the target detection system can detect the CFEA.

Tested Items:

- UAV CADDX Turbo EOS2 camera
- Target detection code

Motivation:

- To validate the target detection system algorithm and design

Success Criteria:

PUT5 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.23	The target detection system must correctly identify the closest CFEA	Success - The target detection algorithm correctly identifies the CFEA. Fail - The target detection system does not correctly identify the CFEA.	Incomplete

Test Procedure:

Equipment:

- UAV
- Ground station
- Manual controller
- CFEA

Setup:
Prepare area for UAV flight (ensure that area is clear of bystanders and hazards). Place CFEA near designated UAV launch site. Prepare UAV and ground station for takeoff (power both systems on and ensure RC and video connections function properly).

Safety Notes:

- Ensure that all personnel remain a safe distance from the UAV at all times.

Procedure:

1. Ensure that the ground station display shows the video feed from the UAV.
2. Launch UAV to an altitude of 25 feet.
3. Fly UAV to CFEA while observer watches the ground station's display to ensure that a false CFEA detection is not reported prematurely.
4. With CFEA in frame, observer ensures that CFEA detection algorithm successfully identifies CFEA.
5. Land UAV on CFEA and shut down motors.

Results: To be completed March 2-6.

PUT6: Landing Location Identification

Objective:
To ensure that the target detection system correctly identifies the farthest corner from the launch vehicle landing site of the CFEA for UAV landing.

Tested Items:

- Target detection algorithm

Motivation:

- To ensure that the UAV will land far away from the operating area of the Rover

Success Criteria:

PUT6 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.24	Target Detection identifies correct corner of CFEA to land on.	Success - The target detection system correctly identifies the proper landing corner of the CFEA Fail - The target detection system does not identify the proper landing corner of the CFEA.	Incomplete

Test Procedure:

Equipment:

- UAV
- Ground station
- Manual controller
- CFEA

Setup:
Prepare area for UAV flight (ensure that area is clear of bystanders and hazards). Place CFEA near designated UAV launch site. Prepare UAV and ground station for takeoff (power both systems on and ensure RC and video connections function properly).

Safety Notes:

- Ensure that all personnel remain a safe distance from the UAV at all times.

Procedure:

1. Ensure that the ground station display shows the video feed from the UAV
2. Launch UAV to an altitude of 25 ft
3. Fly UAV to CFEA while observer watches the ground station's display to ensure that a false CFEA detection is not reported prematurely
4. With CFEA in frame, observer ensures that CFEA detection algorithm successfully identifies CFEA
5. Use ground station display to land UAV on CFEA at position designated by CFEA detection algorithm
6. Land UAV on CFEA and shut down motors
7. Verify that CFEA detection algorithm selected correct corner of CFEA

Results: To be completed March 2-8.

PUT7: Detection of a Simulated CFEA with UAV

Objective:
To validate the target detection system when receiving video from the UAV

Tested Items:

- Target detection algorithm

Motivation:

- To verify the success of the CFEA detection with data from the UAV

Success Criteria:

PUT7 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.23	Target Detection correctly identifies the closest CFEA.	Success - The CFEA is correctly identified from the ground with the UAV camera station Fail - The CFEA is not correctly identified.	Incomplete

Test Procedure:

Equipment:

- CFEA
- Camera

Setup:

Safety Notes:

Procedure:

1. Place CFEA in sunny area.
2. Capture several images of CFEA from different angles and showing all or part of CFEA.
3. Move CFEA to shaded and semi-shaded areas, repeating step 2 each time.
4. Analyze results

Results: To be complete March 15-21.

PUT8: Flight Time

Objective:
Verify that the UAV has sufficient flight time to locate the CFEA.

Tested Items:

- UAV

- UAV Battery
- Drone Controller

Motivation:

- To determine the UAV's ideal maximum flight time
- To ensure that the UAV will be able to fly long enough to complete its mission

Success Criteria:

PUT8 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.12	The UAV must have a minimum flight time of 10 min. A 10 minute flight time will provide adequate time for the UAV to search the area around the Rover.	Success - UAV remains powered after a 10 minute flight test. Fail - UAV loses power and is forced to land prior to the 10 min. mark.	Incomplete

Test Procedure:

Equipment:

- UAV
- Drone Controller
- Timer
- Multimeter

Setup:
Ensure that the UAV's battery is fully charged and secured inside the UAV. Clear an area to fly the UAV. Ensure that the area is free of hazards and no bystanders are nearby.

Safety Notes:

- A grassy area will protect the UAV from minor fall damage in the event of abrupt power loss.

Procedure:

1. Measure the voltage of the batteries prior to powering the UAV.

2. Prepare the UAV for takeoff.

3. Increase throttle until the UAV ascends to a height of one foot above the ground. Begin timing the UAV at the beginning of its hover.
4. Allow UAV to hover one foot above the ground until the battery voltage drop below a certain threshold.

5. Land the UAV safely.

6. Measure the voltage of the batteries after completing a test flight.

Results: To be completed March 2-8.

7.1.5 Payload: Rover Testing

PRT1: Electrical Connections

Objective:
To validate the electrical connections of the rover electrical components, success of components communication protocols, and radio communication to the rover.

Tested Items:

- Power Distribution
- I2C, SPI, UART, PWM protocols
- Radio receiving

Motivation:

- To verify the connections and operations of the rover electrical components and board fabrication.

Success Criteria:

PRT1 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.4	Electrical boards shall be isolated to prevent electrical shorts and ensure signal connections and communication protocols.	Success - A successful test shall verify the correct voltage readings on the PCB, verify sensor readings to the PIC32 memory, verify radio communication to the rover, and verify PWM output waveforms. Fail - The test shall fail if any of the voltage readings, sensor readings, radio receiving, or PWM outputs do not match valid and accepted values.	Pass

Test Procedure:

Equipment:

- Fully assembled rover printed circuit board (PCB)
- Two 11.1 V Li-Ion batteries
- 8 Channel Saleae Logic Analyzer
- Laptop with MPLABX installed
- PICKIT3 debugger
- Multimeter
- Radio test station circuit with Arduino Uno and RFM95W.

Setup:

The rover printed circuit board (PCB) in its fully assembled state shall be placed securely on an electrostatic discharge (ESD) mat or handled with ESD gloves for the outdoor GPS test step. Connect the USB end of the PICkit3 to the laptop and start MPLABX. Do not connect the PICkit3 until instructed in the procedure. Connect the Saleae Logic Analyzer to the laptop and begin the Logic program. Turn on the multimeter. Place the two 11.1V batteries on the ESD mat and do not connect to the board until instructed in the procedure.

Safety Notes:

- Batteries should be stored in a Li-Po safe bag at all times when not in use.
- At any time a battery is out of the safe bag, safety glasses must be worn.
- Handle all components on an ESD mat with appropriate wrist strap grounding. For the outdoor GPS test item, transport the circuit using an ESD bag and handle the circuit wearing ESD gloves.
- Ensure batteries are connected according to their proper polarity to avoid damage to the battery and circuit.

Procedure:

1. Connect the two 11.1V batteries to their corresponding header connectors. CAUTION: Batteries must be connected in the proper polarity indicated or damage may occur to board components.
2. Set the multimeter to measure a DC voltage. Connect the multimeter ground lead to the ground of the 3.3V two pin header, and the positive lead to the positive of the 3.3V pin header. Verify the multimeter reads +3.3V. Repeat for the 5V and 11.1V (Sabertooth) two pin headers.
3. Connect the PICkit3 to the corresponding header on the rover PCB. Download the test program to configure the PIC32 and send a single command over I2C to the BNO055 to read acceleration and magnetometer values and store in an appropriate register. Verify the presence of a valid reading.
4. Download the test program to the PIC32 to communicate with the GPS module over UART. The GPS module should automatically begin transmitting readings when measured. Verify GPS readings are properly stored in the PIC32 register within 5 minutes of outdoor runtime.
5. Power on RFM95W test stand connected to a lab PC. Download onto the Arduino Uno a program to begin transmitting the command "The quick brown fox jumps over the lazy dog 0123456789". Download the test program to the PIC32 to set the radio module to receive mode over SPI. Verify the reception of the test signal stored in a register.
6. Connect GND pin of the Saleae Logic Analyzer to one of the GND header pins on the board. Connect pins 0 and 1 of the logic analyzer to PWM pin, pin 3, on each of the sample retrieval servo connectors. Connect pins 2 and 3 to the pins of the Sabertooth PWM connector. Download the program to the PIC32 to output a 50% duty cycle PWM signal on each of the PWM pins. Verify the expected 5V signal output on the logic analyzer. Repeat with a 25%, 75%, and 100% duty cycle.

Results: This test was completed on 2/13/2020 and all electronics successfully powered on and communicated.

PRT2: Manual Drive

Objective:
To ensure that the rover's manual control is functional and communication with the ground station can be achieved.

Tested Items:

- Rover electronics
- Rover mechanical system
- Rover RC receiver
- Ground station rover transmitter
- Rover manual control remote

Motivation:

- To validate manual control of the rover
- To ensure the ground station can communicate with the rover
- To ensure the ground station can take in manual rover control inputs

Success Criteria:

PRT2 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.7	The Rover must have a manual override switch	Success - The rover is manually driven via the ground station AND performs all desired maneuvers. Fail - The rover cannot be manually controlled via the ground station OR the rover fails to perform all desired maneuvers.	Incomplete

Test Procedure:

Equipment:

- Rover
- Ground Station Rover Control Module (RCM)

Setup:
Ensure the area is free of bystanders and hazards to the rover (e.g. puddles or large obstacles). Power on the rover and the RCM, and ensure that the radio transmitter and receiver are connected.

Safety Notes:

- Rover and ground station batteries should be stored in a Li-Po safe bag at all times when not in use.
- At any time a battery is out of the safe bag, safety glasses must be worn.

Procedure:

1. Drive the rover forwards 10 feet in a straight line.
2. Turn the rover 180° clockwise.
3. Turn the rover 180° counterclockwise.

Results: To be completed March 2-7.

PRT3: Autonomous Drive

Objective:
To ensure that the rover's autonomous control is functional and communication with the ground station can be achieved.

Tested Items:

- Rover electronics
- Rover mechanical system
- Rover RC receiver
- Ground station rover transmitter

Motivation:

- To validate autonomous control of the rover.
- To ensure the ground station can communicate with the rover.
- To validate the rover's navigational GPS system.

Success Criteria:

PRT3 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.8	The Rover will remain dormant until receiving the initiation signal from the UAV.	Success - The rover is autonomously driven by the ground station, AND does not move until commanded by the ground station, AND performs all desired maneuvers. Fail - The rover cannot be autonomously driven by the ground station, OR it moves without being commanded by the ground station, OR the rover fails to perform all desired maneuvers.	Incomplete

Test Procedure:

Equipment:

- Rover
- Ground Station
- Duct tape or scrap wood

Setup:
Note the GPS coordinates of a point on the test site, and physically mark that location with a

piece of tape or scrap wood. Ensure the area is free of bystanders and hazards to the rover (e.g. puddles or large obstacles). Place the rover 10-15 feet away from the marked location. Power on the rover and the ground station, and ensure that the radio transmitter and receiver are connected.

Safety Notes:

- Rover and ground station batteries should be stored in a Li-Po safe bag at all times when not in use.
- At any time a battery is out of the safe bag, safety glasses must be worn.

Procedure:
Program the ground station to send the following commands:

1. Direct the rover to the marked GPS coordinates. Ensure the rover does not move, as it has not been activated.
2. Send the activation signal to the rover.
3. Direct the rover to the marked GPS coordinates again. Ensure the rover navigates to the physically marked location.

Results: To be completed March 2-7.

PRT4: Manual Override Test

Objective:
To validate the rover's autonomous control to manual control handoff.

Tested Items:

- Rover electronics
- Rover mechanical system
- Rover RC receiver
- Ground station rover transmitter
- Rover Control Module (RCM) detachment

Motivation:

- To validate the rover's autonomous to manual control handoff.
- To ensure the RCM remains functional after detachment from the ground station.
- To ensure the ground station can communicate with the rover both autonomously and with manual inputs.

Success Criteria:

PRT4 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.7	The Rover must have a manual override switch.	Success - The rover autonomous to manual control handoff is successful, AND the RCM remains functional after detachment, AND the rover performs all desired maneuvers. Fail - The rover autonomous to manual control handoff is not achieved, OR the RCM does not function after detachment, OR the rover fails to perform all desired maneuvers.	Incomplete

Test Procedure:

Equipment:

- Rover
- Ground Station
- Duct tape or scrap wood

Setup:
Note the GPS coordinates of a point on the test site, and physically mark that location with a piece of tape or scrap wood. Ensure the area is free of bystanders and hazards to the rover (e.g.puddles or large obstacles). Place the rover 10-15 feet away from the marked location. Power on the rover and the ground station, and ensure that the radio transmitter and receiver are connected.

Safety Notes:

- Rover and ground station batteries should be stored in a Li-Po safe bag at all times when not in use.
- At any time a battery is out of the safe bag, safety glasses must be worn.

Procedure:

1. Program the ground station to send the following commands:
   (a) Send the activation signal to the rover.
   (b) Direct the rover to the marked GPS coordinates. Ensure the rover navigates to the physically marked location.
2. Detach the RCM from the rest of the ground station. Perform all following commands using the remote attached to the RCM.
3. Turn the rover 90° clockwise.
4. Turn the rover 90° counterclockwise.
5. Drive in a straight line for 10 feet.

Results: To be completed March 2-7.

PRT5: Terrain Navigation

Objective:
Validate the rover's ability to traverse up various environmental conditions.

Tested Items:

- Vertical climb
- Vertical Descent
- Transverse Stability
- Traction

Motivation:

- To test the Rover's ability to traverse extreme environmental conditions it may experience on launch day

Success Criteria:

PRT5 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.2	The Rover must be able to overcome small obstacles such as rocks, corn stalks, and crop rows	Success - The rover is able to navigate all tested terrains Fail - The rover is not able to navigate all tested terrains	Incomplete
P.3	The Rover must be able to traverse through mud, puddles, corn stalks, and corn fields.	Success - The rover is able to navigate simulated cornfield and mud Fail - The rover is not able to navigate simulated cornfield and mud	Incomplete

Test Procedure:

Equipment:

- Rover
- Several sheets of plywood
- 2x4 ft boards
- Simulated cornfield mud

Setup:
To test the maneuverability of the rover, several environmental conditions are tested individually. First will be the vertical climb and descent of of the rover with the plywood sheet

angled at 45°and negative 45°respectively. The next phase will test the rover's ability to handle transverse inclines as it moves. For this experiment a 2x4 ft board will be placed at one side of the rover for the rover to climb over. This will be tested for both sides of the rover. Next the rover's traction control will be tested in simulated cornfield mud. Pass criteria for this test is if the rover can travel through the mud with relatively little slipping.

Safety Notes:

- Observe proper workshop safety standards when cutting plywood sheets

Procedure:

1. Set plywood sheet at a 45 degree angle.
2. Place rover at base of plywood ramp, and begin the climb. Continue climb until the rover has reached steady state.
3. Set plywood sheet at a negative 45 degree angle. Place rover at the top of the plywood ramp, and begin the descent. Continue descent until the rover has reached steady state.
4. Place 2x4 ft board at the base of one side of the rover. Allow the rover to move over the 2x4 ft board until it has reached steady state.
5. Test this for both sides of the rover.

Results: To be completed March 2-8.

PRT6: Turning Capabilities

Objective:
Validate the rover's ability to turn at a small enough radius for a successful mission.

Tested Items:

- Turn radius of all 8 turn types of the Rover

Motivation:

- To test the rover's ability to make the tight radius turns required for the mission

Success Criteria:

PRT6 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.2	The Rover must be able to overcome small obstacles such as rocks, corn stalks, and crop rows.	Success - The Rover can make turns within a 2 ft x 2 ft space Fail - The rover cannot make turns within a 2 ft x 2 ft space	Incomplete

Test Procedure:

Equipment:

- Paint or dye
- Rover

Setup:
For this test paint is applied to the contact surfaces of the rover body and links. The rover is placed in a fixed location and then the motors are actuated to turn the rover in one direction. The total footprint from this turn is recorded based on the paint splatter of the rover. This process is repeated for the 7 other types of turns the rover can make. The rover can turn in two ways: One motor running and the other idling, or both motors running in the opposite direction. These two types of turns, along with the four directions the rover can turn: front left, front right, reverse left, reverse right results in a total of 8 different types of turns.

Safety Notes:

- Wear gloves for applying paint, as it can be a skin irritant

Procedure:

1. Paint a bright color paint to the contact surfaces of the Rover
2. While paint is still wet navigate rover in all 8 turns
3. Measure footprint of rover left by paint

Results: To be completed March 2-8.

PRT7: Full Scale Structural Integrity

Objective:
To ensure that the 3-D mechanical frame of the Rover can withstand all forces during vehicle flight and recovery.

Tested Items:

- Rover mechanical frame

Motivation:

- To validate the strength of the Rover frame
- To verify that the Rover can withstand flight forces and maintain mechanical integrity.

Success Criteria:

PRT7 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
2.18.2	Payload Demonstration Flight-The payload flown must be the final, active version.	Success - The Rover mechanical frame sustains no damage during flight AND the mechanism of the Rover is not compromised. Fail - The mechanical frame of the Rover is damaged during flight OR the mechanism of the Rover does not function	Pass

Test Procedure:

Equipment:

- Rover
- Rover batteries
- Launch Vehicle
- ROD System

Setup:
Mount all electronics and batteries to the Rover and ensure they are secure. Place the Rover onto the sliding platform and extend the solenoid pins into the Rover body to secure it to the sliding platform. Ensure the Rover is secure by performing a shack test to verify the Rover does not move.

Safety Notes:

- Inspect batteries before use. All LiPo batteries not in use should be transported in fire proof battery bags.

Procedure:

1. Secure electronics and batteries to the Rover.
2. Secure the Rover to the sliding platform using the solenoid pins.
3. Place the Sliding platform in the Payload Bay and secure the Sliding platform to the Rail platform.

4. Place fore-bulkhead over the LSRS and mount and secure the nose cone onto the launch vehicle.

Results: The test was performed on 2/23/2020 and the success criteria was met. The Rover mechanical frame sustained no damage during flight and recovery and was fully retained during flight. The eccentric crank mechanism of the Rover was tested upon arrival to campus after the PDF and the eccentric successfully translated the Rover.

PRT8: Rover Battery Life

Objective:
To verify that the rover electronics have enough battery life to withstand mission requirements for powered-on standby mode and motor drive mode to complete the mission.

Tested Items:

- Rover Standby Battery Requirement
- Rover Maximum Drive Time

Motivation:

- Demonstrate the rover will remain powered through any delays on the launch pad.
- Demonstrate the rover has enough battery life to drive to the sample site and complete the mission.

Success Criteria:

PRT8 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.6	The Rover must have a minimum operating time of 20 minutes.	Success - Rover remains powered after a 2 hour standby and then remains powered after 20 minutes of motor operation. Fail - Rover battery fails to maintain proper voltage for circuit standby or motor operation after 20 minutes.	Incomplete

Test Procedure:

Equipment:

- Assembled Rover
- Rover electronics PCB

- Sabertooth Motor Controller
- 2x ProTek 11.1V battery
- Multimeter

Setup:
Mount the electronics onto the rover and the batteries onto the side linkages. Place the middle section of the rover onto a thin elevated surface such that the wheels and side linkages are able to actuate without touching the ground and moving the rover.

Safety Notes:

- Special care should be taken to plug the batteries in with the correct polarity.
- The rover should be properly placed such that motor actuation will not allow it to physically drive. Caution should be taken that personnel are not in a position to be hit by the rover in the event that it begins to actually drive across the ground.

Procedure:

1. Using the multimeter, measure the voltage of each fully charged battery and record the voltage.
2. Connect the batteries to their corresponding XT90 connectors on the rover PCB.
3. Download code to put the rover in standby mode actively monitoring its radio, similar to how it will look for a deployment signal.
4. Verify the status LEDs light indicating the rover is powered. Leave the rover powered on for 2 hours.
5. Verify the rover is still powered after 2 hours. Measure and record the battery voltages and verify the voltage has not dropped below 11V.
6. Download code to run the drive motors of the rover continuously.
7. Verify the rover is still powered and motors still actuating after 20 minutes. Disconnect the batteries and measure the voltage.

Results: To be completed March 3-6.

PRT9: Sample Retention

Objective:
To validate the security of the sample retention system, specifically the collection bin.

Tested Items:

- Sample Retrieval collection bin
- Sample Retrieval Arichimedes screw
- Sample Retrieval casing

Motivation:

- To verify that the screw transports sample up its body, travels up the case, and falls through the case slot
- To ensure that the collection bin retains the sample

Success Criteria:

PRT9 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.17	The Sample Retrieval system must retain and protect the recovered sample from spillage and contamination.	Success - All sample is retained. Fail - Some sample is lost	Pass
4.3.4	The recovered sample must be stored and transported at least 10 linear ft from the recovery area.	Success - At least 10 mL of sample is recovered. Fail - Less than 10 mL of sample is recovered.	Pass

Test Procedure:

Equipment:

- Sample Retrieval system assembly
- FS90R servo motor
- Preciosa Ornela plastic beads
- Pleated disposable paper cups
- Raspberry Pi
- Laptop

Setup:
The sample retrieval system test is assembled to simulate the sample retrieval process. The system is held at an estimated 65-degree angle and the screw tip is flush with the plastic beads inside the pleated disposable cup. The FS90R servo is activated by a python script on the Raspberry pi and runs for approximately 20 seconds. During these 20 seconds, the system is held consistently at the 65-degree angle while the screw turns and the sample travels up the body. After the 20 seconds, the system is exposed to dramatic forces by vigorous shaking to simulate turbulent terrain and then visually verify if any plastic beads exited the screw or collection bin.

Safety Notes:

- Safety glasses

Procedure:

1. Ensure that the screw connecting the case and the collection bin is secure
2. Measure an angle of 65 degrees to correctly orient the placement of the screw
3. Connect the FS90R servo to the Raspberry Pi and activate the script
4. Hold the screw for the duration of the test and remove the system from the sample pit once time runs out
5. Vigorously shake the sample retrieval system for 5 seconds
6. Gather any leaked sample, if any

Results: The test was completed with a successful outcome. The sample travels up the screw body and falls through the case slot without interference. No sample was lost during the shake test which validates the security of the collection bin.

PRT10: Sample Retrieval Time

Objective:
To measure the time it takes to retrieve at least 10 mL of sample

Tested Items:

- Sample Retrieval collection bin
- Sample Retrieval Arichimedes screw
- Sample Retrieval casing

Motivation:

- To ensure that the sample is retrieved within the allotted hour

Success Criteria:

PRT10 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.15, 4.3.3	The Sample Retrieval system must recover a minimum sample size of 10 mL.	Success - 10 mL of sample is collected Fail - Less than 10 mL of sample is collected	Incomplete

Test Procedure:

Equipment:

- Sample Retrieval system assembly
- FS90R servo motor

- Preciosa Ornela plastic beads
- Pleated disposable paper cups
- Raspberry Pi
- Laptop
- Screwdriver
- Timer

Setup:
The sample retrieval system is held at approximately a 65-degree angle flush to the disposable paper cup filled with loose plastic beads. The paper cup is tested in two different conditions, loosely held and tightly held. The FS90R servo is activated by a python script on the Raspberry pi and runs for approximately 20 seconds. During these 20 seconds, the system is held consistently at the 65-degree angle while the screw turns and the sample travels up the body. Perform multiple tests to gather a range of information.

Safety Notes:

- Safety glasses

Procedure:

1. Ensure that the screw connecting the case and the collection bin is secure
2. Measure an angle of 65 degrees to correctly orient the placement of the screw
3. Connect the FS90R servo to the Raspberry Pi and activate the script
4. Hold the screw for the duration of the test and remove the system from the sample pit once time runs out
5. Unscrew the screw connecting the case and the bin and slide out the case to expose the sample
6. Remove the sample from the bin by turning over the bin and measure the amount of beads collected

Results: This test is in progress, but we have 2 completed time trials that ran for 20 seconds. We wanted to create a small standard of comparison before we ran the test for a longer period of time. In the first timed trial, the screw collected 72 beads and in the second timed trial, the screw collected 142 beads. For the first trial, the sample container was held loosely and as a result, the plastic beads did not move to fill the empty space left behind by the screw when it collected the beads. To resolve this, the cup was held with more pressure to simulate the larger sample bay that would be encountered on launch day. Since a bigger sample bay will hold more sample, there is more force on the beads to fall towards the screw and quickly replace the gaps. This allows the sample retrieval system to collect beads at a faster rate. We were able to increase the collected sample by two-fold. We estimate that 10 mL of sample equates to approximately 215 beads, however, we cannot reliably estimate the time it would take since it is dependent on how the sample is situated in the cup. More tests will be conducted to experimentally determine the time that it takes to reliably collect 10 mL of the sample.

PRT11: Sample Retrieval Deployment

Objective:
To ensure that the Sample Retrieval system is properly secured for safe deployment

Tested Items:

- Sample Retrieval system
- Rack and pinion
- Supporting rods attached to the motor clamp

Motivation:

- To ensure the safety of the sample retrieval system as it deploys
- To ensure the safety of the collected sample as the system retracts

Success Criteria:

PRT11 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.16	The Sample Retrieval system must be able to correctly orient itself for retrieval operations.	Success - The sample retrieval system successfully deploys AND is properly oriented. Fail - The sample retrieval system does not deploy OR the system is not properly oriented.	Incomplete
P.18	The Sample Retrieval system must interface with the Rover electronics.	Success - The sample retrieval system deploys after receiving the initiation signal from the Rover. Fail - The sample retrieval system does not deploy after receiving the signal from the Rover.	Incomplete
4.3.2	Each recovery site will contain sample material extending from ground level to at least 2 in. below the surface.	Success - The sample retrieval system is able to penetrate two inches into the ground AND retrieve sample. Fail - The sample retrieval system is unable to penetrate the sample OR is unable to retrieve sample.	Incomplete

Test Procedure:

Equipment:

- Sample Retrieval system assembly
- FS90R servo motor
- 20 deg pinion gear
- Savox SH-0257
- Rover

Setup:
The supporting rods are mounted around the front motor of the rover. The Savox SH-0257 with the pinion attached is screwed into the cutout on the rover's front plate and electronically connected. The sample retrieval assembly (the screw, case, collection bin, and FS90R servo) is mounted onto the rover at a 65-degree angle. The rover and sample retrieval system are positioned over the sample bay.

Safety Notes:

- Safety glasses
- Testers remain at safe distance from moving rover

Procedure:

1. Mount the Sample Retrieval system as described in the setup
2. Activate the Savox motor to turn the pinion that moves the rack (which is attached to the collection bin) down into the sample bay
3. Activate the FS90R servo to collect the sample
4. Once the FS90R stops running, activate the Savox motor to turn in the opposite direction to move the rack upwards effectively retracting the sample retrieval system
5. Vibrations and system interaction with the motor are observed and recorded in addition to noting the amount of sample retrieved

Results: To be completed March 2-6.

PRT12: Retrieval Deployment Calibration

Objective:
To validate the angle of deployment of the sample retrieval system

Tested Items:

- Sample Retrieval system
- Rack and pinion
- Savox motor

Motivation:

- To ensure that the sample retrieval system will reach the sample
- To optimize the angle for efficient deployment of the system

Success Criteria:

PRT12 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
P.16	The Sample Retrieval system must be able to correctly orient itself for retrieval operations.	Success - When deployed, the tip of the screw (1/8 in) is fully submerged in the sample Fail - When deployed, the tip of the screw (1/8 in) is not fully submerged in the sample	Incomplete
4.3.2	Each recovery site will contain sample material extending from ground level to at least 2 in. below the surface.	Success - Sample retrieval system will have a clearance of 0.25 cm Fail - Less than 0.25 cm of clearance	Incomplete

Test Procedure:

Equipment:

- Sample Retrieval system assembly
- FS90R servo motor
- Preciosa Ornela plastic beads
- Pleated disposable paper cups
- Raspberry pi
- Laptop

Setup:
Sample Retrieval system is mounted on and integrated with the rover and positioned over sample bay.

Safety Notes:

- Safety glasses
- Testers remain at safe distance from moving rover

Procedure:

1. Sample bay is loaded with a comparable amount of sample (3 ft diameter hole)
2. Rover is positioned over sample bay
3. Sample retrieval system is deployed
4. Screw submersion is measured

5. Sample Retrieval system clearance is measured
6. Screw activates to collect the sample and once done, it retracts
7. The amount of sample is measured

Results: To be completed March 2-6.

7.1.6 ABS Testing

ABT1: Subscale Launch

Objective:
To verify that the addition of drag tabs to the sub-scale launch vehicle decreases apogee while maintaining stability, and to test the functionality of the chosen sensors and microcontroller.

Tested Items:

- Apogee change of subscale launch vehicle when drag tabs are implemented
- Stability of flight when drag tabs are implemented
- Capabilities of BNO055 accelerometer, MPL3115 barometer, ADXL345, and Raspberry Pi microcontroller working in sequence

Motivation:

- To verify that the addition of drag tabs lowers the apogee of the launch vehicle as expected
- To ensure that the addition of drag tabs does not cause instability during flight
- To verify that the chosen sensors and microcontroller work in sequence to provide sensible flight data at an acceptable frequency

Success Criteria:

Table 44: ABT1 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
V.4	The addition of the drag tabs will lower the apogee of the launch vehicle.	Success - The recorded apogee for half extension and full extension each subsequently decrease apogee by 80 feet or more. Fail - There is no significant apogee decrease resulting from the addition of the drag tabs.	Pass
V.10, V.14	The addition of the drag tabs will not negatively affect the stability of the launch vehicle.	Success - The launch vehicle undergoes successful flights with the drag tabs attached. Fail - The launch vehicle experiences an unstable flight and fails with the drag tabs attached.	Pass
2.18.1.8	The ABS sensors and microcontroller collect data effectively.	Success - The data collected by the sensors is sensible, and is collected at a frequency of at least 50 Hz. Fail - The data collected by the sensors is not physically accurate, or the data is collected at a frequency below 50 Hz.	Incomplete

Test Procedure:

Equipment:

- Subscale launch vehicle
- 3 removable couplers with 2:5 scale drag tab models
- Sensor sled with Raspberry Pi, BNO055, MPL3115, ADXL345, and 3.7V 250 mAh battery attached
- Computer with micro SD card reader

Setup:
Two sets of 2:5 scale model drag tabs were fabricated out of Nylon 6/6 to best replicate the induced drag that will be generated with full-scale ABS. One model represents the drag tabs at full extension, and the other represents them at half extension. These were epoxied to removable couplers that could be attached and removed at the CP of the sub-scale launch vehicle, along with a third coupler that sat flush to the vehicle body to represent flight without ABS. The fabricated sub-scale drag tabs are shown in Figure 125, and are shown epoxied to the coupler in Figure 126. Additionally, a sensor sled was constructed out of balsa wood to house the microcontroller, battery, and sensors for ABS, as well as all Recovery electronics. It consisted of two bulkheads and a 5 in. web to which all components were secured. This sensor sled was integrated into the sub-scale launch vehicle in the payload bay, and was secured by a screw at its aft bulkhead.

Figure 125: Sub-scale drag tabs

Figure 126: Sub-scale drag tabs on coupler

Safety Notes:

- Before and after flight, inspect the LiPo battery for damage, swelling, or other abnormalities. If any of these are observed, place battery in fireproof bag.

Procedure:

1. Follow the subscale launch procedure outlined in Test LVT2.
2. Plug LiPo battery into the power booster
3. Verify that the Raspberry Pi is taking data from the sensors by checking the LED
4. Integrate the sensor sled into the launch vehicle
5. Conduct launch without tabs.
6. Recover the vehicle and remove the sensor sled. Unplug the battery.
7. Plug the micro SD card into a computer to verify that data was collected
8. Repeat for two more launches with the half-tab and full-tab couplers attached.

Results: Upon inspection of the sensor data, the ability of the ABS to decrease the apogee of the launch vehicle was verified. For reference, the recorded apogees for each of the launches is shown in Table 45.

Table 45: Recorded Altitude at Apogee for Sub-scale Flights

Flight	No Tabs	Half Tabs	Full Tabs
Altitude (ft)	1366	1126.5	1010

The stability of the launch vehicle was not compromised by the implementation of the drag tabs, as was seen in the steady flight path shown by the sensor data, and the visibly stable flight observed at launch. The sensors were only able to collect data at 10 Hz, which is below the target sampling frequency of 50 Hz. The BNO055 was found to be the sensor causing the low sampling frequency. The altitude data from the MPL3115 and the linear acceleration from the ADXL345 were both physically accurate, but the BNO055 did not provide sensible orientation data due to its ±4g ceiling. Because of the low sampling frequency and the lack of physically accurate data collection, the team decided to remove the BNO055 from the system for the final design. Plots of the sensor data recorded during the "No Tabs" subscale flight can be seen in Figure 127.

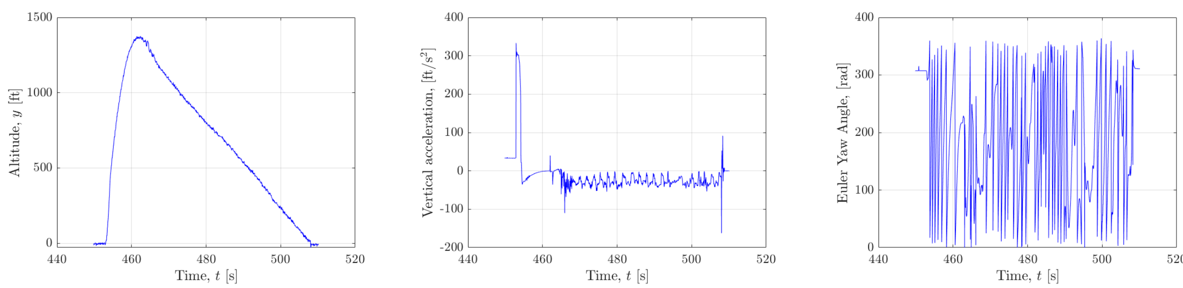


Figure 127: ABS Sensor Data for One Subscale Flight

ABT2: Mechanism and Motor Ground Test

Objective:
To verify that the fully constructed mechanism and motor will function together as intended to produce drag tab actuation from angles of 0° to 63.5°, and to set the PWM pulse widths necessary for the maximum and minimum rotation.

Tested Items:

- Ability to program the HiTec D845WP servo motor
- Servo motor rotation angles in response to PWM signals
- Drag tab extension resulting from servo motor rotation
- Servo motor ability to overcome the internal friction of the mechanism

Success Criteria:

Table 46: ABT2 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
V.4	The servo motor will rotate to the expected angle for a given PWM signal.	Success - When the PWM signal is sent, the servo motor rotates to the correct angle despite resistance from mechanism friction. Fail - The servo motor rotates to an angle too small, or the servo motor stalls due to inability to overcome internal friction.	Pass
V.4	The HiTec Servo Programmer will allow the team to edit D845WP Servo parameters such as max/min rotation.	Success - Success Fail - Failure	Pass
V.4	The HiTec Servo Programmer will allow the team to determine a direct relationship between pulse width (in μs) and angle (in degrees).	Success - Success Fail - Failure	Pass
V.4	The Raspberry Pi can precisely control the servo using the information gathered testing.	Success - Success Fail - Failure	Pass

Test Procedure:

Equipment:

- Fully constructed drag tab deployment mechanism
- HiTec D845WP servo motor attached to the aluminum crosspiece
- Hitec DPC-11 PC Servo Programmer
- Computer with DPC-11 Software installed
- 7.4V 400mAh LiPo battery

Setup:
Connect the D845WP servo to the laptop via the programmer. Then plug the 7.4V 400mAh LiPo battery into the programmer. Run the programming software on the laptop.

Safety Notes:

- A safe distance must be kept from the mechanism during the test, as injury could result from the rapidly moving components.
- Ensure that power is cut from the servo motor before handling the mechanism.
- Inspect the battery for defects and place it in a fireproof case when not in use. Special care should be taken to not reverse the polarity of the battery when connecting it to the servo.

Procedure:

1. Verify that the programming software has successfully connected to the servo motor.
2. Send PWM signals to the servo via the software.

3. Verify visually that the servo is able to overcome friction, especially for discrete rotations
4. Use a protractor to measure the achieved rotation angles for the various PWM signals
5. Take note of the pulse widths that bring the mechanism to its minimum and maximum angles of 0° and 63.5°
6. Program the Raspberry Pi to control the servo motor as intended using the information recorded

Results: The servo was successfully controlled via the HiTec programming interface. The expected angle rotations were verified using a protractor. The maximum and minimum angles were adjusted to limit the servo motor to 63.5 degrees of rotation, as necessary to prevent jamming in flight. The required pulse widths for the maximum and minimum angles were noted as -1500 μs for 0° and 2200 μs for 63.5°. This was then converted into a PWM signal of 400 Hz, yielding a duty cycle of 60% for 0° and a duty cycle of 88% for 63.5°. These values were then programmed into the Raspberry Pi Zero via a SSH connection, and the servo was disconnected from the programmer and attached to the Pi Zero.

ABT3: Control Structure Ground Test

Objective:
To verify that the fully constructed ABS is able to execute an entire simulated flight, ensuring that drag tabs appropriately actuate in response to data input. **Tested Items:**

- Kalman filter data processing
- Flight stage awareness
- Response of the mechanism to a simulated flight

Success Criteria:

ABT3 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
V.4	The Kalman filter is able to accurately filter the input data.	Success - Flight data passed through the Kalman filter is smooth and represents physical accuracy. Fail - The Kalman filter produces physically inaccurate data from the simulated flight data.	Pass
V.4	The PID control algorithm calculates reasonable drag tab extensions for a given flight profile	Success - The PID algorithm signals for large servo angles when velocity error is high and small angles when error is low. Fail - The PID algorithm does not provide sensible servo rotations based on velocity.	Pass
2.18.1.4	The servo actuates the tabs appropriately given a PWM signal	Success - The mechanism actuates the drag tabs as expected from PID output. Fail - The mechanism fails to produce the desired motion.	Pass

Test Procedure:

Equipment:

- Assembled Avionics PCB with associated components
- Servo motor integrated into tab assembly
- Flight simulations generated on OpenRocket

Setup:

The entire system will be constructed exactly as it will be for full-scale flight. Ensure the correct test code is loaded on the Raspberry Pi.

Safety Notes:

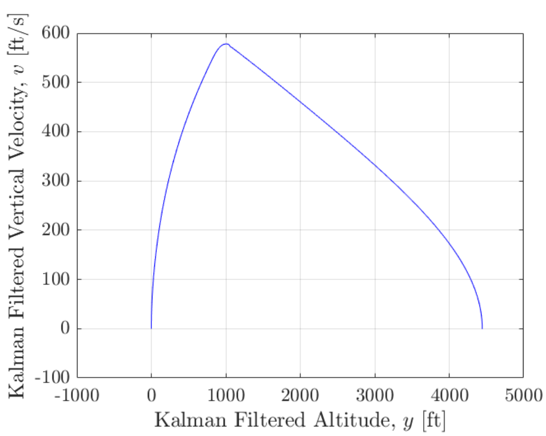
- A safe distance must be kept from the system during the test, as injury could result from the rapidly moving components.
- Ensure that the program on the Raspberry Pi has ended before handling the system.
- Inspect the battery for defects and place it in a fire proof case when not in use.

Procedure:

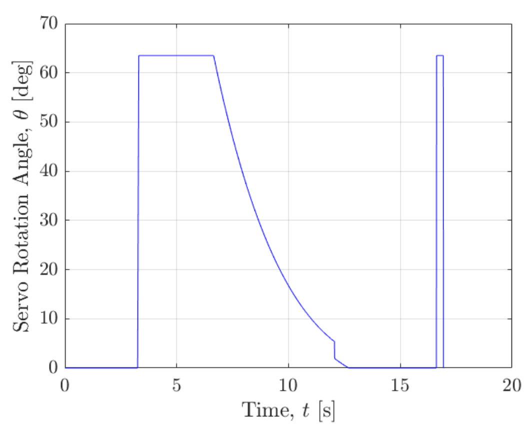
1. Create three simulated flight paths in OpenRocket: one in which the launch vehicle conducts an ideal flight going from an overshoot to the target apogee, one in which it overshoots the target apogee, and one in which it undershoots the target apogee.
2. Export the simulated data into a CSV format matching sensor readings. Modify the code to accept an input file as sensor data.
3. Interface with the Raspberry Pi with SSH and ensure the servo is properly connected.

4. Execute the test script and observe tab extension at different points in flight.
5. View and plot Kalman outputs and PID readings to ensure they match the simulated flight path.

Results: The ABS control structure test was conducted on February 19th. This test allowed the team to fix several bugs in the code. After adjustment of PID gains, the servo was able to appropriately actuate the drag tabs based on input data. The team tested three simulated flight paths and ensured that the servo actuated correctly. In the simulation of a successful flight, the drag tabs actuated fully once burnout occurred, and slowly retracted as the flight path approached the ideal flight path. In the simulation of an overshoot, the tabs remained fully extended from burnout to apogee, which is the correct response. In the undershoot simulation, the tabs fully retracted once the velocity was below the ideal, and remained retracted for the remainder of flight, as desired. These three tests represented the desired drag tab behavior in response to simulated data, ensuring that ABS will function as desired if provided accurate physical data. The data recorded for the simulated flight in which the vehicle goes from an overshoot trajectory to the target apogee is shown in Figure 128.



(a) Kalman Filtered Flight Data



(b) PID Servo Angle Output

Figure 128: Control Structure Simulated Flight Test Data

ABT4: Electromagnetic Interference Test

Objective:
Verify that current draw from D845WP servo does not cause electromagnetic interference in the MPL3115A2 and ADXL345 sensors.

Tested Items:

- D845WP Servo
- MPL3115A2
- ADXL345

Motivation:

- Ensure that the current draw of the servo does not create noise in the sensor data which could result in a failed launch.

Success Criteria:

ABT4 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
V.4	The servo will not generate any perceivable noise on the sensors when actuated using the HiTec Servo programmer.	Success - Servo does not cause sensor noise, or Faraday cage prevents it Fail - Faraday cage is unable to prevent servo from creating sensor noise	Complete, Pass

Test Procedure:

Equipment:

- Assembled avionics system.
- Faraday cage between avionics and servo motor
- Servo motor attached to DWP-11 Programming Interface
- Laptop with DWP-11 software installed

Setup:
The D845WP servo was attached to the ABS mechanism and was connected to a laptop via HiTec Programmer. A Faraday cage was constructed on the deck between the servo motor and the avionics using copper tape. The electronics bay was secured in ABS, and via SSH connection to the Raspberry Pi the sensors started collecting data. The programmer was used to actuate the servo while this data was being collected.

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. Special care should be taken to not reverse the polarity of the battery when connecting it to the servo.

Procedure:

1. Assemble avionics system and connect to laptop via HiTec Programmer.
2. Actuate servo to different angles.
3. Review data collected and determine whether current of D845WP servo interfered with the collection.

Results: The servo actuation was determined to not interfere with the ADXL345 and the MPL3115A2 while the Faraday cage was in use.

ABT5: Pre-Launch Disturbance Test

Objective:
Data shall be read in from sensors while the ABS is on the ground to ensure that sensors are correctly reading data and the Kalman filter is correctly filtering data.

Tested Items:

- D845WP Servo
- MPL3115A2
- ADXL345
- Raspberry Pi

Motivation:

- Ensure avionics hardware performance
- Ensure sensor integration with processor
- Ensure Kalman filter integrity

Success Criteria:

ABT5 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
V.4	The Python script will be able to successfully read sensor data.	Success - Pass Fail - Fail	Complete, Pass
V.4	The sensor data read is reasonable and matches intuition when lifting or rotating the device.	Success - Pass Fail - Fail	Complete, Pass
V.4	The Kalman filter outputs reasonable state estimates given the input sensor data.	Success - Pass Fail - Fail	Complete, Pass

Test Procedure:

Equipment:

- Assembled Avionics PCB with associated components

Setup:
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.

Procedure:

1. Power on system and verify that LED has illuminated.
2. Connect via SSH to the Raspberry Pi to observe sensor and Kalman output.
3. Perturb the system by lifting/lowering, rotating, and accelerating it.
4. Read data from sensor and Kalman filter to it matches up with the physical perturbations.

Results: The ABS printed circuit board was placed under testing on February 13th. Due to issues with communicating with the BNO055, that sensor has been dropped from the configuration. The team has tested the new configuration as described, with good results. Data is read and processed at a rate of 30Hz, and all ground-based sensor readings match intuition. When testing the Kalman filter, the team realized that accelerometer readings were being interpreted as raw acceleration data, which is incorrect. Upon transforming accelerometer readings to a form consistent with the Kalman state equations, the Kalman filter has produced a reasonable estimate of the system's position, velocity, and acceleration given its inputs.

ABT6: Full Scale

Objective:
ABS demonstrates flight readiness through system performance in a full-scale flight.

Tested Items:

- Fully constructed ABS
- Launch vehicle

Success Criteria:

ABT6 Success Criteria

Requirement ID	Description	Pass/Fail Criteria	Result
2.18.1.4, 2.15	If the payload changes the external surfaces of the rocket or manages the total energy of the vehicle, those systems will be active during the full scale Vehicle Demonstration Flight.	Success - The drag tabs successfully actuate in a demonstration flight Fail - The drag tabs do not actuate during a demonstration flight	Complete, Pass
2.18.1.8	Proof of a successful flight shall be supplied in the FRR report. Altimeter data output is required to meet this requirement.	Success - ABS records data successfully that matches data from Recovery and Telemetry Fail - Data is lost, or does not physically match Recovery and Telemetry data	Complete, Pass
2.18.2.2, V.4	ABS responds to the sensor data as expected	Success - Drag tabs actuate if an overshoot is indicated and retract if an undershoot is indicated Fail - ABS does not actuate correctly in response to reported data	Complete, Pass
2.1, V.4	The launch vehicle reaches its target apogee of 4,444 ± 25 feet	Success - Apogee indicated by sensor data is within the error bounds of the target apogee Fail - Apogee indicated by sensor data is outside the error bounds of the target apogee	Incomplete, Fail
V.13	ABS does not experience any structural failures during any stage of the flight	Success - Inspection of ABS after flight verifies that no structural failures occurred Fail - Structural failures due to in-flight loading on ABS are observed	Complete, Pass

Test Procedure:

Equipment:

- Assembled ABS structural components
- Assembled PCB secured to ABS
- Fully charged 7.4V 1500 mAh LiPo battery
- Fully charged 3.4V 500 mAh LiPo battery
- Phillips head screwdriver
- Four 10-32 Thread, 1" long pan head phillips screws

Setup:
Ensure that the correct control code is uploaded on the Raspberry Pi. Inspect the system for any structural or electrical damage. Inspect electronics for secure connections and mounting.

Safety Notes:

- Carefully inspect LiPo batteries before and after launch. If any signs of swelling or damage are seen, store the battery in a fireproof LiPo bag immediately. Keep batteries stored in fireproof battery bag leading up to and after launch

Procedure:

1. Follow the launch procedure outlined in 7.1.1
2. Ensure the SD card is inserted in the Raspberry Pi prior to powering the system
3. Duct tape the 7.4V battery right next to the servo motor
4. Duct tape the 3.7V battery to the wall adjacent to the PCB
5. Plug in the 7.4V battery into the servo
6. Plug in the 3.7V battery into the PowerBoost 500
7. Once the Raspberry Pi has had time to boot up, inspect the LED to verify that the system is powered and data is being collected
8. Integrate ABS into the fin can by aligning the drag tabs to the slotted openings, ensuring the sensors are facing the barometric hole.
9. Secure ABS into the fin can by screwing in the 10-32 phillips screws through the fin can into the threaded holes in the aluminum bulkhead
10. Once the launch vehicle is on the launch pad, inspect the LED through the barometric holes to verify that the system is still powered on and collecting data
11. Follow post-launch procedures to safely recover rocket after landing with safety officer approval
12. Extract ABS from the fin can
13. Inspect the mechanical system and full payload bay for damage
14. Verify that the LED is still on, indicating that the system remained active throughout flight

Results: In the second demonstration flight, ABS successfully recorded the vehicle flight state and actuated the drag tabs accordingly. The system flew with no structural failures, and without creating any destabilizing forces or moments. The drag tabs can be seen deployed during the flight in Figure 129, showing a screenshot from the on-board flight camera.

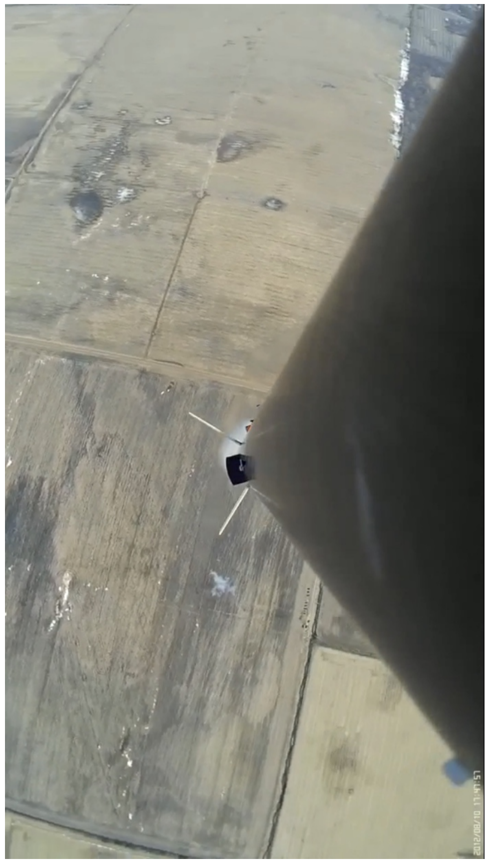


Figure 129: Drag tab deployment during demonstration flight

The in-flight drag tab deployment satisfied NASA Requirement 2.18.1.4, which states that any payload that changes the external surfaces of the launch vehicle must be active in a demonstration flight. The ABS remained powered for the entire duration of flight, actively collecting data and correctly identifying the current launch stage as it was designed to do. For verification of the recorded altitude data, the ABS sensor data was compared to the Recovery altimeters, as shown plotted in Figure 130.

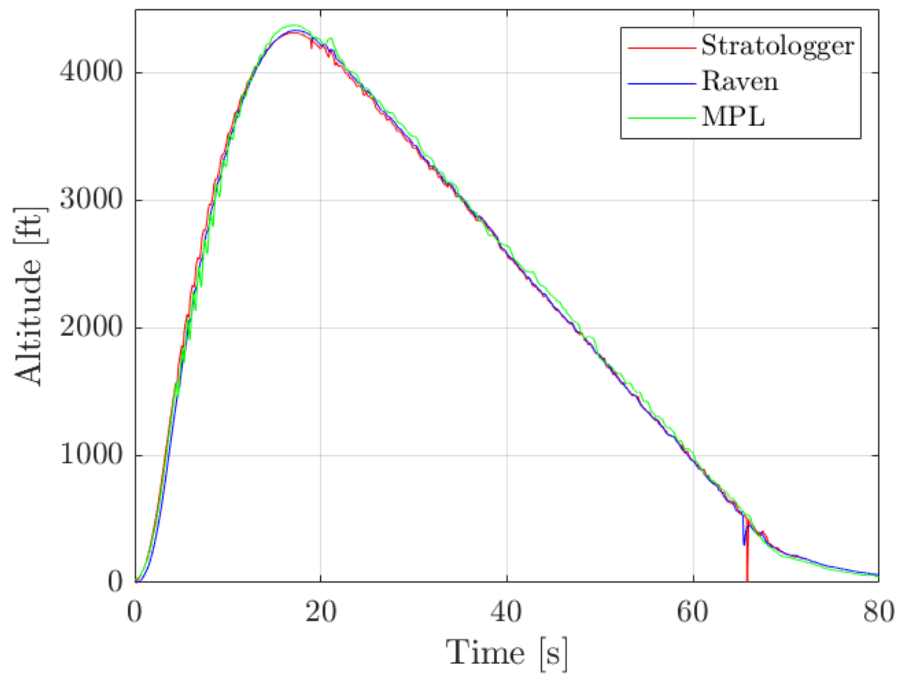


Figure 130: ABS MPL3115 altitude data compared to recovery altimeter data

The closeness in comparison of the altitude data between ABS and recovery sensors verifies that both systems recorded physically accurate data. The recorded apogees from ABS, telemetry, and recovery are summarized in Table 47.

Table 47: Apogee comparison between systems

ABS	Recovery	Telemetry
4373 ft	4322 ft	4320 ft

The recorded apogees once again verify that the recorded data was physically accurate, but they also indicate that the launch vehicle did not reach its target apogee of 4,444 feet. The recorded apogee was more than 100 feet below the target apogee. From inspection of the video recorded by the on-board camera, the tabs were observed to actuate quickly in and out of the fin can, reaching full extension each time. The expected motion of the drag tabs in an ideal flight involves full extension followed by a gradual retraction as the flight data approaches the ideal trajectory, as was seen in the simulated ideal flight in 7.1.6. However, inspection of the servo angle commands from the flight indicated that the rapid deployment and retraction was the correct response. The observed motion was caused by sudden drops in the measured altitude, which occurred each time the drag tabs were deployed. These altitude drops can be seen in a close-up of the flight data from burnout to apogee in Figure 131.

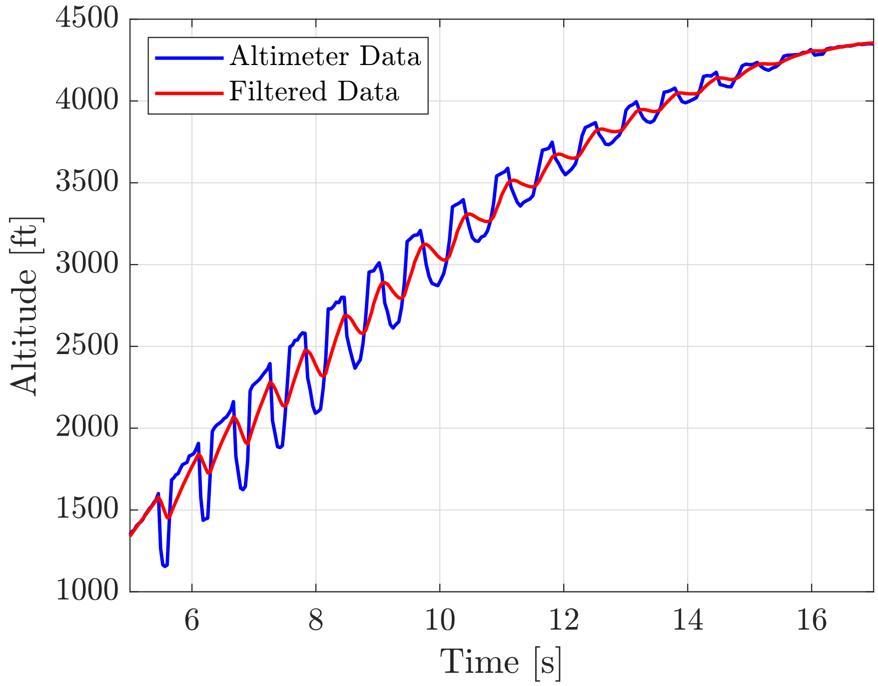


Figure 131: Close-up showing drops in the altitude data

The drag tab deployment caused a change in the pressure measured by the MPL3115, leading to the altitude drops shown. The Kalman filter was able to partially smooth the data, but the velocity showed rapid spikes up and down because of the inconsistency between the altitude change and the vertical acceleration, ultimately leading the PID algorithm to determine the motion that was observed. Two changes will be made to ensure that the altimeter data does not cause this problem in competition: the pressure in the avionics bay will be supplied from a tube that reads static pressure at a location fore of the drag tabs, rather than the current barometric hole aft of the drag tabs, and the Kalman gains will be adjusted to give more credence to vertical acceleration, which will smooth out the altitude data further. Despite a minor fault in the altitude data collection, ABS completed a successful demonstration flight. The mechanical response to the data was correct, the system remained active for the entire flight, there were no structural failures, and the deployment of the drag tabs did not cause any stability issues, thus demonstrating that ABS is prepared to fly active in competition.

7.2 Requirements & Verifications

7.2.1 NASA Requirements

Table 48: General Requirements

Requirement		Verification Method				Verification Plan	Status
ID	Description	A	I	D	T		
1.1	Students on the team will do 100% of the project and flight preparation (except for items to be done by the team's mentor). Teams will submit new work.		X	X		NDRT is completely student led. Team officers will delegate all work to student members and verify students conduct all activities except those that mentors are required to conduct (i.e. assembling motors, handling ejection charges).	Complete
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		Team captains are actively maintaining a project plan including a GANTT chart for scheduling milestone targets, team budget, and software such as Slack for organization and task delegation.	Complete
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 on site at Marshall Space Flight Center.		X			Design team leads will collect team member information, inform Foreign Nationals of the launch week restrictions, and ensure all Foreign Nationals attending launch week are properly registered in time to attend available activities.	Complete
1.4	The team must identify all team members attending launch week activities by CDR. Team members will include: Students actively engaged in the project throughout the entire year, one mentor, and no more than two adult educators.		X			Team members, mentors, and educators will be required to express interest in attending launch week prior to CDR submission.	Complete
1.5	The team will engage a minimum of 200 participants in educational, hands-on STEM activities by FRR.			X		An Educational Outreach officer has been elected and will communicate outreach activities with community partners and team members. Educational Engagement Activity Reports will accurately describe outreach activities and community impact.	Complete
1.6	The team will establish a social media presence to inform the public about team activities.			X		A Social Media Manager has been elected and will maintain the team's online presence and interaction with the public.	Complete
1.7	Teams will email all deliverables to the NASA project management team by the deadline specified in the handbook for each milestone.		X			Team Captains will confirm deliverables are delivered via email by the deadline and will confirm receipt with the NASA project management team.	Complete
1.8	All deliverables must be in PDF format.		X			Documentation will be prepared using Overleaf and Google Suite products accessed via an academic license. All documentation shall be compiled into a PDF format.	Complete
1.9	In every report, teams will provide a table of contents including major sections and their respective sub-sections.		X			Documentation prepared using Overleaf will contain a table of contents and sections will be updated automatically to ensure accuracy.	Complete
1.10	In every report, the team will include the page number at the bottom of the page.		X			Documentation prepared using Overleaf will be formatted to include the page number at the bottom of the page.	Complete
1.11	The team will provide any computer equipment necessary to perform a video teleconference with the review panel.		X	X		NDRT maintains a set of teleconferencing equipment and will verify its functionality prior to each presentation. The team will reserve a room in the college of engineering two weeks prior to each presentation.	Complete
1.12	All teams will be required to use the launch pads provided by Student Launch's launch services provider.			X		The launch vehicle shall be designed to launch with the required launch pads and rails as provided by the launch service provider.	Complete
1.13	Each team must identify a "mentor" as defined in the Student Launch Handbook.		X			NDRT works with a mentor who meets all requirements.	Complete

Table 49: NASA Launch Vehicle Requirements

Requirement		Verification Method				Verification Plan	Status
ID	Description	A	I	D	T		
2.1	The vehicle will deliver the payload to an apogee altitude between 3,500 and 5,500 ft AGL.	X		X	LVT4	Accurate simulations of the vehicle design will be created in RockSim and OpenRocket to project the vehicle apogee and ensure the vehicle will be within the required range and projected to hit the set apogee target. Test flights will be performed to demonstrate this.	Complete

Requirement		Verification Method				Verification Plan	Status
ID	Description	A	I	D	T		
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	X			Analysis of the preliminary vehicle and payload design and dimensions were used to set the final target altitude. The target altitude was declared in the PDR report to be 4,444 ft.	Complete
2.3	The vehicle will carry one commercially available, barometric altimeter for recording the official altitude used in determining the Altitude Award winner.		X			The team will select a commercially available barometric altimeter and verify with team mentors and launch managers that the selected altimeter is a reliable selection. The team will be using three altimeters for deployment redundancy, so one altimeter will be identified to the launch managers as the scoring altimeter.	Complete
2.4	The launch vehicle will be designed to be recoverable and reusable.			X	LVT4, LVT3	The vehicle will be designed to be reusable. Extensive ground testing of recovery and payload systems will be conducted to ensure written procedures allow for a recoverable and reusable vehicle and payload. This will be verified during full scale flight tests.	Complete
2.5	The launch vehicle will have a maximum of 4 independent sections.		X			The team will verify during the design and fabrication phases of development that the vehicle has a maximum of 4 independent sections.	Complete
2.5.1	Coupler/airframe shoulders which are located at in-flight separation points will be at least 1 body diameter in length.		X			Team will verify that coupler/airframe shoulders at in-flight separation points are at least 1 body diameter in length.	Complete
2.5.2	Nosecone shoulders which are located at in-flight separation points will be at least 1/2 body diameter in length.		X			Team will verify that nosecone shoulders at in-flight separation points will be at least 1/2 body diameter in length.	Complete
2.6	The launch vehicle will be capable of being prepared for flight at the launch site within 2 hours of the time the FAA flight waiver opens.			X	LVT4	Systems and Safety team will prepare launch day procedures which shall be fully practiced (with the exception of arming any energetics) prior to the first launch day. Full scale test flights will be used to ensure the vehicle is prepared within 2 hours.	Complete
2.7	The launch vehicle and payload will be capable of remaining in launch-ready configuration on the pad for a minimum of 2 hours without losing the functionality of any critical on-board components.	X			RT6, PDT8, PRT9, PRT8	During the design phase analysis will be conducted on the power draw of system components and available capacity of on-board batteries. Testing of the vehicle and payload systems will be performed to ensure they are capable of remaining in a launch-ready configuration for at least 3 hours while still having enough capacity to perform the maximum length of the mission without risk of losing power.	Complete
2.8	The launch vehicle will be capable of being launched by a standard 12 V DC firing system, provided by the NASA-designated launch services provider.		X	X		The vehicle will be designed to launch with a standard 12 V DC firing system. The team will work with our launch manager to ensure compatibility prior to demonstration flights.	Complete
2.9	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	X		The team will work with the launch manager to ensure compatibility without external circuitry.	Complete
2.10	The launch vehicle will use a commercially available solid motor propulsion system using APCP, which is approved and certified by the NAR, TRA, and/or the CAR.		X			The team will review NAR, TRA, and CAR certifications to ensure the selected motor is in compliance.	Complete
2.10.1	Final motor choices will be declared by the CDR milestone.		X			Final motor is the L1395 Blue Streak	Complete
2.10.2	Any motor change after CDR must be approved by the NASA RSO and will only be approved if the change is for the sole purpose of increasing the safety margin.		X	X		All motor changes requested after the CDR milestone will be requested with accompanying analysis demonstrating a safety derived reasoning. The team accepts a penalty regardless of the reasoning if the change is approved.	Complete
2.11	The launch vehicle will be limited to a single stage.		X			The team shall design the vehicle as a single stage with a motor in accordance with Req. 2.10	Complete
2.12	The total impulse provided by a University launch vehicle will not exceed 5,120 Ns (L-class).		X			As a University launch team, the team shall select a motor providing a total impulse which does not exceed 5,120 Ns (L class).	Complete
2.13	Pressure vessels on the vehicle will be approved by the RSO and will meet the criteria outlined in Req. 2.13.1-2.13.3.		X			No pressure vessels are used	Complete
2.13.1	The minimum pressure vessel FOS will be 4:1 with supporting design documentation included in all milestone reviews.	X				No pressure vessels are used	Complete
2.13.2	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				No pressure vessels are used	Complete
2.13.3	The full pedigree of the tank will be described, including the application for which the tank was designed and the history of the tank as defined in the NASA SL Handbook.		X			No pressure vessels are used	Complete
2.14	The launch vehicle will have a minimum static stability margin of 2.0 at the point of rail exit.	X			LVT6	Software such as OpenRocket and RockSim verify a static stability margin of 2.0 at the point of rail exit, and full-scale Cg tests confirm results	Complete

Requirement		Verification Method				Verification Plan	Status
ID	Description	A	I	D	T		
2.15	Any structural protuberance on the rocket will be located aft of the burnout center of gravity.	X	X		LVT6	All structural protuberance on the vehicle including but not limited to ABS shall be located aft of the burnout center of gravity as determined by analysis and center of gravity testing	Complete
2.16	The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit.	X		X	LVT4	Vehicle design softwares OpenRocket and RockSim shall be used to ensure the vehicle will accelerate to a minimum velocity of 52 fps at the rail exit, demonstrated at full-scale launches by analyzing recorded flight data.	Complete
2.17	All teams will successfully launch and recover a subscale model of their rocket prior to CDR.			X		The team has launched and recovered a subscale model of the rocket prior to CDR.	Complete
2.17.1	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			The subscale model was designed to be as accurately resembling the full scale model as possible, and was a separate vehicle from the full scale.	Complete
2.17.2	The subscale model will carry an altimeter capable of recording the model's apogee altitude.		X			The subscale model was designed with a payload section for carrying the same altimeter selected for scoring purposes in the full scale rocket.	Complete
2.17.3	The subscale rocket must be a newly constructed rocket, designed and built specifically for this year's project.		X			Team leaders ensured that the subscale rocket was newly constructed based on this year's design.	Complete
2.17.4	Proof of a successful flight shall be supplied in the CDR report.		X			A post launch assessment with test results and altimeter data has been published in this report	Complete
2.18	All teams will complete demonstration flights as outlined in Req. 2.18.1-1.18.2.4.			X	LVT4	The team shall complete demonstration flights under the supervision of team launch manager Dave Brunsting and the RSO.	Complete
2.18.1	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 criteria outlined in Req. 2.18.1.1-2.18.19 must be met. Req. details can be found in the NASA SL Handbook.			X	LVT4	The full scale vehicle shall be launched and safely recovered prior to FRR to verify the vehicle metrics listed in the NASA SL Handbook. The rocket flown shall be the final fight configuration and all major vehicle or payload changes shall be approved by the NASA Student Launch team and require a re-flight in accordance with the vehicle demonstration deadlines.	Complete
2.18.1.1	The vehicle and recovery system will have functioned as designed.			X	LVT4, RT4	The vehicle and recovery system shall function safely as designed and meet the relevant launch requirements as determined by collected flight data.	Complete
2.18.1.2	The full-scale rocket must be a newly constructed rocket, designed and built specifically for this year's project.		X			Team leaders shall ensure that the full-scale rocket is newly constructed, designed and built for this year.	Complete
2.18.1.3	The payload does not have to be flown during the full-scale Vehicle Demonstration Flight. Req. 2.18.1.3.1 and 2.18.1.3.2 still apply.		X			The team shall inspect whether the payload is flight-ready prior to the full-scale demonstration flight.	Complete
2.18.1.3.1	If the payload is not flown, mass simulators will be used to simulate the payload mass.			X		An appropriate mass simulator was secured in the same section as the payload to simulate payload mass during the first flight; See Section 5	Complete
2.18.1.3.2	The mass simulators will be located in the same approximate location on the rocket as the missing payload mass.			X		Mass simulator was secured in the payload bay	Complete
2.18.1.4	If the payload changes the external surfaces of the rocket or manages the total energy of the vehicle, those systems will be active during the full-scale Vehicle Demonstration Flight.			X	ABT6	ABS was active during the second full-scale demonstration flight, see Section 3.5.5	Complete
2.18.1.5	Teams shall fly the launch day motor for the Vehicle Demonstration Flight. The team may request a waiver for the use of an alternative motor in advance if the home launch field cannot support the full impulse of the launch day motor or in other extenuating circumstances.		X			The CTI L1395-BS motor was used for both demonstration flights, see Section 5	Complete
2.18.1.6	The vehicle must be flown in its fully ballasted configuration during the full-scale test flight. Additional ballast may not be added without a re-flight of the full-scale launch vehicle.			X		18 oz of ballast was added to the second demonstration flight, which will be the maximum flown at competition	Complete
2.18.1.7	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 RSO.		X			Systems and Safety officers shall enforce requirements that the launch vehicle and its components are not handled or modified by team members following flight without the approval of the NASA or local launch site RSO.	Complete
2.18.1.8	Proof of a successful flight shall be supplied in the FRR report. Altimeter data output is required to meet this requirement.			X		See section 5	Complete
2.18.1.9	Vehicle Demonstration flights must be completed by the FRR submission deadline. No exceptions will be made. If the Student Launch office determines that a Vehicle Demonstration Re-flight is necessary, then an extension may be granted (for re-flight only). Teams completing a required re-flight must submit an FRR Addendum by the FRR Addendum deadline.		X			Completed	Complete

Requirement		Verification Method				Verification Plan	Status
ID	Description	A	I	D	T		
2.18.2	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, further described in the NASA SL Handbook. Requirements 2.18.2.1-2.18.2.4 shall be met.		X			Completed. See section 4.8	Complete
2.18.2.1	The payload must be fully retained until the intended point of deployment (if applicable), all retention mechanisms must function as designed, and the retention mechanism must not sustain damage requiring repair.		X	X	PDT6	Retention validated in full-scale test flight	Complete
2.18.2.2	The payload flown must be the final, active version.		X			The team flew the final active payload. Any changes to the payload following the flight will require NASA Student Launch team approval and re-flight in accordance with the demonstration flight deadlines.	Complete
2.18.2.3	If the above criteria are 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			Payload and demonstration flights completed. See Sections 5 and 4.8	Complete
2.18.2.4	Payload Demonstration Flights must be completed by the FRR Addendum deadline.		X			A Payload Demonstration Flight was completed; See section 4.8	Complete
2.19	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 team shall complete an FRR Addendum for any required vehicle demonstration re-flights after the FRR deadline.	Complete
2.19.1	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			The team shall complete a vehicle demonstration re-flight and FRR addendum by the deadline as necessary or forfeit the permission to fly at launch week.	Complete
2.19.2	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 completed a successful payload demonstration flight prior to the Payload Demonstration Flight deadline.	Complete
2.19.3	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.		X			Full payload retention success is detailed in Section 4.8	Complete
2.20	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 include team information including name and contact information on the external of the vehicle by incorporating the information into the vehicle paint or applying external labels.	In Progress
2.21	All LiPo batteries will be sufficiently protected from impact with the ground and will be brightly colored, clearly marked as a fire hazard, and easily distinguishable from other payload hardware.		X			All LiPo batteries in the vehicle are sufficiently protected from impact with the ground and shall be clearly labeled with bright colors as a fire hazard. The team uses fire-proof lithium polymer battery carrying cases for transporting and storing batteries before and after the flight, shown in the Checklists	Complete
2.22	Vehicle Prohibitions		X			The listed vehicle prohibitions shall be inspected prior to all flights to ensure the vehicle is in compliance.	Complete
2.22.1	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		LVT4		The camera housings used do not affect vehicle stability, shown by full-scale flight tests	Complete
2.22.2	The launch vehicle will not utilize forward firing motors.		X			The vehicle does not utilize forward firing motors.	Complete
2.22.3	The launch vehicle will not utilize motors that expel titanium sponges.		X			The motor does not expel titanium sponges	Complete
2.22.4	The launch vehicle will not utilize hybrid motors.		X			The vehicle does not utilize hybrid motors	Complete
2.22.5	The launch vehicle will not utilize a cluster of motors.		X			The vehicle does not utilize a cluster of motors	Complete
2.22.6	The launch vehicle will not utilize friction fitting for motors.		X			Motor retention does not utilize friction fitting, shown in Section 3.3	Complete
2.22.7	The launch vehicle will not exceed Mach 1 at any point during flight.	X		X		The launch vehicle shall not exceed Mach 1 at any point during flight as determined by OpenRocket and RockSim analysis, and demonstrated by analyzing the recorded flight data.	Complete

Requirement		Verification Method				Verification Plan	Status
ID	Description	A	I	D	T		
2.22.8	Vehicle ballast will not exceed 10% of the total unballasted weight of the rocket as it would sit on the pad.		X			The vehicle ballast flown during Demonstration Flights was less than 10% of the total weight	Complete
2.22.9	Transmissions from onboard transmitters will not exceed 250 mW of power (per transmitter).	X				Transmissions from onboard transmitters does not exceed 250 mW of power as determined by the specifications of on-board transmitters	Complete
2.22.10	Transmitters will not create excessive interference. Teams will utilize unique frequencies, handshake/passcode systems, or other means to mitigate interference caused to or received from other teams.		X		X	Transmitters do not create excessive interference and utilize unique frequencies	Complete
2.22.11	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			Excessive and/or dense metal is not be utilized in the construction of the vehicle	Complete

Table 50: NASA Recovery Requirements

Requirement		Verification Method				Verification Plan	Status
ID	Description	A	I	D	T		
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 launch vehicle contains two separate parachute bays, one for the drogue parachute and one for the main. Each of the altimeters will be programmed to eject the drogue parachute at or shortly after rocket apogee, and the main parachute at 600 ft	Complete
3.1.1	The main parachute shall be deployed no lower than 500 ft			X	RT4	All of the recovery altimeters are programmed to eject the main parachute at an altitude of 500 ft or greater, verified with simulated flight tests and vehicle demonstration flights.	Complete
3.1.2	The apogee event may contain a delay of no more than 2 s		X			All of the recovery altimeters are programmed to eject the drogue parachute at apogee or between 0 and 2 s after apogee.	In Progress
3.1.3	Motor ejection is not a permissible form of primary or secondary deployment.		X			All recovery black powder ejection charges are controlled by commercial altimeters	Complete
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.				RT1	Before any rocket launch by the team, a ground separation test is performed on the rocket using an ejection charge of the same type and size to be used for the launch.	Complete
3.3	Each independent section of the launch vehicle will have a maximum kinetic energy of 75 $ft\text{-}lb_f$ at landing.	X		X		The main parachute will be appropriately sized to minimize KE. The expected landing KE simulated using OpenRocket and a custom Matlab simulator is about 63 $ft\text{-}lb_f$. Descent velocity data confirmed simulation accuracy, shown in Section 5.3.7	Complete
3.4	The recovery subsystem will contain redundant, commercially available altimeters.		X			The recovery ejection charges is controlled by two Featherweight Raven3 altimeters and one PerfectFlite Stratologger SL100 altimeter.	Complete
3.5	Each altimeter will have a dedicated power supply, and all recovery electronics will be powered by commercially available batteries.		X			Each altimter has a dedicated commercially available power supply, as described in Section 3.6.3	Complete
3.6	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			Section 3.6.4 discusses the arming switches used for recovery	Complete
3.7	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		RT4	The switches are rotary, preventing undesired disarming	Complete
3.8	The recovery subsystem electrical circuits will be completely independent of any payload electrical circuits.		X		RT2	In simulated launch environment, the full function of the recovery electronics was tested without the payload present to ensure independence from the payload	Complete
3.9	Removable shear pins will be used for both the main parachute compartment and the drogue parachute compartment.		X			The same number and configuration of shear pins was be used to secure the parachute compartments during ground separation tests and full launches.	Complete
3.10	The recovery area will be limited to a 2,500 ft radius from the launch pads.	X		X	RT4	The drift distance of the rocket after apogee was simulated in both OpenRocket and a custom Matlab simulator and was under 2,500 ft. The second demonstration flight, with higher winds, resulted in a drift distance of 2,110 ft	Complete
3.11	Descent time will be limited to 90 seconds (apogee to touch down).	X		X	RT4	The descent time after apogee was simulated using OpenRocket and a custom Matlab simulator to be 86 s worst case scenario. The descent time after apogee for demonstration flights was 68 and 83 s	Complete

Requirement		Verification Method				Verification Plan	Status
ID	Description	A	I	D	T		
3.12	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		The launch vehicle telemetry contains an active GPS transmitter, which is currently undergoing further testing	In Progress
3.12.1	Any rocket section or payload component, which lands untethered to the launch vehicle, will contain an active electronic tracking device.		X			All sections of the rocket will be tethered together, with a single dedicated GPS transmitter in one of the sections.	Complete
3.12.2	The electronic tracking device(s) will be fully functional during the official flight on launch day.			X	RT4	The GPS transmitter will be tested for functionality before the official flight on launch day.	In Progress
3.13	The recovery subsystem electronics will not be adversely affected by any other on-board electronic devices during flight (from launch until landing).			X	RT4	The rocket was be flown with all electronics active during a test launch before competition. Altimeter data was inspected afterwords and no adverse effects were detected.	Complete
3.13.1	The recovery subsystem 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			The recovery electronics are mounted in a recovery bay separate from the payload and any RF or EM transmitters or receivers.	Complete
3.13.2	The recovery subsystem electronics will be shielded from all onboard transmitting devices to avoid inadvertent excitation of the recovery subsystem electronics.		X			A conductive Faraday cage encases the recovery altimeters to prevent interference by any outside transmitters.	Complete
3.13.3	The recovery subsystem electronics will be shielded from all onboard devices which may generate magnetic waves to avoid inadvertent excitation of the recovery subsystem.		X			A conductive Faraday cage encases the recovery altimeters to prevent interference by any internal magnetic wave producing devices.	Complete
3.13.4	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			A conductive Faraday cage encases the recovery altimeters to prevent interference by any internal transmitters and other electronics.	Complete

Table 51: NASA Payload Requirements

Requirement		Verification Method				Verification Plan	Status
ID	Description	A	I	D	T		
4	All payload designs must be approved by NASA. NASA reserves the authority to require a team to modify or change a payload, as deemed necessary by the Review Panel, even after a proposal has been awarded.			X		The team acknowledges that designs must be approved by NASA and that NASA may request design changes.	Complete
4.2	University teams will design a system capable of being launched in a high power rocket, landing safely, and recovering simulated lunar ice from one of several locations on the surface of the launch field. The methods utilized will be at the teams' discretion and will be permitted so long as the designs are deemed safe, obey FAA and legal requirements, and adhere to the intent of the challenge. An additional experiment is allowed, and may be flown, but will not contribute to scoring. If the team chooses to fly an additional experiment, they will provide the appropriate documentation in all design reports so the experiment may be reviewed for flight safety.		X		PDT6	The team shall be competing in the university division and shall design a payload which meets the listed requirement. The team shall have discretion to design the payload but shall work with team mentors to verify the design is safe, meets FAA requirements, and adheres to the requirements of the challenge. An additional experiment will be flown (ABS), and is thoroughly documented in Section 3.5.5.	Complete
4.3.1	The launch vehicle will be launched from the NASA-designated launch area using the provided Launch pad. All hardware utilized at the recovery site must launch on or within the launch vehicle.		X			The launch vehicle will be launched from the NASA designated launch area using the provided launch pad. All hardware utilized at the recovery site shall be launched on or within the vehicle.	Complete
4.3.2	Five recovery areas will be located on the surface of the launch field. Teams may recover a sample from any of the recovery areas. Each recovery site will be at least 3 ft in diameter and contain sample material extending from ground level to at least 2 in. below the surface.			X	PRT13, PRT14	The team shall design the payload to be capable of traveling to one of the recovery areas and recover a sample extending at least 2 in. below the surface. The sample retrieval system will be tested.	In Progress
4.3.3	The recovered ice sample will be a minimum of 10 mL.			X	PRT13	The payload will be designed to be capable of recovering an ice sample with a minimum volume of 10 mL and the system will be tested.	In Progress
4.3.4	Once the sample is recovered, it must be stored and transported at least 10 linear ft from the recovery area.			X		The payload will be designed to be capable of transporting the recovered sample at least 10 linear ft from the recovery area and will be tested.	In Progress

Requirement		Verification Method				Verification Plan	Status
ID	Description	A	I	D	T		
4.3.5	Teams must abide by all FAA and NAR rules and regulations.		X			The team shall abide by all FAA and NAR rules and regulations. The team shall conduct a review with the team launch manager prior to the launch day to verify all regulations are met.	Complete
4.3.6	Black powder and/or similar energetics are only permitted for deployment of in-flight recovery systems. Any ground deployments must utilize mechanical systems.		X			The payload deployment shall utilize an in-flight black powder nose cone ejection system. See Section 4.5.2 for details.	Complete
4.3.7	Any part of the payload or vehicle that is designed to be deployed, whether on the ground or in the air, must be fully retained until it is deployed as designed.			X	PDT4, PDT6	The payload shall be designed to be fully retained until it is deployed as designed. This shall be verified in tests prior to launches and demonstrated during the demonstration flights.	Complete
4.3.7.1	A mechanical retention system will be designed to prohibit premature deployment.	X				The mechanical system was designed to prohibit premature deployment and has been analyzed using methods such as FEA to determine forces on the system to avoid premature deployment. See Section 4.5.1 for details on the retention system design and analysis.	Complete
4.3.7.2	The retention system will be robust enough to successfully endure flight forces experienced during both typical and atypical flights.			X	PDT4, PDT6	The retention system shall be subjected to shake tests to ensure the system is capable of enduring typical and atypical flight forces while still being reusable per Req. 2.4.	Complete
4.3.7.3	The designed system will be fail-safe.		X		PDT4, PDT6	The retention system is designed to be fail-safe to ensure that failure of any system components does not result in the payload being damaged or released prematurely. The system shall be designed with redundancy and thoroughly tested to avoid failures.	Complete
4.3.7.4	Exclusive use of shear pins will not meet Req. 4.3.7.		X			The team will not exclusively use shear pins for retention. See Section **??** for retention design details.	Complete
4.4.1	Any experiment element that is jettisoned during the recovery phase will receive real-time RSO permission prior to initiating the jettison event.		X			The payload will be completely retained during flight and recovery.	Complete
4.4.2	UAV payloads, if designed to be deployed during descent, will be tethered to the vehicle with a remotely controlled release mechanism until the RSO has given permission to release the UAV.		X	X		The payload will be completely retained during flight and recovery.	Complete
4.4.3	Teams flying UAVs will abide by all applicable FAA regulations, including the FAA's Special Rule for Model Aircraft.		X			The team shall abide by all FAA regulations and shall carefully review the regulations during each step of the development process.	Complete
4.4.4	Any UAV weighing more than .55 lbs. will be registered with the FAA and the registration number marked on the vehicle.		X			The team UAV weighing more than 0.55 lbs will be registered with the FAA and the registration number marked on the vehicle.	In Progress

Table 52: NASA Safety Requirements

Requirement		Verification Method				Verification Plan	Status
ID	Description	A	I	D	T		
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 LRR and any launch day operations.		X			The team shall write and maintain a launch and safety checklist which shall be included in the FRR and LRR reports. The Safety and Systems team shall lead development and enforcement of these safety procedures.	Complete
5.2	Each team must identify a student safety officer who will be responsible for all items in Req. 5.3.		X			The team has elected Brooke Mumma to serve as the safety officer who will lead the Safety and Systems team. As such she shall be responsible for all safety matters in accordance with Req. 5.3.	Complete
5.3	The role and responsibilities of the safety officer will include, but are not limited to those listed in Req. 5.3.1-5.3.4.		X			The safety officer shall manage the responsibilities listed.	Complete
5.3.1.1-5.3.1.9	The safety officer shall monitor team activities with an emphasis on safety during design of vehicle and payload, construction of vehicle and payload components, assembly of vehicle and payload, ground testing of vehicle and payload, full-scale launch test(s), subscale launch test(s), launch day, recovery activities, and STEM engagement activities.		X			The safety officer shall monitor all listed team activities during the full development cycle of the team throughout the year. The safety officer shall focus on the safety of the team and shall have the discretion to maintain enforcement methods for handling safety violations.	Complete
5.3.2	The safety officer shall implement procedures developed by the team for construction, assembly, launch, and recovery activities.		X			The Safety and Systems team shall manage the design teams in writing procedures for construction, assembly, launch, and recovery activities and shall ensure the procedures meet safety requirements following a standardized format set by the team.	Complete

Requirement		Verification Method				Verification Plan	Status
ID	Description	A	I	D	T		
5.3.3	The safety officer shall manage and maintain current revisions of the team's hazard analyses, failure modes analyses, procedures, and MSDS/chemical inventory data.		X			The Safety and Systems team shall maintain the team's hazard analyses, failure mode analyses, procedures, and MSDS inventory data. The team shall conduct frequent revision meetings.	Complete
5.3.4	The safety officer assist in the writing and development of the team's hazard analyses, failure modes analyses, and procedures.		X			The Safety and Systems team shall lead writing and development of the analyses and procedures listed.	Complete
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 Safety and Systems lead, team captains, and team launch manager shall communicate with the local RSO to ensure the vehicle meets all local configuration requirements and address any safety concerns of the local RSO.	Complete
5.5	Teams will abide by all rules set forth by the FAA.		X			The team shall abide by all FAA rules and regulations and will conduct frequent reviews to ensure continued compliance.	Complete

7.2.2 Team Derived Requirements

Table 53: Derived Launch Vehicle Requirements

Requirement				Verification Method				Verification Plan	Status
ID	NASA Parent ID	Description	Justification	A	I	D	T		
V.1	2.5	The vehicle will have three in-flight separation points to allow for a drogue and main parachute deployment and payload deployment, and ABS integration will occur through a separation point not used in-flight.	A drogue parachute is necessary to slow vehicle and decrease drift, and nose cone ejection allows for payload deployment.		X			The design of the rocket will have three in-flight separation points, two covered by bulkhead for recovery, one for nose cone ejection, and a fourth for ABS integration not in-flight.	Complete
V.2	3.11	The separated sections must be approximately equal in weight during descent.	This will minimize descent time.		X			An updated weight budget for the launch vehicle will be kept updated at all times.	Complete
V.3	2.22.8	The vehicle must have a fully designed and integrated ballast area at the rocket's Cg to diminish ballast's effect in the vehicle's stability. The ballast area must hold up to 10% of total vehicle weight.	In the case that payloads are under weight budget, ballasting will be necessary to meet target apogee		X			The ballast area will be designed to fit in the area closest to the rocket's Cg.	Complete
V.4	2.1, 2.2	The vehicle is designed to reach a 4,444 ft altitude.	Target apogee must be set by the team	X			LVT4, ABT1-ABT5	Simulation software will be used to verify vehicle designs reach a 4,444 ft apogee in a simulated environment, and full scale test flights shall be used to verify the accuracy of the simulation and completion of the requirement.	Complete
V.5		The payload bay shall be a fiber glass body tube with an 8 in. OD and 20 in length.	Payload bay must be radio transparent for signals to payload		X			The team designed the rocket to provide the required dimensions for the payload system. See Section 3.3 for design details.	Complete
V.6		ABS must be secured to the rest of the vehicle and fill the full aft diameter of the rocket.	Avoid force unbalance due to movement of the tabs.		X			ABS will be designed for ideal integration into the aft part of the rocket. See Section 3.5.2 for details on ABS design.	Complete
V.7		The vehicle shall not exceed a maximum length of 12 ft.	Vehicle must be easily transported		X			The total length of the full scale rocket will be measured when construction material is delivered.	Complete
V.7.1		The recovery body tube will not exceed a maximum length of 48 in.	Length budget to fulfill V.7	X				The recovery body tube was designed under that length, shown in Section 3. Measurements will be made during fabrication to confirm that this requirement is met.	Complete
V.7.2		ABS will not exceed 11.5 in. in length to fulfill V.7.		X				ABS was designed within this length restriction. See Section 3.5.2 for design details. Measurements will be made during fabrication to confirm that this requirement is met.	Complete
V.8	2.2	The vehicle shall not exceed a maximum weight of 70 lbs.	Vehicle must be able to achieve target apogee			X		The launch vehicle will be weighted with all of the systems before launch.	Complete
V.8.1		ABS will not exceed 70 oz in weight.	Weight budget to fulfill V.8		X			ABS was designed to weigh less than 70 oz. Design details can be found in Section 3.5.2. Measurements will be made during fabrication to confirm that this requirement is met.	Complete
V.9		The vehicle must house a camera that looks downward with an angle of visibility that includes ABS.	Allows view of ABS tab extension and retraction.		X			A housing area will be integrated and a securing mechanism will be designed to safely hold the camera in place. See Section 3.3 for design details.	Complete
V.10	2.14	The stability margin of the vehicle with the motor must be between 2 and 3 calibers.	Avoid any possibility of vehicle tilting into the wind	X		X	LVT6	Flight simulation applications will be used to design for a 2-3 caliber stability margin and before test flights the actual Cg will be measured to calculate the stability margin.	Complete
V.11	4.2	The motor selection must tend towards overshooting rather than undershooting the target apogee.	Allow use of ABS	X		X		The motor selection will be based on flight simulations and test flights will determine predicted vs actual apogee. See Appendix ?? for simulation details.	Complete
V.12		Epoxied bulkheads must be able to hold the load of drogue and main parachute deployments.	Load bearing bulkheads must not break under max load				LVT3	Solid testing will be designed to test max force that an epoxied bulkhead can withstand.	Complete

Requirement				Verification Method				Verification Plan	Status
ID	NASA Parent ID	Description	Justification	A	I	D	T		
V.13		Removable bulkhead attached to ABS must be able to withstand the load of drogue and main parachute deployments.	Failure of the bulkhead or the securing screws would prevent the ability to execute a successful landing	X				Analysis of the stresses experienced by the bulkhead and screws during deployment will help determine material and dimensional requirements to ensure these components will not fail.	In Progress
V.14	2.15	The ABS drag tabs must extend at a location no greater than 1 in. from the CP.	The induced drag force shall not result in destabilizing moments		X			The integration design of ABS will focus on the location of the tabs in relation to the CP, shown in Section 3.3. Measurements will be made during fabrication to confirm that this requirement is met.	In Progress

Table 54: Derived Recovery Requirements

Requirement				Verification Method				Verification Plan	Status
ID	NASA Parent ID	Description	Justification	A	I	D	T		
R.2		The parachutes, shroud lines, and shock cordage shall be protected from potential damage due to the ejection charges.	Ejection charges can burn the parachute, reducing its ability to successfully slow down the rocket			X	RT1	A Nomex deployment bag is used to contain the folded main and drogue parachutes to protect them from the ejection charges. Ground separation tests have been performed to ensure adequate parachute protection before launch.	Complete
R.4	3.4	System shall be redundant such that any 2 component failures (such as altimeter malfunction, battery disconnect, or defective E-match) do not compromise the ability to safely recover the vehicle and complete the mission.	Redundant components increase the reliability of the recovery system and decrease the likelihood of parachute deployment failure			X		Three independent altimeters are used to control parachute deployment, with each altimeter fully capable of deploying both parachutes at the proper times.	Complete
R.5		The altimeter compartment shall be sealed off from the parachute compartment to prevent the ejection charges from damaging the electronics.	Ejection charges can damage exposed altimeters and hinder main parachute deployment			X	RT1	Ground separation testing has been performed and altimeter data has been analyzed after both test flights for sudden dips in altitude just after apogee, which is indicative of the ejection charge gasses entering the altimeter bay.	Complete
R.6		The recovery system shall be capable of being "safed" after landing, in the event that an ejection charge has failed to deploy.	A method of external safety allows for safe retrieval of the rocket in the case of a live deployment charge.			X	RT6	In a simulated launch environment, an attempt has be made to initiate the ejection charge with one of the stops in place.	Complete
R.7	3.12	On-vehicle telemetry shall weigh less than 20 ounces	Weight budget ensures apogee is reached			X		Weight will be measured	Complete
R.8	3.12	On-vehicle telemetry shall be packaged in nose cone	Adequate space must be available for other subsystems, specifically for the LSRS			X		CAD Model will be used to verify the size of the final system	Complete
R.9	3.12, 2.7	Portable power sources shall keep on-vehicle telemetry and relay station operational for well over the mission time	Telemetry goals cannot be met under power shortage	X				From calculations of max. current draw from the system, selected batteries will yield operational times orders of magnitude beyond mission time	Complete
R.10	3.12	On-vehicle telemetry shall store all transmitted data locally	Verifies that data was not corrupted in the wireless link			X		Sample data will be stored on the SD card before flight, and it will be verified that it can be read from a laptop; during test launches, on-vehicle stored data will be read and inspected after launch	Complete
R.11	3.12	On-vehicle telemetry shall transmit reliably over an approximate range of 5500 ft through empty atmosphere	Ensures data is able to be transmitted to the relay station throughout entirity of the flight of the vehicle				RT3	Transmitter Range Test	Complete
R.12	3.12	Telemetry relay station shall transmit reliably over an approximate range of 2500 ft at ground level	Ensures data can be transmitted from the relay station to the ground station			X	RT3	Transmitter Range Test	Complete

Requirement				Verification Method				Verification Plan	Status
ID	NASA Parent ID	Description	Justification	A	I	D	T		
R.13	3.12	Ground station GUI shall report GPS data (latitude, longitude, altitude), accelerometer data (three axis acceleration, angular velocity, vehicle orientation), and altimeter data (vehicle altitude) as received	GUI should report a live view of the current status of the vehicle		X			Data received by the ground station will be accurately displayed by the GUI by inspection	In Progress

Table 55: Derived Payload Requirements

Requirement				Verification Method				Verification Plan	Status
ID	NASA Parent ID	Description	Justification	A	I	D	T		
P.1		The Rover must not have an overall width larger than 6 in.	Constraining the Rover to a 6 in. maximum width gives the other subsystems a dimension to design around		X			All Rover body designs will be constrained to a width of 6 in.	Complete
P.2	4.3.2	The Rover must be able to overcome small obstacles such as rocks, corn stalks, and crop rows.	The terrain where the launch will be conducted is not flat and easy to navigate, so the Rover should be able to overcome any obstacles it may encounter.			X	PRT5, PRT6	The translation mechanism will be tested traversing multiple types of obstacles	In Progress
P.3	4.3.2	The Rover must be able to traverse through mud, puddles, corn stalks, and corn fields.	The state of the terrain is variable and the rover should be designed to overcome any terrain it may experience.			X	PRT5	The rover will be tested traversing through various terrains that may be present at the launch including mud, puddles, and high cut corn	In Progress
P.4	4.3.2	The Rover must secure all electronics.	As the Rover traverses rough terrain, all electronics must stay in place to remain functioning.		X	X	PRT5	After a drive test, electronics will be inspected to see if they have shifted.	In Progress
P.5		The Rover must not weigh more than 40 oz.	The Rover must not contribute more than 40 oz to the overall payload weight budget so that the launch vehicle weight is on target.		X			An up to date weight budget of all components will be maintained to keep track of the weight of the systems.	Complete
P.6	4.3.2	The Rover must have a minimum operating time of 20 min.	A 20 min operating time will provide adequate time for the Rover to traverse to the closest CFEA			X	PRT9	Operating time calculations will be conducted at various design milestones to verify the selected components will enable the Rover to operate for a minimum of 20 min. A drive time test will be completed.	In Progress
P.7		The Rover must have a manual override switch.	A manual override enables the operator to take control of the Rover should an error occur in the control code.		X	X	PRT4	All control software will be required to have a manual override built into the code. A manual override test will be completed.	Complete
P.8	2.7	The Rover will remain dormant until receiving the initiation signal from the UAV.	A low power mode will conserve the battery life of the Rover prior to deploying.			X	PRT10	Various testing will be conducted with the Rover in the low power mode to ensure that no external force or signal will bring the Rover out of the dormant state.	In Progress
P.9		The UAV must be no larger than 4 in x 4 in.	This constraint enables the UAV to fit inside the payload bay without the need for moving arms.		X			The UAV design was restrained to 4 in x 4 in. See Section **??** for UAV design details.	Complete
P.10		The UAV frame must protect the battery.	Damage to the battery can result in catastrophic failure.		X	X		All UAV frame designs will be required to have no moving parts and all components will need to be statically secured. See Section **??** for design details.	Complete
P.11		The UAV must weigh under 24 oz.	Constraining the UAV to a maximum weight will prevent the payload from going over weight.		X			An up to date weight budget of all components will be maintained to keep track of the weight of the systems.	Complete

Requirement				Verification Method				Verification Plan	Status
ID	NASA Parent ID	Description	Justification	A	I	D	T		
P.12	4.3.2	The UAV must have a minimum flight time of 10 min.	A 10 minute flight time will provide adequate time for the UAV to search the area around the Rover.			X		Flight time calculations will be conducted at various design milestones to verify the selected components and the selected frame design will enable the UAV to fly for a minimum of 10 min.	In Progress
P.13		The UAV must use a commercial flight controller.	Using a commercially available flight controller expedites the flight software development process		X			A commercial flight controller for the UAV has been selected.	Complete
P.14		The UAV must have a manual override switch.	A manual override enables the operator to take control of the UAV should an error occur in the flight code		X	X	PUT3	All flight software will be required to have a manual override built into the code.	Complete
P.15	4.3.3	The Sample Retrieval system must recover a minimum sample size of 10 mL	A 10 mL sample collection is required for mission success.			X	PRT12	The system has been designed to collect 10 mL of sample. The system will be extensively tested to ensure it consistently retrieves a sample no smaller than 10 mL.	Complete
P.16	4.3.2	The Sample Retrieval system must be able to correctly orient itself for retrieval operations.	A self orienting sample retrieval system will allow the Rover to be in any position while the retrieval system is operating			X	PRT13	The retrieval system has been extensively tested to verify it can correctly orient itself to perform the retrieval operations consistently and reliably.	Complete
P.17	4.3.4	The Sample Retrieval system must retain and protect the recovered sample from spillage and contamination.	Securing the sample once it is collected will ensure successful deliver of the sample from the CFEA.		X	X	PRT11	The sample container has been water tested to ensure no contaminants can leak into the container and the containerhas been tested through sample retrieval simulations to ensure no amount of sample can spill out of the container during the translation of the Rover.	Complete
P.18		The Sample Retrieval system must interface with the Rover electronics.	Reduces system complexity and reduces the risk of failure			X	PRT13	The sample retrieval team will communicate regularly with the Rover electronic team to ensure that the retrieval system can integrate into the electronic system of the Rover.	In Progress
P.19		The Sample Retrieval system must be easily integrated with the Rover frame.	Reduces system complexity and reduces the risk of failure		X	X		The team is utilizing Fusion 360 and cloud based models to ensure all assemblies use up to date models and all systems integrate together.	Complete
P.20	4.3.7.3	The Deployment system must have multiple fail-safes.	This will ensure system success despite a component failure within the system	X		X	PDT4, PDT6	All designs of the deployment system will include a minimum of two redundant locking mechanisms for restricting motion of components in the bulkhead of the vehicle. See Section 4.5 for deployment design details.	Complete
P.21		The Deployment system must be able to correctly orient the Rover and UAV regardless of the landing position of the upper section of the vehicle.	The orientation of the Rover is paramount to mission success			X	PDT1, PDT6	The orientation system will be extensively tested with the bulkhead section of the vehicle to ensure that it consistently and reliably orients the Rover and UAV for multiple orientations and landings of the bulkhead section of the vehicle.	In Progress
P.22	4.3.7.1	The Deployment system must restrict motion of the Rover and UAV in all directions until the deployment sequence is initiated.	Flight stability is dependent on all components in the payload bay remaining locked in place			X	PDT2-PDT6	All designs of the deployment system will be required to restrict motion of the Rover and UAV in the X, Y, and Z directions. All motion restricting designs will be extensively tested to verify proper functionality.	Complete
P.23	4.3.2	The target detection system must correctly identify the closest CFEA.	Minimize travel time and distance for the Rover.			X	PUT5, PUT7	The target detection software will be tested to consistently locate the closest CFEA during multiple simulations in which fluorescent material will be placed on multiple types of terrain. See Section 4.6.3 for system details.	In Progress
P.24	4.3.2	The target detection system must identify the corner of the CFEA that is furthest from the Rover.	Reduced risk of the Rover driving over the UAV			X	PUT6	The target detection software will be tested to correctly and reliably identify the corner of the CFEA that is furthest from the Rover.	In Progress

Requirement				Verification Method				Verification Plan	Status
ID	NASA Parent ID	Description	Justification	A	I	D	T		
P.25	4.3.7	The nose cone must eject after main parachute deployment at 400 ft.	To facilitate payload deployment, the nose cone will be ejected at 400 ft. This will ensure that nose cone ejection does not interfere with recovery.			X	PDT6, PDT7	Ground black powder ejection tests will be performed as well as a full scale test with nose cone deployment.	Complete

Table 56: Derived Systems and Safety Requirements

Requirement				Verification Method				Verification Plan	Status
ID	NASA Parent ID	Description	Justification	A	I	D	T		
S.1	5.3.1.7	Prior to any launch, team members shall be briefed and tested about safety and procedures in accordance with NAR/TAR and NDRT regulations.	To ensure the safety of team personnel, members must be informed of the hazards at launch and proper procedures		X			Attendance will be taken at pre-launch briefings and any members not in attendance will not be eligible to attend the launch. Members failing to pass the safety quiz will not be eligible to attend the launch.	Complete
S.2	5.3.1.2	Prior to construction of subsection components and the full assembly, schematics and procedures shall be published to ensure correct and safe manufacturing and assembly techniques.	Provides clarity which makes the construction process safer and more efficient.		X			Schematics will be created based on finalized 3D models and available in the workshop prior to any construction.	Complete
S.3	5.3.3	The team shall maintain updated records of the team's hazard analyses, failure modes analyses, procedures, and MSDS/chemical inventory data and will use this information to drive design, construction, and testing decisions.	Allows the team to make safer and improved decisions		X			Documentation will be available, reviewed, and updated on a regular basis. The most current version will be available on the team shared drive.	Complete
S.4	5.3.1.2	Each NDRT member participating in construction shall be certified on the machines and tools used in accordance to the Notre Dame Student Fabrication Lab standards.	Requiring certifications for workshop tools ensures that members learn the proper technique and are informed of workshop hazards.		X			Members will receive a card that indicates which tools they are certified on. Each team member must present this card to a team officer before working on any construction.	Complete
S.5	5.3.1.4	Each subsection of the vehicle and payload shall be tested individually before the full scale test.	Allows the team to identify and correct errors prior to full-scale testing, increasing probability of a successful mission.		X			The Safety and Systems Team will work with each design team to develop testing plans and rigs prior to conducting tests. The physical copy of the testing plan will be used for running the test, and the test results will be filed digitally.	Complete
S.6	5.3.1.4	The team will develop detailed test procedures at the component and full-scale level to ensure that the designs are robust and reliable.	Allows for standardization of documentation and streamlined communication; ensures that members go into testing fully prepared.		X			A generic test procedure format will be available to the technical leads to modify. Each subsystem will present their testing results prior to full scale assembly.	Complete

7.3 Project Budget

The Notre Dame Rocketry Team has budgeted $20,753 for this year's NASA Student Launch. Itemized budgets with allocations outlined in Table 59 are kept up to date by each lead. The captain monitors the overall budget. Each purchase is carefully researched to ensure the selection of the most reliable and affordable vendor. Per General Requirement 1.2, updates and modifications to the budget will continue until the submission of the final budget summary in PLAR.

7.3.1 Project Sponsorship

The Notre Dame Rocketry Team's participation in the NASA Student Launch would not be possible without the support of our generous sponsors. Table 57 catalogs the contributors to Notre Dame's project.

Table 57: NDRT 2019-2020 Sponsorship

Funding Source	Amount
Carryover (2018/19)	$2,722
Team Merchandise	$160
ND Day Fundraising	$671
The Boeing Company	$10,000
Pratt & Whitney	$5,000
ND EE Department	$1,000
Jim Lampariello (Blue Origin Systems Engineer)	$1,000
GE Aviation	$200
TOTAL FUNDING	**$20,753**

As shown in Table 57, corporate sponsorship constitutes the primary revenue source for the team. This year's corporate sponsors include The Boeing Company, Pratt & Whitney, NDRT's founder Jim Lampariello, and GE Aviation. The Notre Dame Rocketry Team is optimistic about funding from the following sources, listed in Table 58, for the remainder of the year.

Table 58: NDRT 2019-2020 Future Pursuits

Funding Source	Amount
Michiana Rocketry Club Raffle Proceeds	$200
Notre Dame Rocketry Class of 2018 Donation	$200
Notre Dame Department of Aerospace and Mechanical Engineering	$1,000
TOTAL FUNDING	**$1,400**

7.3.2 Project Revenue Allocation

NDRT has allocated approximately 40% of the budget to Vehicle Design, which encompasses the Air Braking System and the Recovery Subsystem. At $2,000, the Lunar Sample Retrieval System was allocated approximately 10% of the budget. Funding for travel to the competition comprises approximately 43% of the budget. Purchases for Competition Travel include team lodging, mentor lodging, gasoline, vehicle rental, and meals for the team. The remaining 7% of the $20,753 was apportioned to Systems & Safety, STEM Engagement, and miscellaneous purchases such as networking dinners with donors and car repairs for test launch travels. Table 59 outlines NDRT's current revenue allocation (not including future pursuits).

Table 59: NDRT 2019-2020 Project Allocation

Allocation	Amount	Spent	Percent Spent
Vehicle Design	$5,000	$4,420.48	88.41%
Air Braking System	$1,300	$1,051.15	80.86%
Recovery Subsystem	$2,000	$1,459.06	72.95%
LSRS	$2,000	$1,837.96	91.90%
Systems & Safety	$650	$231.44	35.61%
STEM Engagement	$300	$132.25	44.08%
Competition Travel	$9,000	$9,000	100%
Miscellaneous Expenses	$500	$488.63	97.73%
TOTAL ALLOCATION	**$20,750**	**$18,620.97**	**89.74%**

7.3.3 Line Item Budgets

Table 60 details NDRT's project revenue allocation. Listed are the items that the team has purchased thus far. Table 60 presents the purchased materials for the Recovery Subsystem, Systems & Safety, Vehicle Design, LSRS, ABS, and STEM Engagement. Also included in the table are Miscellaneous Expenses and Competition Travel expenses.

Table 60: Itemized Budget.

Recovery Subsystem Components	Vendor	Description	Qty	Price per Unit	Total Cost
3.7 V 170 mAh LiPo	Wing Deli Storefront	Rechargeable Battery Pack	5	$7.48	$37.40
UP-S6 1 s LiPo Battery Charger	Crazepony-Power	LiPo Battery Charger	1	$24.21	$24.21
AC to DC Power Adapter 12 V	Crazepony-Power	Power Cord for Charger	1	$11.56	$11.56
Through Mount Slotted Switch	Aerocon Systems	Switch for Recovery Activation	3	$9.01	$27.00
Magnetic Switch	Featherweight Altimeters	Switch for Recovery Activation	3	$28.34	$85.00
JST PH 2.0 MM Connectors, 30 sets	LATTECH	Connectors for Batteries	1	$7.99	$8.55
$\frac{1}{8}$ in. Kevlar Shock Cord	Top Flight Recovery LLC	Subscale Shock Cord	10	$2.55	$25.50
1 in. Tubular Nylon Shock 35 ft Cord	OneBadHawk Recovery	Full-Scale Shock Cord	2	$38.00	$76.00
1 in. by 8 in. Oak Board	Home Depot	CRAM Body and Adapter Material	8	$6.28	$50.25
IFC-120-S	FruityChutes	Main Parachute	1	$575.12	$575.12
1.566 in. Slider Ring	FruityChutes	Main Parachute Slider Ring	1	$4.00	$4.00
6 in. 13 in. Deployment Bag	FruityChutes	Protection for Main Parachute	1	$51.60	$51.60

$\frac{1}{8}$ in. Garolite G10	McMaster-Carr	CRAM bulkhead material	1	$18.64	$18.64
CAM-M8C-0-10 GPS	Digi-Key	RF Receiver, GLONASS, GNSS, GPS 1.575 GHz-167 dBm	1	$25.00	$25.00
KX222-1054 Accelerometer	Digi-Key	Accelerometer	1	$9.41	$9.41
BNO055 Accelerometer	Digi-Key	Accelerometer	1	$11.16	$11.16
MPL3115A2 Altimeter	Digi-Key	Altimeter	1	$5.80	$5.80
3.7 V 2500 mAh Lithium Ion Polymer Battery	Adafruit	Lithium Ion Polymer Battery	2	$14.95	$29.90
32-bit PIC32 Microcontroller	Microchip Technology	Microcontroller	3	$4.00	$12.00
ADF7030-1 RF Transceiver	Mouser Electronics	Transceiver	3	$5.10	$15.30
HMC452ST89 1 W Power Amplifier	Analog Devices	Power Amplifier	2	$11.71	$23.42
ANT-433-MHW-SMA-S 433 MHz Antenna	Digi-Key	Antenna	1	$15.04	$15.04
128 GB Micro SD Card - SDSQUAR-128G-GN6MA	SanDisk	Memory Card	1	$19.49	$19.49
FTDI FT230XS-R USB to UART	Mouser Electronics	USB Interface	1	$2.04	$2.04
ADF7030-1 EZ-KIT Evaluation & Development Kit	In House	Evaluation board	1	$0.00	$0.00
ADZS-UCM3029EZLITE Motherboard	In House	Motherboard	1	$0.00	$0.00
$\frac{1}{4}$-20 Hex Head Screws, 10 pack	McMaster-Carr	Bolts for CRAM	1	$7.51	$7.51
$\frac{1}{4}$-20 Hex Nuts, 100 pack	McMaster-Carr	Nuts for CRAM	1	$6.36	$6.36
$\frac{3}{8}$ Extreme-Strength Steel Coupling Nut	McMaster-Carr	Eyebolt Coupling Nut	1	$38.83	$38.83
$\frac{3}{8}$ 1.25 in. Steel Eyebolt	McMaster-Carr	Recovery eyebolts	2	$5.28	$10.56
$\frac{3}{8}$ 2.5 in. Steel Eyebolt	McMaster-Carr	Recovery eyebolts	2	$13.95	$27.88
$\frac{3}{8}$ Stainless Steel Quicklink	McMaster-Carr	Recovery Quicklinks	2	$11.50	$23.00
Buna-N Rubber Sheet, 1/32 in., 1 ft by 3 ft	McMaster-Carr	Black Powder Seals	1	$13.31	$13.31
Buna-N Rubber Sheet, 1/16 in., 1 ft by 3 ft	McMaster-Carr	Black Powder Seals	1	$16.98	$16.98
Foam Mounting Tape	McMaster-Carr	Battery Retention	1	$24.67	$24.67
Copper Foil Tape	McMaster-Carr	EM Shielding	1	$21.85	$21.85
20 pcs Solderable Prototype Boards	Chanzon	Solderable perfboards	1	$9.50	$9.50
Wago 221-412 2 Conductor Lever Nuts	Amazon Services LLC	E-match wire connectors	1	$24.68	$24.68
Oversized $\frac{3}{8}$ Washers	McMaster-Carr	Payload Bulkhead Washers	1	$13.29	$13.29
$\frac{1}{8}$ in. Garolite G10, 12 by 12 in.	McMaster-Carr	Telemetry Bulkhead	1	$25.88	$25.88
#2-56 Socket Head Cap Screws	McMaster-Carr	Altimeter Retention	1	$11.20	$11.20
#2-56 Low-Strength Hex Nuts	McMaster-Carr	Altimeter Retenton	1	$3.73	$3.73
#2 Unthreaded Nylon Spacers, $\frac{1}{4}$ in.	McMaster-Carr	Altimeter Retention	1	$12.26	$12.26
#4-40 by 1 in. Machine Screws	Lowes	Altimeter/Board Retention	1	$1.37	$1.37
#4-40 by $\frac{3}{4}$ in. Machine Screws	Lowes	Altimeter/Board Retention	1	$1.37	$1.37
#10-24 by $\frac{1}{2}$ in. Machine Screws	Home Depot	Telemetry Retention	1	$1.42	$1.42
		TOTAL COST			**$1459.06**
		Budget Allocation			$2000.00
		Margin			$540.94
Systems & Safety Components	Vendor	Description	Qty	Price per Unit	Total Cost
Vinyl Gloves (200)	Walmart	PPE	1	$11.98	$11.98
Face Masks (5)	Walmart	PPE	4	$0.97	$3.88
Lysol Wipes	Walmart	Cleaning	1	$2.98	$2.98
Microblading Cotton Swab Tips (400)	PRESKBOO	Epoxy Applicators	1	$16.68	$16.68
$\frac{3}{16}$ in. G10 12 by 24 in.	McMaster-Carr	Testing	1	$43.94	$58.77
$\frac{1}{8}$ in. G10 12 by 24 in.	McMaster-Carr	Testing	1	$27.89	$27.89
Nitrile Gloves (50)	Home Depot	PPE	1	$8.21	$11.22
5 Minute Epoxy	Evenu	Epoxy	1	$17.92	$19.17
Rocketpoxy	Apogee Components	Epoxy	1	$43.75	$59.10
24 Sandpaper Set	SmellS	Sand Paper	1	$5.99	$7.28
ESG Bags	LJY Direct	ESG Bags	1	$12.49	$12.49
		TOTAL COST			**$231.44**
		Budget Allocation			$650.00
		Margin			$418.56
Vehicle Design Components	Vendor	Description	Qty	Price Per Unit	Total Cost
RockSim Licenses	Apogee Components	General	4	$20.00	$80.00
G80T-7 Motors	Apogee Components	Subscale	3	$35.30	$105.90
Motor Retainer	Apogee Components	Subscale	1	$10.00	$10.00
Nose Cones 11.25 in. long	Apogee Components	Subscale	2	$22.19	$44.38
Payload Bay (3 in. tube)	Apogee Components	Subscale	1	$11.17	$11.17
66 mm Tubing	Apogee Components	Subscale	1	$13.00	$13.00
Balsa Sheet	Apogee Components	Subscale	1	$1.76	$1.76
Couplers	Apogee Components	Subscale	5	$16.75	$83.75

Motor Mount (29 mm Tubing)	Apogee Components	Subscale	1	$4.99	$4.99
Epoxy Clay	Apogee Components	Subscale	1	$14.95	$14.95
Taxes & Shipping	Apogee Components	Subscale	1	$86.48	$86.48
$\frac{1}{8}$ in. Plywood	Home Depot	Subscale	1	$11.74	$11.74
RocketPoxy	Apogee Components	Solid Testing	1	$43.75	$43.75
Fiberglass Bulkhead	Apogee Components	Solid Testing	3	$9.80	$29.40
Taxes & Shipping	Apogee Components	Solid Testing	1	$17.41	$17.41
G80 Motors	Impulse Buys Motor Dealer	Subscale	2	$30.00	$60.00
FIN-2SQFT-125	Public Missiles	Full-Scale: G10 Sheet for Fins	3	$67.89	$203.67
CFAF-3.0-PRMx60 (0.054 thickness)	Public Missiles	Full-Scale: Carbon Fiber Motor Mount	1	$229.95	$229.95
CFAF-6.0-PRMx60 (0.054 thickness)	Public Missiles	Full-Scale: Carbon Fiber Tubing	2	$439.95	$879.90
CFCT-6.0x11.75 (0.056 thickness)	Public Missiles	Full-Scale: Carbon Fiber Tubing	2	$94.95	$189.90
CF Airframe Cutting	Public Missiles	Full-Scale: Custom Cuts	3	$6.00	$18.00
CF Airframe Slotting	Public Missiles	Full-Scale: Custom Slots	8	$6.00	$48.00
8 in. G12 Airframe	Madcow Rocketry	Payload Bay Fiberglass Tubing	1	$340.00	$388.00
Motor Retainer	Apogee Components	Full-Scale Motor	1	$56.67	$56.67
Fiberglass Tube Bulkhead	Apogee Components	ABS Aft Bulkhead	2	$9.80	$19.80
1515 Large Rail Buttons	Apogee Components	Rail Buttons	1	$11.17	$11.17
$\frac{3}{16}$ in. Fiberglass Sheet	McMaster-Carr	Bulkhead for Main Parachute	1	$25.28	$25.26
316 Stainless Steel Washer 2 in. OD	McMaster-Carr	Washer for Main Deployment	1	$7.62	$7.62
Nose Cone & Transition Section	Innovation Park at Notre Dame	Full-Scale 3D Prints	1	$816.62	$816.62
CFCT-6.0 by 14.75	Public Missiles	Full-Scale Coupler	1	$129.95	$129.95
Apogee Tax & Shipping	Apogee Components	Various Full-Scale Components	1	$17.00	$17.00
PML Tax & Shipping	Public Missiles	Full-Scale Coupler	1	$12.95	$12.95
Cesaroni L1395 Blue Streak Rocket Motor	Wildman Rocketry	Motor	1	$353.44	$353.44
Steel Eyebolt with Shoulder $\frac{1}{4}$ in.-20 Thread Size, 1 in. Length	McMaster-Carr	Eyebolts (Telemetry)	1	$3.21	$3.21
High-Strength Steel Nylon-Insert Locknut $\frac{1}{4}$ in.-20 Thread Size	McMaster-Carr	Locknuts (Telemetry)	1	$3.22	$3.22
Nylon Unthreaded Spacer, $\frac{1}{4}$ in. OD, 1 in. Long, for Number 8 Screw Size	McMaster-Carr	Spacers (Telemetry)	1	$12.79	$12.79
18-8 Stainless Steel Nylon-Insert Locknut, 8-32 Thread Size	McMaster-Carr	Locknuts (Telemetry)	1	$5.16	$5.16
Steel Socket Head Screw, 8-32 Thread Size, 1-$\frac{1}{2}$ in. Long, Partially Threaded	McMaster-Carr	Head Screws (Telemetry)	1	$8.87	$8.87
Steel Socket Head Screw, 8-32 Thread Size, 2-$\frac{1}{2}$ in. Long, Partially Threaded	McMaster-Carr	Head Screws (Telemetry)	1	$11.26	$11.26
Oil-Resistant Buna-N Rubber Sheet, 36 in. Wide, $\frac{1}{16}$ in. Thick	McMaster-Carr	Rubber Sheets (Telemetry)	1	$14.65	$14.65
Telemetry Sales Tax	McMaster-Carr	Tax	1	$4.62	$4.62
Telemetry Shipping Tax	McMaster-Carr	Shipping	1	$6.82	$6.82
High-Strength Steel Nylon-Insert Locknut, Grade 8, $\frac{1}{2}$ in.-13 Thread Size	McMaster-Carr	Locknuts (Payload)	1	$3.44	$3.44
Zinc Yellow-Chromate Plated Hex Head Screw, Grade 8 Steel, $\frac{1}{2}$ in.-13 Thread Size, 1-$\frac{1}{2}$ in. Long	McMaster-Carr	Screws (Payload)	1	$8.77	$8.77
Ball Bearing, Sealed with Extended Ring, for $\frac{1}{2}$ in. Shaft Diameter, $\frac{3}{8}$ in. Wide	McMaster-Carr	Ball Bearing (Payload)	1	$13.24	$13.24
Flame-Retardant Garolite G-10/FR4 Sheet, 12 in. Wide x 12 in. Long, $\frac{3}{16}$ in. Thick, Yellow	McMaster-Carr	Bulkhead (Payload)	1	$25.26	$25.26
Off-White Nylon Unthreaded Spacer, $\frac{1}{4}$ in. OD, 1 in. Long, for Number 4 Screw Size	McMaster-Carr	Spacer (Payload)	1	$12.79	$12.79
PCB Manufacturing Estimate	Osh Park	PCB	1	$210.00	$210.00
MicroSD Card	Amazon	Camera	2	$25.00	$50.00
		TOTAL COST			**$4420.48**
		Allocation			$5000.00
		Margin			$579.52
Lunar Sample Retrieval System Components	Vendor	Description	Qty	Price Per Unit	Total Cost
98 RPM Econ Gear Motor	ServoCity	Gear Motor	4	$14.99	$73.94
Raspberry Pi 3	CanaKit	Pi 3 with 2.5 A USB Power Supply	1	$49.62	$49.62

16 GB Memory Card	SanDisk	Ultra microSDHC Memory Card with Adapter	1	$5.79	$5.79
$\frac{1}{4}$ in. OD Retaining Ring	McMaster-Carr	Ring	1	$8.13	$15.45
$\frac{1}{4}$ in. ID PTFE Tube	McMaster-Carr	Tubing	1	$11.20	$20.12
25 mm Bore Motor Mount	ServoCity	Motor Mount	2	$5.99	$18.97
4-40 Set Screws	McMaster-Carr	Set Screws	1	$3.17	$3.17
Plastic Washers	McMaster-Carr	Washers	1	$3.00	$3.00
6-32 $\frac{3}{8}$ in. Socket Head Bolts	McMaster-Carr	Bolts	1	$8.86	$8.86
6061 $\frac{7}{16}$ in. Rod	McMaster-Carr	Rod	1	$13.19	$13.19
6061 0.625 in. x 3 in. Flat Bar	Grainger Industrial Supply	Bar	1	$2.87	$2.87
Glass Beads	Fire Mountain Gems and Beads, Inc.	Lunar Ice	15	$2.25	$42.52
HDPE Sheet	McMaster-Carr	HDPE	1	$14.25	$14.25
$\frac{1}{4}$ in. Shaft Collar	Ruland Manufacturing Co., Inc.	Collar	4	$6.36	$25.44
Plastic Gear	McMaster-Carr	Gear	1	$2.46	$2.46
Plastic Rack	McMaster-Carr	Rack	1	$3.69	$3.69
High Speed Micro Servo	AMain Hobbies	Servo	1	$29.99	$29.99
Micro CR Motor	Adafruit Industries	Motor	1	$7.50	$7.50
Flight Controller	GetFPV	F4 Nano	1	$29.99	$29.99
Adafruit Itsy Bitsy 3 V	Adafruit Industries	Microcontroller Board	1	$9.95	$9.95
Retention Solenoid	Adafruit Industries	Medium Push Pull Solenoid	4	$7.50	$30.00
Transistor for Solenoid	SparkFun Electronics	Transistor	4	$0.95	$3.80
Diodes for Solenoid	Adafruit Industries	Diodes	1	$1.50	$1.50
5V Regulator for Solenoid	Adafruit Industries	Regulator	4	$0.75	$3.00
3.3V regulator for Itsy Bitsy	Adafruit Industries	Regulator	1	$1.25	$1.25
Tenergy Li-Ion 11.1 V 2600 mAh	Tenergy Power	Rover Battery	2	$41.99	$83.98
Sabertooth 2x5	RobotShop	Motor Driver	1	$57.95	$57.95
Ori32 BLHeli32	GetFPV	Electronic Speed Controller	1	$39.99	$39.99
Caddx Turbo EOS2 Micro Camera	GetFPV	Camera	2	$15.99	$31.98
TBS Crossfire Nano Receiver	GetFPV	Receiver	2	$29.99	$59.98
Matek M8Q-5883 GPS	GetFPV	GPS	1	$32.99	$32.99
TBS Unify Pro32 Video Transmitter	GetFPV	Transmitter	2	$29.95	$59.90
Lumenier AXII 5.8 GHz Antenna	GetFPV	UAV Antenna	1	$19.99	$19.99
TBS Crossfire TX Bluetooth	GetFPV	Bluetooth	1	$149.99	$149.99
Lumenier AXII LR Antenna	GetFPV	Ground Station Antenna	1	$19.99	$19.99
Propellers	BetaFPV	UAV Props	1	$8.99	$8.99
RCX H1304 Motor	MyRcMart	Motor	4	$9.99	$39.96
AKK RC832 Receiver	AKK	Receiver	1	$16.99	$16.99
3DR Telemetry Kit	ReadytoSky	Telemetry	1	$24.99	$24.99
Lumenier 3S2P Battery	GetFPV	UAV Battery	1	$39.99	$39.99
Bulkhead Bearing	McMaster-Carr	Bearing	1	$13.24	$13.24
3-D Printed Parts	Innovation Park at Notre Dame	Payload Custom Prints	1	$650.00	$650.00
BNO055	Digi-Key	Accelerometer, Gyroscope, Magnetometer, 9 Axis	1	$11.16	$11.16
MTK3339	Adafruit Industries	GPS Module	1	$29.95	$29.95
RFM95W-915S2 LoRa Module	Digi-Key	Radio Module	1	$13.57	$13.57
32 kHz Crystal Oscillator	Digi-Key	Crystal Oscillator	1	$1.19	$1.19
3.3 V DC-DC Converter	Digi-Key	Converter	1	$4.91	$4.91
5 V DC-DC Converter	Digi-Key	Converter	1	$4.91	$4.91
Logic Converter 3.3 V-5 V	Digi-Key	Converter	1	$1.05	$1.05
		TOTAL COST			**$1837.96**
		Allocation			$2000.00
		Margin			$162.04
ABS Components	Vendor	Description	Qty	Price Per Unit	Total Cost
MPL3115A2 - I2C Barometric Pressure, Altitude, Temperature Sensor	Adafruit Industries	Barometric pressure sensor	1	$21.55	$21.55
9-DOF Absolute Orientation IMU Fusion Breakout - BNO055	Adafruit Industries	Accelerometer and gyroscope	1	$33.76	$33.76
Wear-Resistant Black Nylon Sheet, 6 in. x 6 in. x $\frac{1}{2}$ in.	McMaster-Carr	Nylon sheet for sub-scale drag tabs	1	$22.94	$22.94
Raspberry Pi Zero	Adafruit Industries	Microcontroller	1	$16.25	$16.25
Raspberry Pi 3 Power Supply 5 V 2.5 A Micro USB AC Adapter Charger US Plug	Amazon LLC	Plug for powering Raspberry Pi from wall	1	$10.69	$10.69
Adafruit PowerBoost 500 Basic - 5 V USB Boost @ 500 mA from 1.8 V+	RM Gadgets	Power booster for powering Raspberry Pi with battery	1	$12.35	$12.35
AmazonBasics High-Speed Mini-HDMI to HDMI TV Adapter Cable - 6 Feet	Amazon LLC	HDMI cable for connecting Raspberry Pi to monitor	1	$7.48	$7.48

1578 Lithium Ion Polymer Battery - 3.7 V 500 mAh	Adafruit Industries	Batteries for sub-scale	2	$10.06	$20.12
2-Port USB Hub 1 Male to 2 Female USB y Splitter Cable	Amazon LLC	USB splitter to connect mouse and keyboard to Raspberry Pi	1	$8.99	$8.99
Male Micro USB 2.0 to Female USB	Amazon LLC	USB adapter for Raspberry Pi	1	$5.97	$5.97
Multipurpose 6061 Aluminum, 1 in. Thick x 2-$\frac{1}{2}$ in. Wide, 1 Foot Long	McMaster-Carr	Aluminum to fabricate mechanism	1	$23.16	$23.16
Multipurpose 6061 Aluminum, $\frac{1}{4}$ in. Thick x 1-$\frac{1}{2}$ in. Wide, 1 Foot Long	McMaster-Carr	Aluminum to fabricate mechanism	1	$3.68	$3.68
Slippery MDS-Filled Wear-Resistant Nylon Sheet, 12 in. x 12 in. x $\frac{1}{4}$	McMaster-Carr	Nylon to fabricate drag tabs	1	$30.31	$30.31
Slippery MDS-Filled Wear-Resistant Nylon Sheet, 12 in. x 12 in. x $\frac{1}{2}$ in.	McMaster-Carr	Nylon to fabricate slotted deck for drag tabs	1	$55.76	$55.76
Ultra-Low-Profile Precision Shoulder Screw, Slotted, $\frac{1}{4}$ in. Shoulder Diameter, $\frac{1}{2}$ in. Shoulder Length, 10-32 Thread	McMaster-Carr	Shoulder screws for mechanism	8	$4.55	$36.40
Low-Strength Steel Threaded Rod, $\frac{1}{4}$ in.-20 Thread Size, 1 Foot Long	McMaster-Carr	Threaded rods for structure	4	$0.64	$2.56
Birch Rod, 36 in. Long, $\frac{1}{2}$ in. Diameter	McMaster-Carr	Dowel rod for alignment	1	$7.45	$7.45
Steel Locknut with External-Tooth Lock Washer, Zinc-Plated, $\frac{1}{4}$ in.-20 Thread Size	McMaster-Carr	Lock nuts for attaching decks to threaded rods	1	$5.42	$5.42
Ball Bearing, Open, Trade Number R10, for $\frac{5}{8}$ in. Shaft Diameter	McMaster-Carr	Ball bearing for mechanism	2	$6.66	$13.32
RCD 36845 D-845WP 32-Bit Monster Torque Waterproof Steel Gear Servo	Hitec	Servo motor	1	$94.31	$94.31
7.4 V 350 mAh 2S Lipo Battery 25C with USB charger	CBB Store	Pack of 2 batteries for servo motor	1	$19.99	$19.99
3.7 V 450 mAh 502535 Lipo battery Rechargeable Lithium Polymer ion	Wing Deli	Batteries for full-scale electronics	3	$6.49	$19.47
T453 6-Port LiPo Battery Charger	Tenergy	Charger for LiPo batteries	1	$8.99	$8.99
PCB Manufacturing	Osh Park	PCB	1	$37.00	$37.00
Shipping & Taxes for McMaster-Carr Order	McMaster-Carr	Shipping & Taxes	1	$30.76	$30.76
Hitec RCD 44429 D Pieces-11 Universal Programming Interface for Hitec Programmable Servos	Hitec	Programming Interface for Servo Motor	1	$24.65	$24.65
Multipurpose 6061 Aluminum, $\frac{3}{8}$ in. Thick, 8 in. by 8 in.	McMaster-Carr	Aluminum Fore Bulkhead	2	$26.11	$52.22
Steel Pan Head Phillips Screws, 10-32 Thread, 1 in. Long	McMaster-Carr	Screws for Bulkhead Integration	1	$19.36	$19.36
Adafruit Mini Lipo w/Mini-B USB Jack	Adafruit Industries	New Batteries and Charger	1	$51.16	$51.16
RCD 36845 D-845WP 32-Bit Monster Torque Waterproof Steel Gear Servo	Hitec	Servo Motor	2	$140.46	$280.92
#10 Washers, Zinc	Home Depot	Washers	1	$1.42	$1.42
Raspberry Pi 4	Best Buy	Raspberry Pi 4	1	$64.19	$64.19
USB C-A	Office Depot	USB C-A	1	$8.55	$8.55
		TOTAL COST			**$1051.15**
		Allocation			$1300.00
		Margin			$248.85
STEM Engagement Components	Vendor	Description	Qty	Price Per Unit	Total Cost
Straws	Walgreens	Mission to Mars	1	$2.29	$2.29
Trashbags	Walgreens	Mission to Mars	1	$4.49	$4.49
LifeSavers Candy	CVS	Mission to Mars	1	$2.69	$2.69
Rubber Bands	CVS	Mission to Mars	1	$1.69	$1.69
Candy Canes (large)	Walgreens	Mission to Mars	2	$1.99	$3.98
Candy Canes (small)	Walgreens	Mission to Mars	1	$3.29	$3.29
Ball	Walmart	Mission to Mars	1	$1.97	$1.97
Yarn	Walmart	Mission to Mars	1	$2.78	$2.78
Duct Tape	Walmart	Mission to Mars	1	$3.24	$3.24
Index Cards	Meijer	Mission to Mars	1	$0.99	$0.99
Rubber Bands	Meijer	Mission to Mars	1	$1.99	$1.99
Spinrite Yarn	Meijer	Mission to Mars	1	$1.99	$1.99
Jumbo Straws	Meijer	Misson to Mars	1	$1.99	$1.99
Labels	Meijer	Mission to Mars	1	$1.89	$1.89
Marshmallows	Meijer	Mission to Mars	1	$1.00	$1.00
Disposable Cups	Meijer	Mission to Mars	1	$2.69	$2.69
Meijer Bags	Meijer	Mission to Mars	1	$5.99	$5.99
Hallmark Tissue Paper	Walgreens	Mission to Mars	1	$3.39	$3.39
Colored Construction Paper (96 sheets)	Walgreens	Mission to Mars	1	$3.39	$3.39
Candy	Walmart	Mission to Mars	1	$11.98	$11.98

Uber - BGC Carmichael	Uber	BGC Series	1	$38.95	$38.95
Life Savers	Martin's	Mission to Mars	2	$2.19	$4.38
Neon Straws	Martin's	Mission to Mars	1	$1.99	$1.99
Flexible Straws	Martin's	Mission to Mars	3	$0.99	$2.97
Rubber Bands	Meijer	Mission to Mars	1	$2.29	$2.29
Pencils	Meijer	Mission to Mars	2	$2.49	$4.98
Straws	Meijer	Mission to Mars	1	$2.99	$2.99
LifeSavers Candy	Meijer	Mission to Mars	1	$9.99	$9.99
		TOTAL COST			**$132.25**
		Allocation			$300.00
		Margin			$167.75
Miscellaneous Expenses	Vendor	Description	Qty	Price Per Unit	Total Cost
Proposal Dinner	Bruno's Pizza	Lead Compiling Session	1	$49.26	$49.26
Preliminary Design Review Dinner	Bruno's Pizza	Lead Compiling Session	1	$27.24	$27.24
Boeing Meet & Greet	Chick-Fil-A	Session with Pat Dolan	1	$177.57	$177.57
Test Launch Tire Repair	Discount Tire	Test Launch Flat Tire	1	$204.89	$204.89
Tab Launch Gas	QuikTrip	Gas for Test Launch	1	$29.67	$29.67
		TOTAL COST			**$488.63**
		Allocation			$500.00
		Margin			$11.37
Competition Travel Expenses	Vendor	Description	Qty	Price Per Unit	Total Cost
Team Lodging	Airbnb	Rental Home for 4 Nights of Launch Week	4	$500	$2775.78
Team Vehicle Rental	Notre Dame Transportation Services	Mini-Van Rentals	5	$275.00	$1375.00
Team Mentor Hotel	Marriott Hotels	Hotel Room for 4 Nights of Launch Week	4	$96.00	$449.60
Gasoline	Gas Stations en route	Fuel for 5 Mini-Vans per mile	470	$2.61	$1500.00
Food	Restaurants en route and in Alabama	Food budget per member for the entirety of the competition	28	$103.56	$2899.62
		TOTAL COST			**$9000.00**
		Allocation			$9000
		Margin			$0

A References and Acknowledgements

Acknowledgements

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References

1. FruityChutes. Stainless Steel Quick Link.
   https://fruitychutes.com/buyachute/recovery-and-launch-hardware-c-12/316-inch-stainless-steel-quick-link-875lb-p-101.html

B Full Black Powder Calculations

First Separation Event: Drogue Parachute Deployment

$$F = (\tau)(A_s)(n) = (10,000\,\text{psi})(\frac{\pi}{4}(0.086\ (\text{in.}))^2)(2\ \text{Shear Pins}) = 116\,\text{lb}_\text{f}$$

$$P = \frac{F}{A_b} = \frac{116\,\text{lb}_\text{f}}{\frac{\pi}{4}(6\,\text{in.})^2} = 4.1\ \text{psi} = 0.28\ \text{atm}$$

$$\text{Chamber Volume} = \frac{\pi}{4}(\text{bulkhead diameter (in.)}^2)(\text{height (in.)}^2)$$
$$= \frac{\pi}{4}(6\ (\text{in.})^2)(11\ (\text{in.})) = 311\ (\text{in.})^3 = 5.1\ \text{L}$$

$$n_g = \frac{PV}{RT} = \frac{(0.28\ \text{atm})(5.1\ \text{L})}{(0.082057\ (\text{L*atm/mol/K}))(1837.2\ \text{K})} = 0.0095\ \text{moles gas}$$

$$\frac{0.0095\ \text{moles gas}}{1} \times \frac{2\ \text{mol KNO}_3}{4\ \text{mol gas}} \times \frac{101.1\ \text{g KNO}_3}{1\ \text{mol KNO}_3} = 0.48\ \text{g KNO}_3$$

$$\frac{0.0095\ \text{moles gas}}{1} \times \frac{1\ \text{mol S}}{4\ \text{mol gas}} \times \frac{32.1\ \text{g S}}{1\ \text{mol S}} = 0.076\ \text{g S}$$

$$\frac{0.0095\ \text{moles gas}}{1} \times \frac{3\ \text{mol C}}{4\ \text{mol gas}} \times \frac{12.0\ \text{g C}}{1\ \text{mol C}} = 0.085\ \text{g C}$$

$$0.48\ \text{g KNO}_3 + 0.076\ \text{g S} + 0.085\ \text{g C} = 0.64\ \text{g Black Powder}$$

With a FOS of 25%, 0.8 g of black powder is needed for the initial separation event. This will be rounded to 1 g of black powder for ease of measuring in the launch field. The back-up charges for drogue deployment both have 1.5 g of black powder.

Second Separation Event: Main Parachute Deployment

$$F = (\tau)(A_s)(n) = (10,000\,\text{psi})(\frac{\pi}{4}(0.086\ (\text{in.}))^2)(4\ \text{Shear Pins}) = 232\,\text{lb}_\text{f}$$

$$P = \frac{F}{A_b} = \frac{232\,\text{lb}_\text{f}}{\frac{\pi}{4}(6\,\text{in.})^2} = 8.2\ \text{psi} = 0.56\ \text{atm}$$

$$\text{Chamber Volume} = \frac{\pi}{4}(\text{bulkhead diameter (in.)}^2)(\text{height (in.)}^2)$$

$$= \frac{\pi}{4}(6\ (\text{in.})^2)(31\ (\text{in.})) = 876\ (\text{in.})^3 = 14.3\ \text{L}$$

$$n_g = \frac{PV}{RT} = \frac{(0.56\ \text{atm})(14.3\ \text{L})}{(0.082057\ (\text{L*atm/mol/K}))(1837.2\ \text{K})} = 0.053\ \text{moles gas}$$

$$\frac{0.053\ \text{moles gas}}{1} \times \frac{2\ \text{mol KNO}_3}{4\ \text{mol gas}} \times \frac{101.1\ \text{g KNO}_3}{1\ \text{mol KNO}_3} = 2.7\ \text{g KNO}_3$$

$$\frac{0.053\ \text{moles gas}}{1} \times \frac{1\ \text{mol S}}{4\ \text{mol gas}} \times \frac{32.1\ \text{g S}}{1\ \text{mol S}} = 0.43\ \text{g S}$$

$$\frac{0.053\ \text{moles gas}}{1} \times \frac{3\ \text{mol C}}{4\ \text{mol gas}} \times \frac{12.0\ \text{g C}}{1\ \text{mol C}} = 0.48\ \text{g C}$$

$$2.7\ \text{g KNO}_3 + 0.43\ \text{g S} + 0.48\ \text{g C} = 3.6\ \text{g Black Powder}$$

With a FOS of 25%, $\boxed{4.5\ \text{g}}$ of black powder is needed for the second separation event for main deployment. The two main back-up charges have 5.0 g of black powder.

Tertiary Separation Event: Nose Cone Ejection for Payload Deployment

$$F = (\tau)(A_s)(n) = (10,000\ \text{psi})(\frac{\pi}{4}(0.086\ (\text{in.}))^2)(4\ \text{Shear Pins}) = 232\ \text{lb}_\text{f}$$

$$P = \frac{F}{A_b} = \frac{232\ \text{lb}_\text{f}}{\frac{\pi}{4}(8\ \text{in.})^2} = 4.6\ \text{psi} = 0.31\ \text{atm}$$

$$\text{Chamber Volume} = \frac{\pi}{4}(\text{bulkhead diameter (in.)}^2)(\text{height (in.)}^2)$$

$$= \frac{\pi}{4}(8\ (\text{in.})^2)(7\ (\text{in.})) = 352\ (\text{in.})^3 = 5.8\ \text{L}$$

$$n_g = \frac{PV}{RT} = \frac{(0.31\ \text{atm})(5.8\ \text{L})}{(0.082057\ (\text{L*atm/mol/K}))(1837.2\ \text{K})} = 0.012\ \text{moles gas}$$

$$\frac{0.012\ \text{moles gas}}{1} \times \frac{2\ \text{mol KNO}_3}{4\ \text{mol gas}} \times \frac{101.1\ \text{g KNO}_3}{1\ \text{mol KNO}_3} = 0.61\ \text{g KNO}_3$$

$$\frac{0.012\ \text{moles gas}}{1} \times \frac{1\ \text{mol S}}{4\ \text{mol gas}} \times \frac{32.1\ \text{g S}}{1\ \text{mol S}} = 0.097\ \text{g S}$$

$$\frac{0.012\ \text{moles gas}}{1} \times \frac{3\ \text{mol C}}{4\ \text{mol gas}} \times \frac{12.0\ \text{g C}}{1\ \text{mol C}} = 0.011\ \text{g C}$$

$$0.61 \text{ g } KNO_3 + 0.097 \text{ g S} + 0.011 \text{ g C} = 0.81 \text{ g Black Powder}$$

With a FOS of 25%, $\boxed{1.0 \text{ g}}$ of black powder is needed for the third separation event.

Summary of Black Powder Charges

Table 61: Summary of Black Powder Charges

Separation Event	Charge	Calculated 4F (g)	Actual 4F (g)
Drogue	Initial	1.0	5.0
	Secondary	1.5	5.0
	Tertiary	1.5	5.0
Main	Initial	4.5	5.0
	Secondary	5.0	5.0
	Tertiary	5.0	5.0
Nose Cone	Initial	1.0	1.5