Tacho Lycos
2016 NASA Student Launch
MAV FRR

High-Powered Rocketry Team

911 Oval Drive

Raleigh NC, 27695

March 14, 2016

Table of Contents

List of Figures

List of Tables

List of Equations

1. Summary of Flight Readiness Review

1.1. Team Summary

1.1.1. Team Name and Mailing Address

Tacho Lycos
Engineering Building III
911 Oval Drive
Raleigh, NC 27606

1.1.2. Name of Mentor, TRA Number, and Certification Level

Alan Whitmore	James Livingston	Dr. Charles Hall
acwhit@nc.rr.com	livingston@ec.rr.com	chall@ncsu.edu
TRA Certification: 05945	TRA Certification: 02204	TRA Certification: 14134
Certification Level: 3	Certification Level: 3	Certification Level: 3

1.2. Launch Vehicle Summary

1.2.1. Size and Mass

Table 1 Size and Mass Properties

FRR	
Length	102 in
Diameter	5.5 in
Loaded Weight	33.7 lbs
Center of Pressure	76.3 in
Center of Gravity	64.5 in
Stability	2.15 Caliber
Apogee	5344-5349 ft
Max Velocity	661-689 ft/s
Max Acceleration	297 ft/s^2
Recovery System	1 Drogue/2 Main Parachutes
Motor	L1150R

1.2.2. Motor Choice

The team has selected the AeroTech L1150R motor for the full-scale rocket. It has a specific impulse of 790.6 seconds and a burn time of 3.1 seconds. It is 20.87 inches long and has a diameter of 2.95 inches.

1.2.3. Recovery System

The vehicle will come down in two separate sections. A 1.5 foot drogue parachute will deploy at apogee, controlled by the aft avionics bay StratoLogger altimeters. This will separate the nosecone and forward airframe from the fin section and aft airframe. The drogue will be attached to an Advanced Retention Release Device (ARRD) in the forward airframe and to a bulkhead in the aft airframe. At 1,100 feet AGL, the Entacore altimeters in the forward avionics bay will trigger the ARRD to separate the nosecone and forward airframe from the aft airframe and fin section. Shortly after, at 1,000 feet AGL, the Entacore altimeters will trigger the sample section and nosecone to separate, releasing a 4 foot main parachute. A 7 foot main parachute will deploy at 700 feet between the aft airframe and fin section. This event will be controlled by the StratoLogger altimeters.

1.2.4. Rail Size

The launch rail will have a 1.5 square inch cross section and a length of 120 inches, which allows the vehicle enough distance to obtain a velocity of 63 feet per second as it leaves the launch rail.

1.2.5. Milestone Review Flysheet

The Milestone Review Flysheet can be found in Appendix A Milestone Review Flysheetof this document. It can also be obtained from the Tacho Lycos website at www.ncsurocketry.com.

1.3. AGSE Summary

1.3.1. AGSE Title

The Autonomous Ground Support Equipment (AGSE) will be referred to as System To Orient Rocket on Mars (STORM).

1.3.2. Size and Mass

Table 2 AGSE Size

AGSE Size	Horizontal (inches)	Vertical (inches)
Length	132	73.5
Width	31.5	31.5
Height	31	133
Total Volume	128,898 in^3 (74.59 ft^3)	307,928 in^3 (178.2 ft^3)

Table 3 AGSE Mass Statement

Weight (pounds)	
Robotic Arm Subassembly	4.2
Igniter Insertion Subassembly	5.9
Rocket Erection Subassembly	13.0
Launch Rail	8.8
Supporting Frame and Electronics Box	49.7
Blast Plate	3.9
Total Weight	85.5

1.3.3. Summarize Autonomous Procedure for AGSE

The system begins with the robotic arm. The sample will be placed in a predetermined position away from the AGSE. The robotic arm will move to the sample and grasp it with the gripper. After procuring the sample, the robotic arm will move it to the payload section where it will be securely enclosed by polyurethane foam. The robotic arm will then close the door and move a safe distance away from the rest of the system. The launch rail will then erect to 85 degrees from the horizontal. Once the launch angle is achieved, the igniter insertion system stepper motor will begin the procedure of raising the igniter into the vehicle's motor.

2. Changes Made Since CDR

2.1. Changes made to Vehicle Criteria

After the full-scale test flight, altimeter data revealed that the aft half of the launch vehicle had descended much more rapidly than predicted based on advertised values. The kinetic energy for that section was found to be an unsafe 111 foot-pounds. In order to correct this so that the kinetic energy would be restricted to the required maximum of 75 foot-pounds, the 5 foot diameter aft parachute is being exchanged for a 7 foot diameter parachute.

The sample bay was originally to be located in the forward airframe. It has been moved to the aft airframe so that the robotic arm can more easily place the sample in the compartment.

Changes to the Arduino code that actuates and retracts the airbrakes have been implemented after the first test launch to include additional measures ensuring safe and proper operation of the system as well as to simplify the process of acquiring flight data post-launch. The changes made include; a failsafe system to guarantee that the deployment of the airbrakes is between 1700 and 2800 feet AGL to ensure that the airbrakes cannot actuate before motor burnout and to ensure that they actuate at the maximum possible effective altitude if there is an error in the program, a time-based condition that will ensure that the airbrakes retract prior to the landing of the fin section (acting in concordance with an altitude-based condition that retracts the airbrakes at 1100 feet AGL), and a system that will record the altitude at which the airbrakes deploy and retract to simplify the post-flight data analysis.

The only change in the airbrake hardware is the addition of 2 3-D mounting points that will bolster the mounting of the 8mm linear bearing guide shafts to ensure that the guide rails cannot move in their mounting flanges. These mounting points will be epoxied directly to the fiberglass motor tube.

In order to reduce the potential for electromagnetic interference in the altimeters that could be caused by the BigRedBee GPS unit, a small sheet of aluminum foil will be placed between the GPS and the altimeters. This should deflect any stray electromagnetic waves away from the altimeters.

2.2. Changes Made to AGSE Criteria

Since the completion of the CDR the robot arm was rigorously tested to find the combination of servo controller, servos, and gearing that would work best for inserting the sample into the payload bay. A full procedure of the experiment can be found in Section 4.6.2. The combination that was found to work best is by using the three stock servos that came with the arm and to have them controlled by the new servo controller.

Figure 1 Servo Mounted into Servo Mount

After further analysis of the kinematics of the launch rail erection and igniter insertion systems it was determined that a non-load bearing section of STORM had to be removed to accommodate the full rotation of the launch rail with the igniter insertion system in place.

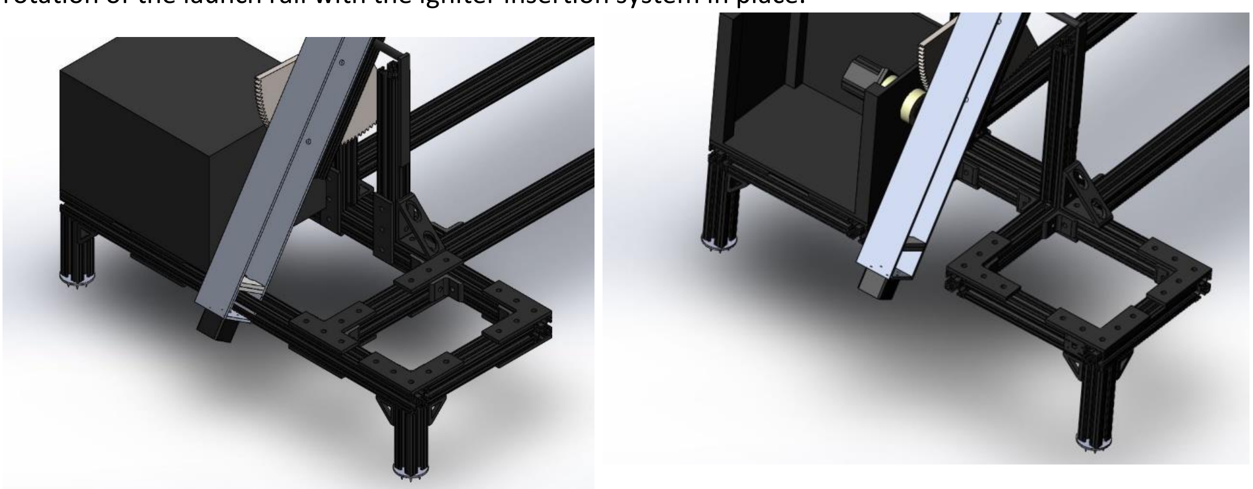


Figure 2 SolidWorks Rendering of Igniter Insertion Interference and Resolution

2.3. Changes Made to Project Plan

Several changes have been made to the project plan since the CDR, although the majority of the plan has remained a constant. Another ejection charge test has been scheduled to test the new, 7ft parachute that is replacing the 5ft parachute. The pre-launch checklist was altered after full scale launch to correct procedural discrepancies and improve clarity of the steps. The verification section of the FMECAs was rewritten to provide actionable steps and experiments that were done prior to launch. The budget has changed very little, as the materials needed to construct the rocket and AGSE have been purchased and funding received from our student organizations and other sources, the numbers in the budget have been finalized.

3. Vehicle Criteria

3.1. Design and Verification of Launch Vehicle

3.1.1. Design and Construction of Launch Vehicle

3.1.1.1. Structural Elements

The vehicle is constructed from 5.5 inch fiberglass tubing. Fiberglass was chosen due to its greater strength compared to phenolic tubing or Blue Tube 2.0. Additionally fiberglass tubing is highly resistant to abrasion and cracking, which makes it unnecessary to add additional airframe reinforcements and will allow the vehicle to be launched and recovered safely.

The vehicle is split into four sections, the Nosecone section, Forward Airframe, Aft Airframe and Fin section. Sections of fiberglass coupler provide structure at the joints and shear pins are used to secure the sections during launch. Each section of the airframe is bookended with a ¾ inch bulkhead made from three pieces of ¼ inch birch aircraft grade plywood. The bulkheads are secured into the body tube with four screws. Hatches are used to access the avionics and electronics in the Forward and Aft Airframe sections and are attached to the body tube with four screws that fit into holes in the bulkheads, two on the forward bulkhead of the section and two in the aft bulkhead. The bulkhead for the nose cone section is epoxied in to eliminate the drag that screws would create extruding from the sides of the nose cone. Each bulkhead has a stainless steel U-bolt screwed into it that provides a hard point for attaching parachutes and shock cords.

The fins are ¼ inch thick and are constructed from two pieces of 1/8th inch birch aircraft grade plywood epoxied together. There are four fins and the fins are epoxied into the rocket both at the base of the fin tab, where the tab touches the motor tube, and where the fins meet the outside of the rocket. In both places the epoxy has been thickened with glass microspheres so that the epoxy does not drip and so that the epoxy on the outside of the rocket can be filleted.

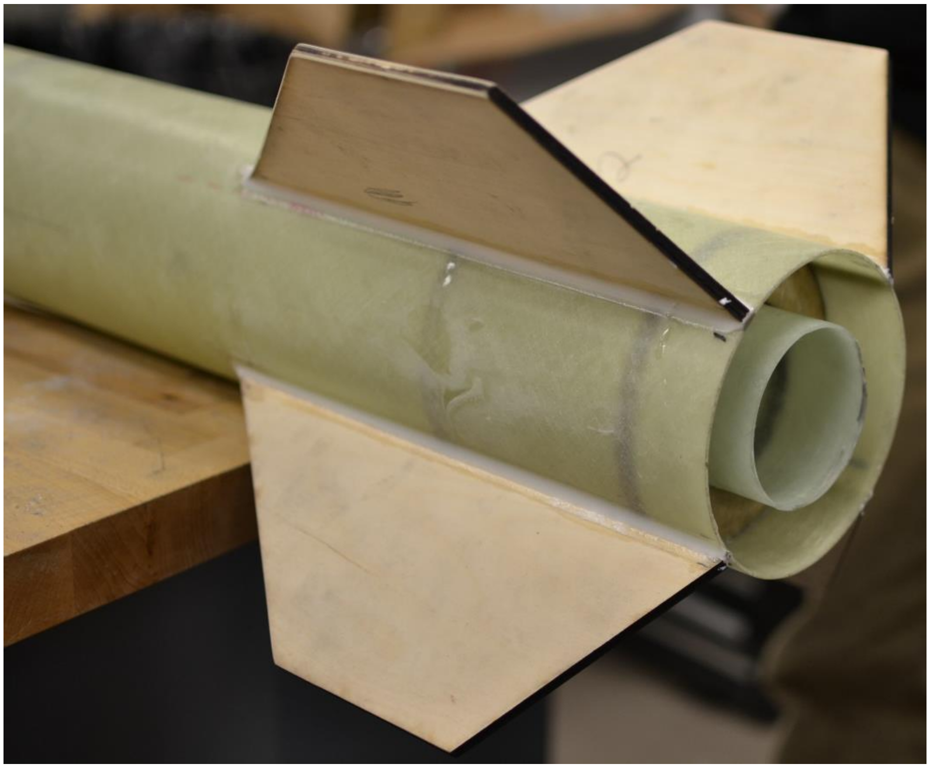


Figure 3 Photo of Constructed Fin Section

The fins and bulkheads are laser cut and epoxied together using a wet layup. A large, clean surface that is free of any debris will be covered with a plastic lining that is sized to accommodate the number of bulkheads needed. The size of the lining is such that the desired quantity of bulkheads and fins take up half of the sheet's size. This is so the lining can be folded in half over itself. Prior to placing the lining, thin strips of plumber's putty are placed along the entire outer perimeter of the lining. The bulkheads and fins then have the epoxy applied using a sponge to evenly spread over the bulkhead surface.

Once the bulkheads, fins, and centering rings have been cut out and have had epoxy applied between each layer, each component is carefully placed on the lining. Sheets of peel ply are cut to cover the items with approximately 2 inches of overhang along the entire edge. Breather is then be cut to the same size as the peel ply and placed directly over the peel ply. Strips of breather are then bridged from between each component all the way to the location of the vacuum tubing. This will ensure no air pockets remain trapped and an even pressure is applied at all points.

Plumber's putty is then be placed adjacent to and along the entire previous putty lining on the inside edge, except for a one inch gap at the open end of the plastic lining fold. The vacuum tubing is then inserted in this location and additional putty is applied around the tubing to keep an airtight seal. The vacuum will be applied to a pressure of -20 inches of mercury for 8-12 hours minimum to allow the epoxy to cure.

3.1.1.2. Electrical Elements

Each avionics compartment contains one primary and one redundant altimeter. The upper avionics compartment contains two Entacore AIM 3.0 altimeters. Each altimeter is wired such that the main charge port is connected to the terminal blocks on the forward bulkhead. These terminals are then connected to the black powder charges and are responsible for the 48 inch parachute event at 1,000 feet. The secondary charge ports are wired to the terminal blocks on the aft bulkhead of the avionics bay. From these terminals, e-matches connect to the ARRD and are programmed to detonate at 1,100 feet.

The aft avionics compartment houses one Stratologger SL100 and one Stratologger CF. Each is wired such that the main charge port is wired to the terminal blocks on the top bulkhead. These terminals are then connected to the black powder charges and are responsible for the 1.5 foot drogue parachute event at apogee. The drogue charge ports are wired to pass through the bottom bulkhead of the lower avionics bay and connect to the terminal blocks on the bulkhead and the aft section of the middle airframe. These terminals are then connected to the black powder charges responsible for the 48 inch main parachute event at 700 feet.

Each altimeter is secured with machine screws to its respective avionics sled. Each is powered independently by a 9 volt battery with the batteries also secured to the avionics sleds with retaining clips. Toggle switches mounted to the body of the rocket will be responsible for the powering on and off of each switch. The altimeters will be connected to the switches and the terminal blocks on the bulkheads with 20 gauge wire.

The fin section houses the airbrake system which utilizes an Arduino Mega that sends a PMW signal to a Firgelli Linear Actuator Control (LAC) board. This board then sends a signal that drives the Firgelli P16-50-22-12-P linear actuator. The Arduino determines when to extend the airbrakes by measuring the launch vehicles vertical velocity at 1500 feet AGL (well above the altitude of motor burnout), and comparing it to values in a pre-existing table. From this table the Arduino receives an altitude at which to deploy the airbrakes to attain an apogee of 5280 feet AGL. The Arduino receives altitude and velocity data from a BMP180 Barometric Pressure/Temperature/Altitude Sensor. Once the rocket has reached apogee, the Arduino is programmed to retract the airbrakes at 1100 feet AGL. If for some reason the pressure sensor malfunctions after apogee, the Arduino is programmed to retract the airbrakes 70 seconds after apogee. This will retract the airbrakes at an altitude of about 350 feet AGL while the tail section is descending under the 7 foot main parachute. The Arduino code is located in Appendix G Arduino Code Referenced by MATLAB. The entirety of the airbrake system is powered by a 3 cell 11.1 volt RHINO 1050 LiPo battery.

The table that the Arduino references is generated using a purpose built MATLAB program that iteratively determines the apogee of the launch vehicle with various deployment angles of the airbrake flaps and various motor burnout velocities and altitudes. The table compares the launch vehicles velocity at 1500 feet AGL to the appropriate altitude at which the airbrakes should be deployed to attain a 5280 feet AGL apogee. This MATLAB program is located in Appendix F MATLAB Code for Airbrakes.

3.1.1.3. Drawings and Schematics

Nosecone Section

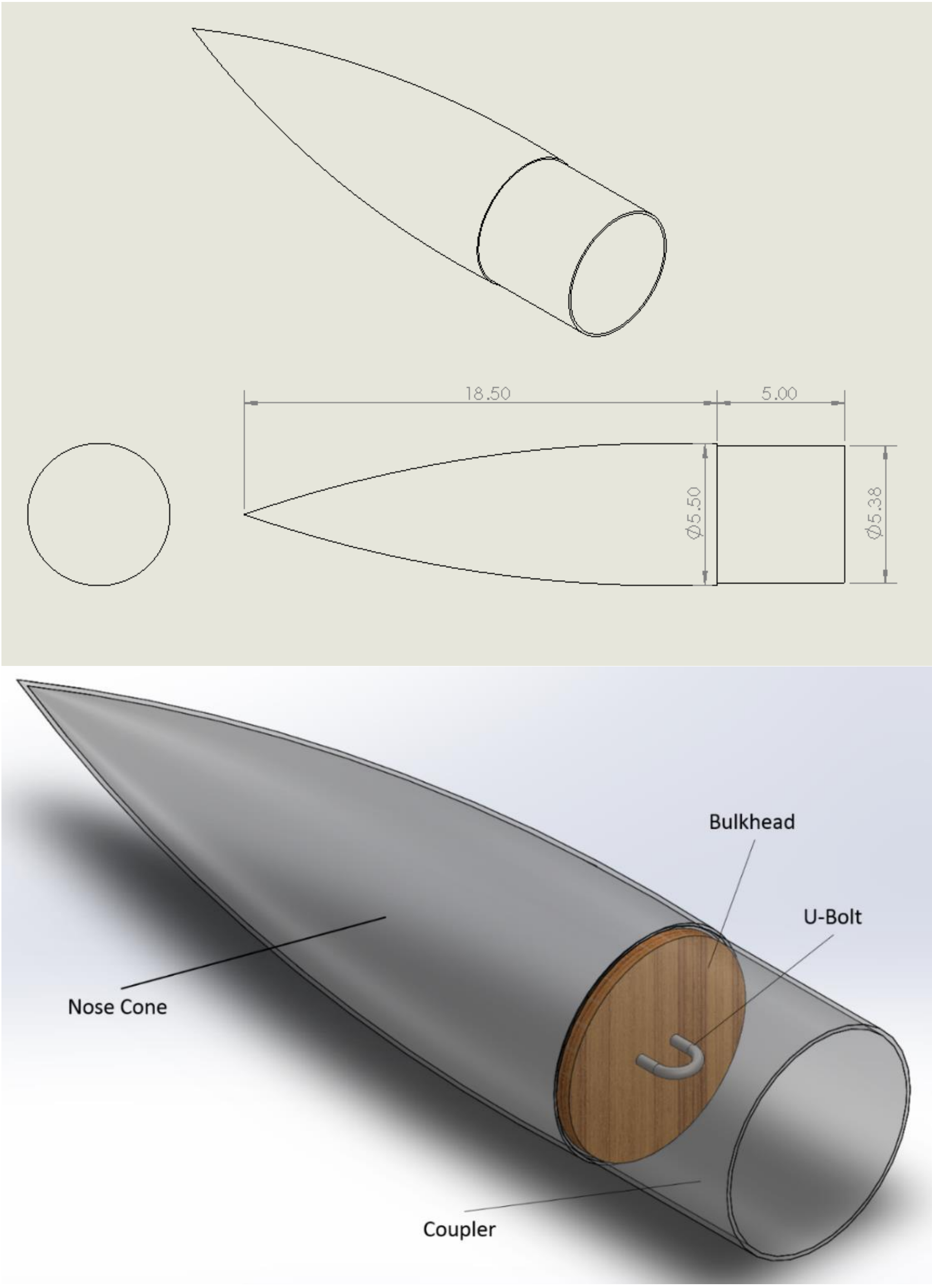
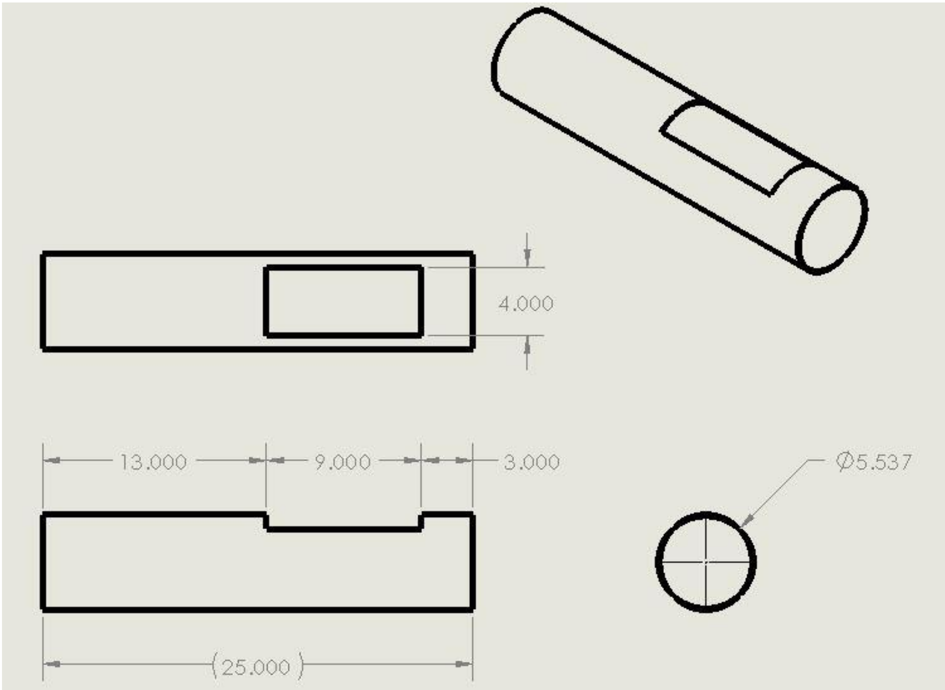


Figure 4 Nosecone Section Drawing and 3D Model

Forward Airframe Section



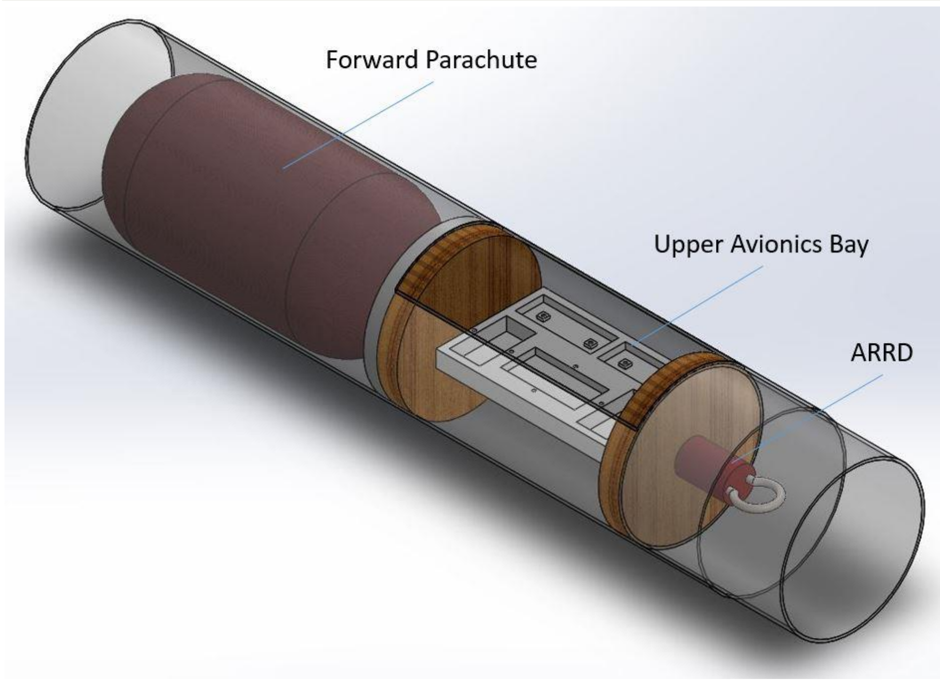


Figure 5 Forward Airframe Section Drawing and 3D Model

Aft Airframe Section

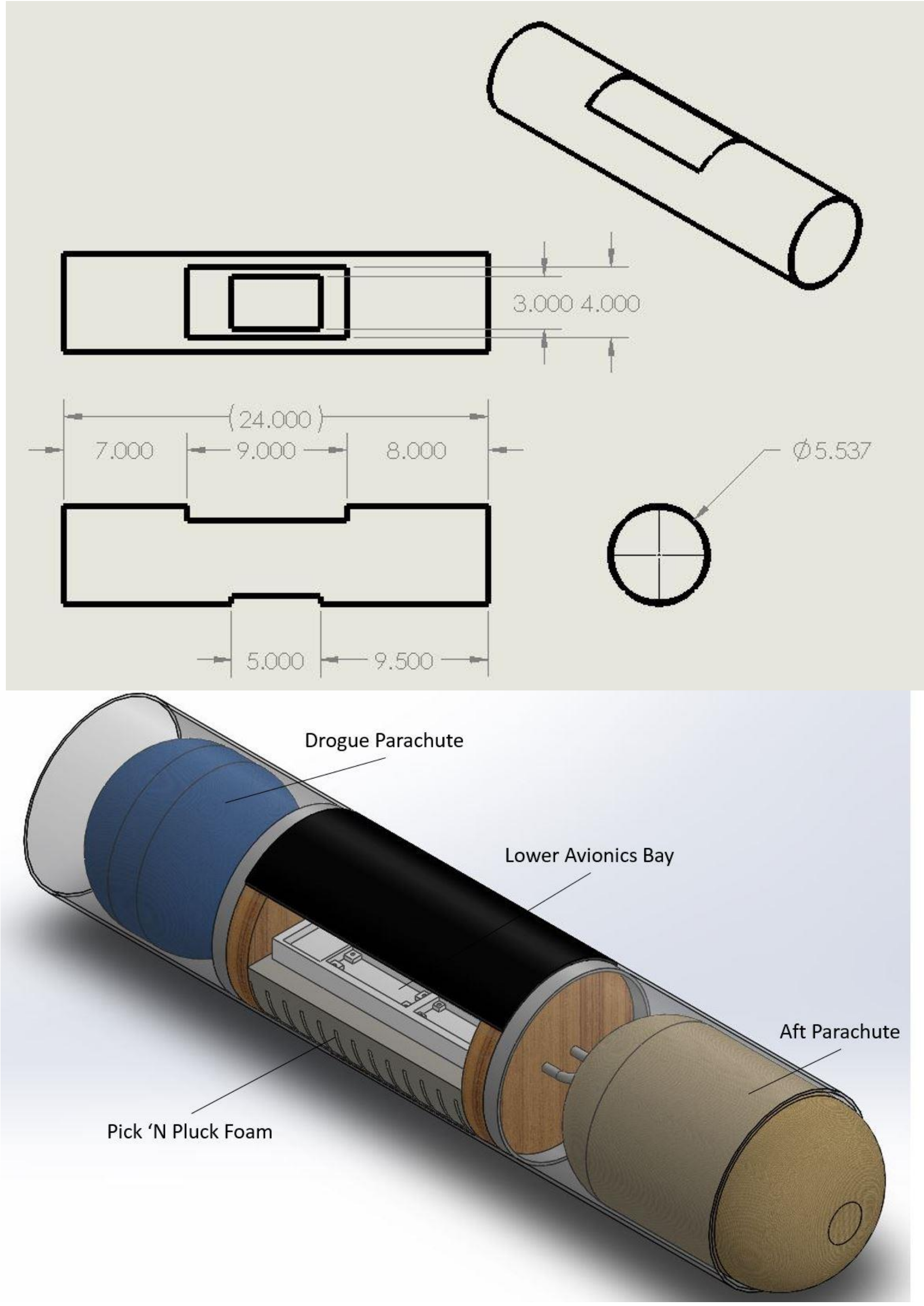


Figure 6 Aft Airframe Section Drawing and 3D Mode

Fin Section

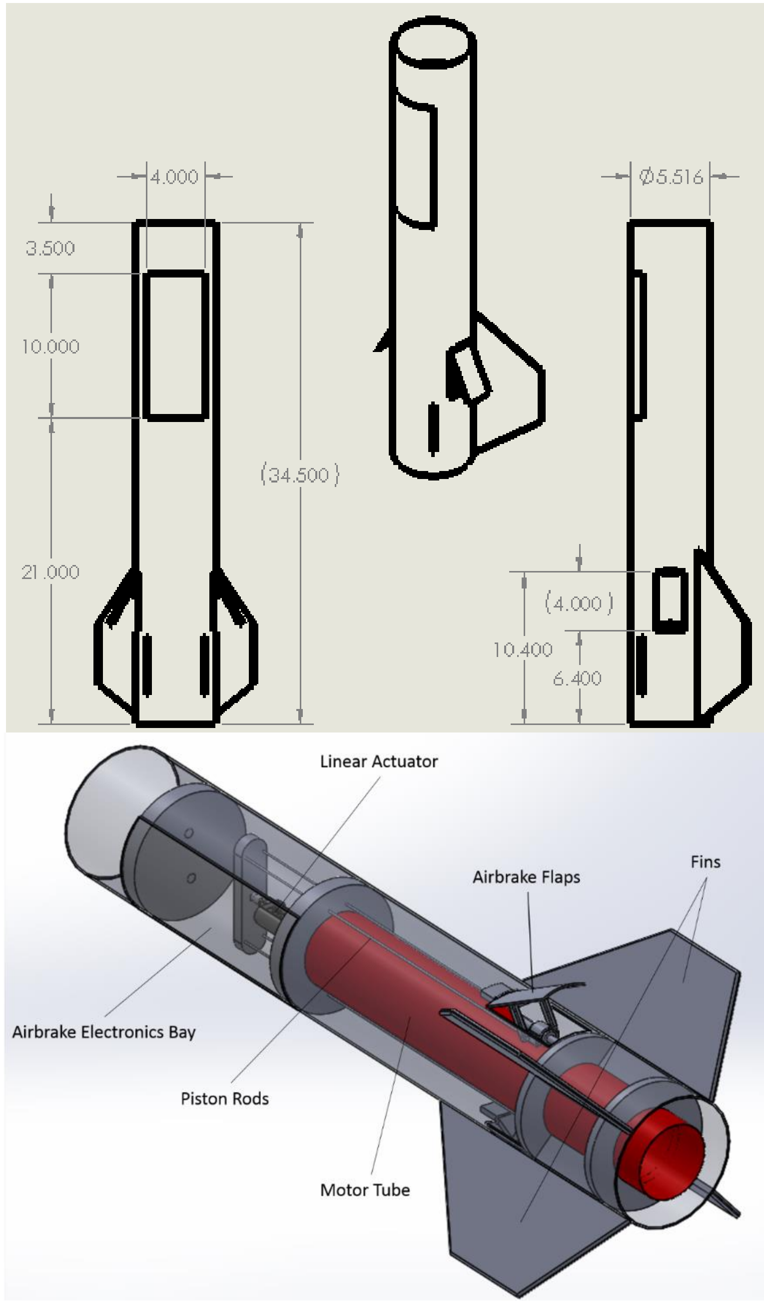


Figure 7 Fin Section Drawing and 3D Model

3.1.2. Flight Reliability Confidence

Testing was done on the altimeters, black powder charges, and airbrakes prior to the launch of the full scale vehicle.

The team is confident that the full scale launch vehicle will meet the mission success criteria because the vehicle has already launched to the target altitude and had a successful recovery. Full information about the launch of the full scale vehicle can be found in Section 3.1.6.

3.1.3. Test Data and Analysis

In order to simulate a flight to test the altimeters, a vessel was hooked up to a vacuum tube in order to depressurize the container. The drop in pressure simulated the change in altitude. A pressure gauge linked to the vacuum system allowed the team to control the pressure altitude that the altimeters experienced. LEDs were attached to the altimeters in place of e-matches so that the team could verify that the recovery events would be activated at the correct altitudes. This test, coupled with the results from the subscale flight, verified the team's confidence that the altimeters would perform as needed.

Two days prior to launch, the black powder charge sizes were tested. A switch was used to remotely activate the charges from a safe distance. All parachute compartments successfully separated with the calculated charge sizes of 3.3 grams, 2.1 grams, and 2.2 grams for the forward, drogue, and aft parachutes, respectively. An example of the successful test can be seen in Figure *8*. The charge sizes were calculated using the following formula:

$$charge\ size\ in\ grams = l * d^2 * .007$$

Equation 1

Where l is the length of the compartment and d is the diameter. All measurements are in inches.

Figure 8 Ejection Charge Test

The Airbrake system was tested to ensure that the Arduino code would reference the inputted velocity/extension altitude table. This was done using a vacuum chamber and by decreasing the internal pressure in the chamber rapidly. The Arduino would constantly read the pressure and when it reached a level equivalent to that of 1500 feet AGL, the system would determine the rate of increasing perceived altitude and compare it with values in the inputted table. The system was deemed functioning when it extended the actuator during depressurization and retracted it during repressurization (symbolizing descent of the rocket under canopy). The test setup, within the vacuum chamber, is shown below in Figure *9*. This test, when paired with the data received from the Arduino altitude data obtained from the sub-scale launch, verified the team's confidence that the system would act as designed.

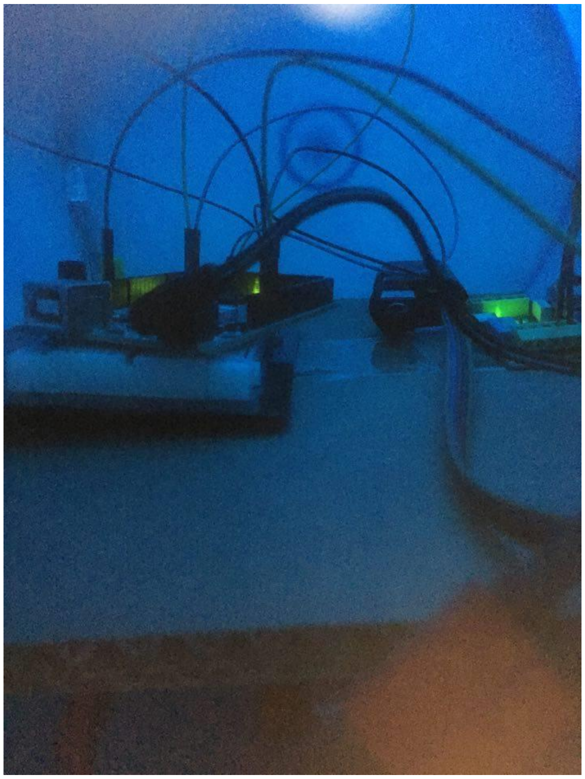


Figure 9 Vacuum Chamber Test

GPS Experiment

We are using two BigRedBee 900 MHz GPS units to track both pieces of the launch vehicle. In order to test the transmission of data from both units simultaneously, we sent two team members to run around campus (at least travel .5 km away) so that we could test the GPS tracking on both units. Figure 10 shows the paths traveled. This data was collected live and plotted on Google Earth to show what places on campus were traveled to. Each color represents the different paths traveled by the two team members.

Figure 10 BigRedBee 900 MHz Test

Serial Radio Experiment

The goal of this experiment is to test how well serial data can be transmitted to the ground station. We will be using several protocols to identify what type of data each data packet contains. The radios were able to communicate simple text data, however we wanted to see if it was possible to send images from the camera to the ground station. In order to do this, the Beagle Bone Black must convert the image into a text file. That text file must then be streamed through the radio byte by byte. The text will then be rebuilt back into the image. Figure *11* is the result of converting the image to text, sending the text across serial radio, and then rebuilding the image on the ground station.

Figure 11 Conversion of Image across Radio Transmission

3.1.4. Approach to Workmanship

Improper construction of the vehicle may lead to failure of the mission or loss of the vehicle entirely. Therefore, it is imperative that care is taken to uphold quality workmanship when the vehicle is being manufactured. The team believes that the quality of the workmanship is the foundation for success of the mission. To accomplish this mission, all senior members with experience in construction and design are the primary contributors to manufacturing with guidance given to younger members whenever possible.

3.1.5. Safety and Failure Analysis

A complete list of FMECAs can be found in Appendix C Failure Mode Effects and Criticality Analysis.

3.1.6. Full-Scale Launch Test Results

The launch vehicle was modeled in OpenRocket, shown in Figure 12, to match the CAD model from SolidWorks prior to launch. From this model, the vehicle's simulated mass was 29.5 pounds with a length of 102 inches and a diameter of 5.5 inches. The CG was located at 64.8 inches aft of datum and the CP was located 76.3 inches aft of datum. This provided a static margin of 2.1 caliber.

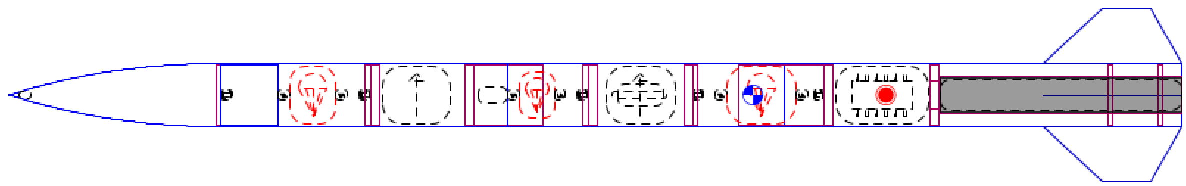


Figure 12 Final OpenRocket Model of the Launch Vehicle

Flight conditions were modeled based on predicted weather for launch day. The pressure was set to 29.9 inHg, temperature set as 52° Fahrenheit, and winds set to 10 miles per hour. From these parameters, the following flight characteristics are presented in Table 4 with the flight profile plotted in Figure 13.

Table 4 Flight Characteristics from Full Scale OpenRocket Simulation

Exit Rail Velocity (ft/s)	69.4
Apogee (ft)	5415
Max Velocity (ft/s)	736
Max Acceleration (ft/s^2)	297
Time to Apogee (s)	17.8
Flight Time (s)	120

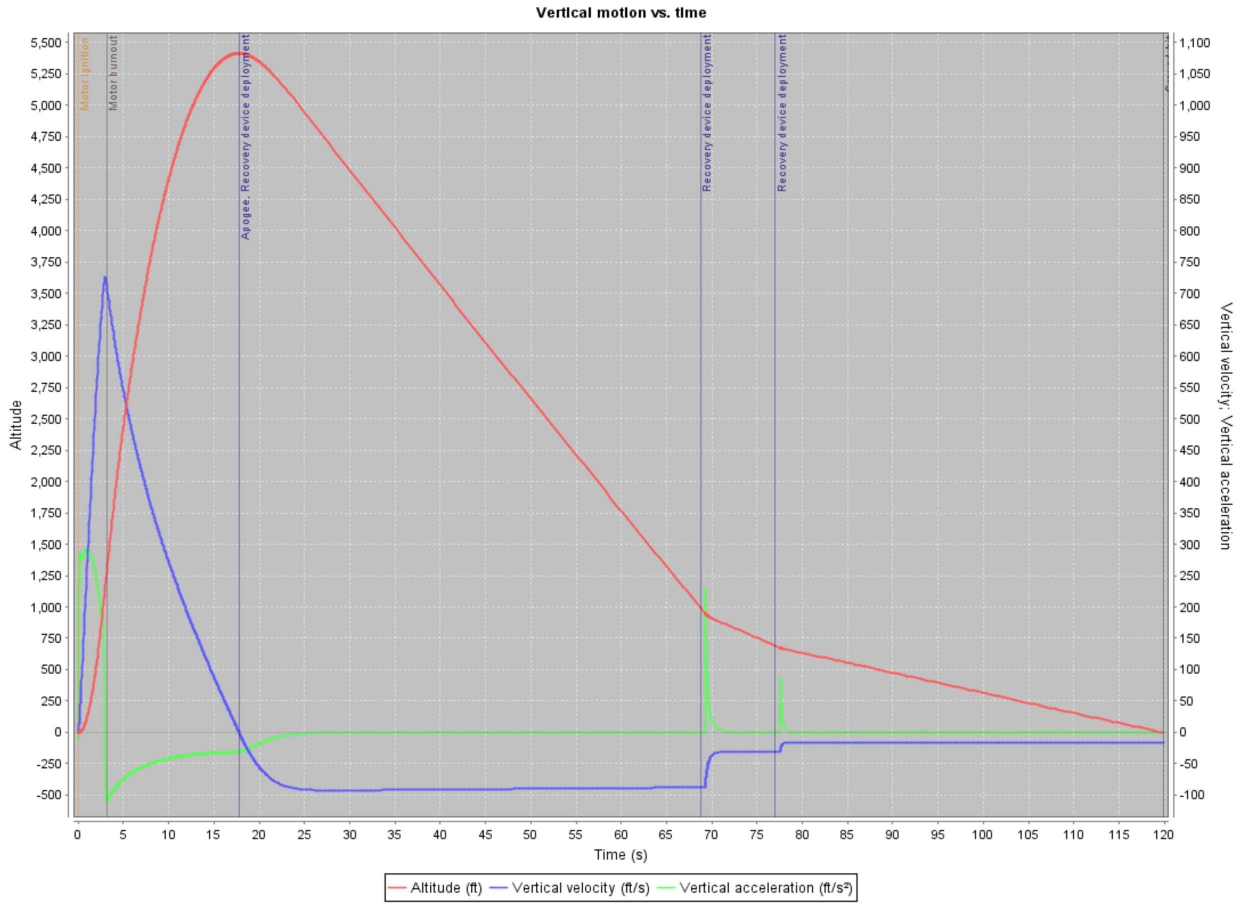


Figure 13 Graph of the Full Scale OpenRocket Simulation

The full-scale test launch occurred in Bayboro, NC on Saturday, February 27 at approximately 1:30 pm local time. Temperatures were between 50° and 55° Fahrenheit with winds gusting to 10 miles per hour. Visual observation showed a perfect launch and sequence of recovery events.

The vehicle had a straight flight up until airbrake deployment, at which point slight damped oscillations were observed which did not significantly affect the flight path. At apogee, the vehicle's drogue parachute was deployed and the vehicle was observed on its descent to 1,100 feet. At this point, the ARRD activated and released the aft airframe and fin section from the forward airframe and nosecone. Moments after, the 48 inch main parachute for the upper airframe and nosecone was deployed at its target altitude of 1,000 feet and the 84 inch main parachute for the fin section and middle airframe was deployed at its target altitude of 700 feet. Once the range was cleared, the vehicle was retrieved and post-launch checklists were initiated. Images from this flight as shown in Figure 14 and Figure 15.

Figure 14 Close Up Photo of Launch

Figure 15 Photo of the Aft Airframe and Fin Section after a Successful Recovery

Altimeters were connected to data transfer programs for detailed flight analysis. Stratologgers were first evaluated using PerfectFlite DataCap. From the primary CF, it was determined that apogee occurred at 5,344 feet in 18.55 seconds with a flight time of 105.6 seconds for the aft airframe and fin section and a maximum velocity of roughly 660 feet per second. The secondary SL100 altimeter showed nearly identical results. The plot for only the CF is shown in Figure 16 due to the strong similarities between the two plots.

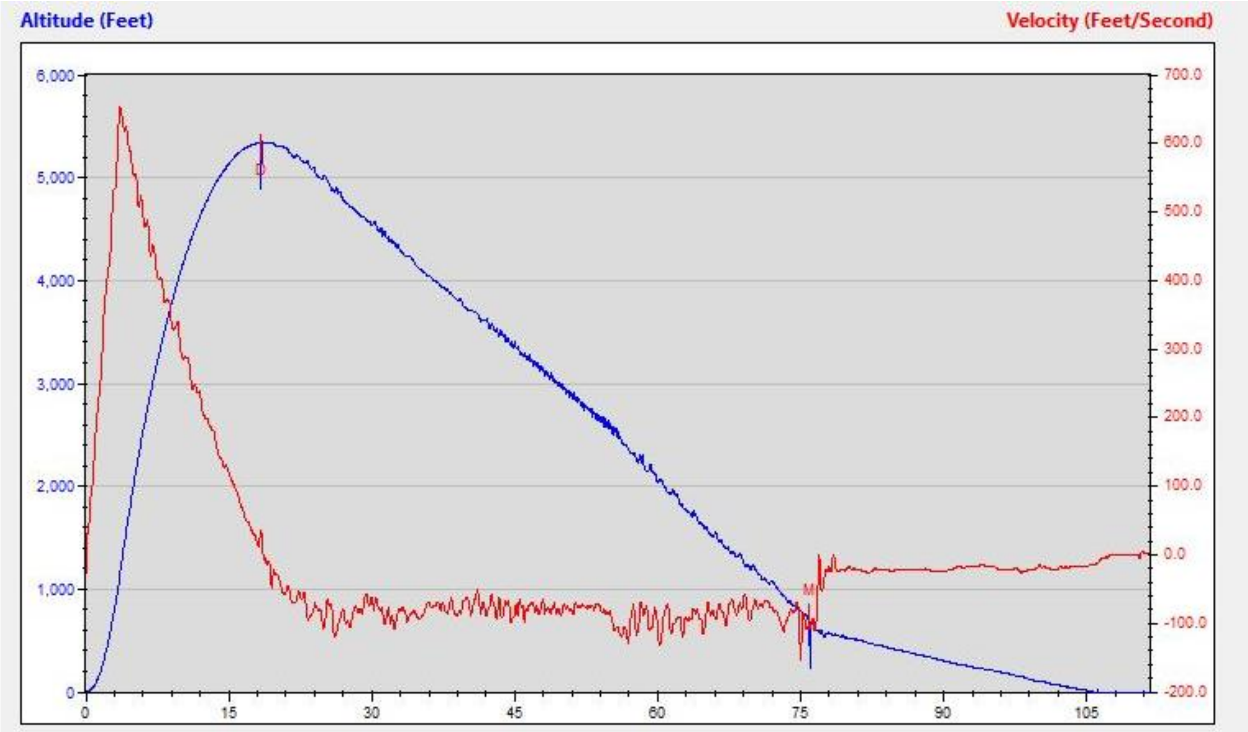


Figure 16 Full Scale Launch Altitude and Velocity Curves Collected by the StratoLogger CF Altimeter

The curve for the CF indicates a pressure spike at the drogue event. This did not affect the performance of the altimeters; this pressure spike should be eliminated or at least reduced by sealing the compartment during charge detonation with a weather stripping at the top of the avionics sled. If this is not sufficient to reduce the spike, the Stratologger altimeters are programmed with a spike recognition. If the pressure spike does not last longer than a pre-determined amount of time, the altimeter recognizes that is not at that indicated altitude and proceeds to activate the main charge at the set altitude.

Comparing actual to predicted results, the data validates the design and performance for a successful mission based on the selected atmospheric and environmental conditions expected. Recorded apogee overshot expected by 70 feet. An overshoot was preferred as weight was added after the test flight from painting and the MATLAB code can be easily modified to deploy the airbrakes earlier. Between the airbrakes reducing the velocity and maximum altitude and the main parachute having a lower drag coefficient than advertised, the flight time was approximately 15 seconds shorter than simulated.

The Entacore 3.0 altimeters showed slightly different results from the StratoLoggers. Both Entacores had extremely similar results, so only the data from the primary is shown below in Figure 17. The recorded apogee was 5,349 feet and the maximum velocity was 689 feet per second.

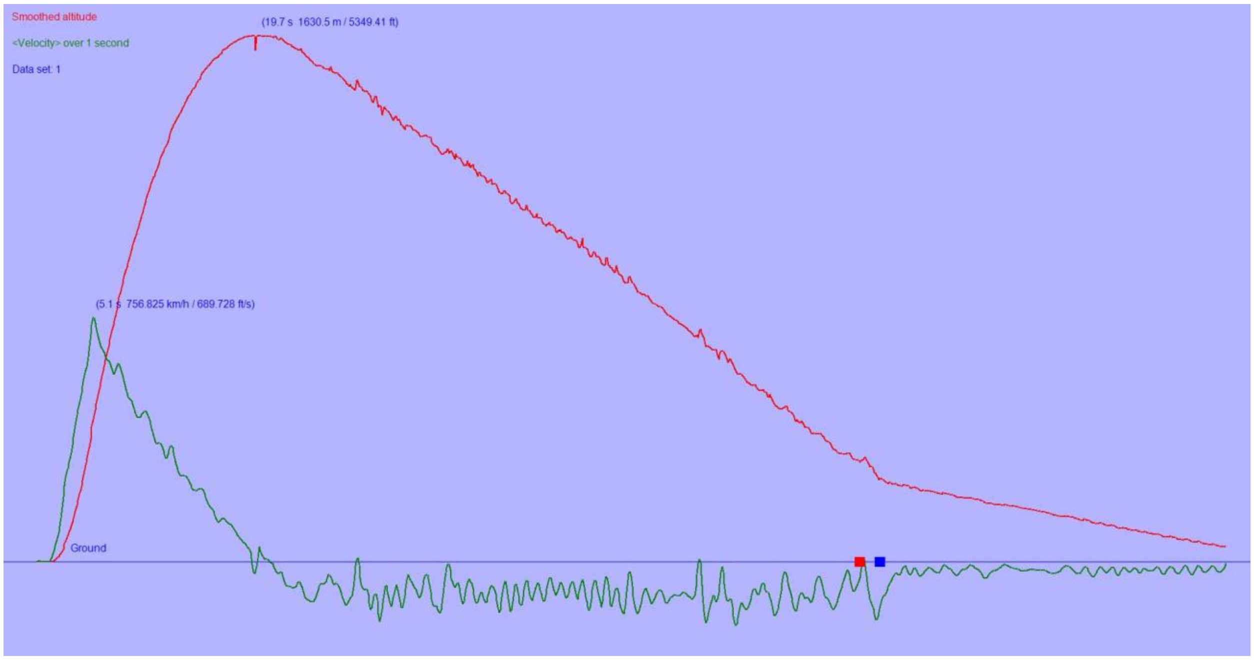


Figure 17 Full Scale launch Altitude and Velocity Curves Collected by Entacore AIM 3.0 Altimeter

3.1.7. Mass Report

Table 5 Launch Vehicle Mass Properties

Component	Weight (lbs)
Nosecone	3.0
Forward Airframe	5.2
Aft Airframe	4.9
Fin Section	8.8
18” Parachute, Harness, and Quick Links	0.9
48” Parachute, Harness, and Quick Links	1.2
84” Parachute, Harness, and Quick Links	1.6
L1150R Propellant and 75/3840 Casing	8.1
Total	33.7

For the maiden flight of the launch vehicle, the airbrake system did not contain any hardware to record data about the system’s performance. Performance data was then extrapolated from altimeter data as well as well as from observations on the ground. Altimeter data was exported into Microsoft Excel, and the acceleration of the rocket was determined by taking the first time derivative of the vertical velocity (the second time derivative of the altitude). Because of the roughness of the raw data, both the vertical velocity and the vertical acceleration of the ascent had to be exponentially smoothed to yield useful results. It can be seen in Figure 18 that the vertical acceleration reached its maximum negative value at about 3200 feet AGL. After this, the acceleration stays almost even at about negative 45 feet per second squared. The fact that acceleration stayed mostly constant suggests that the airbrakes deployed. Visually, members of the team noticed that the launch vehicle’s path wavered about a second after the coasting phase began. This was attributed to the extension of the airbrakes as it was determined that a new force must have been acting on the rocket after coasting had begun.

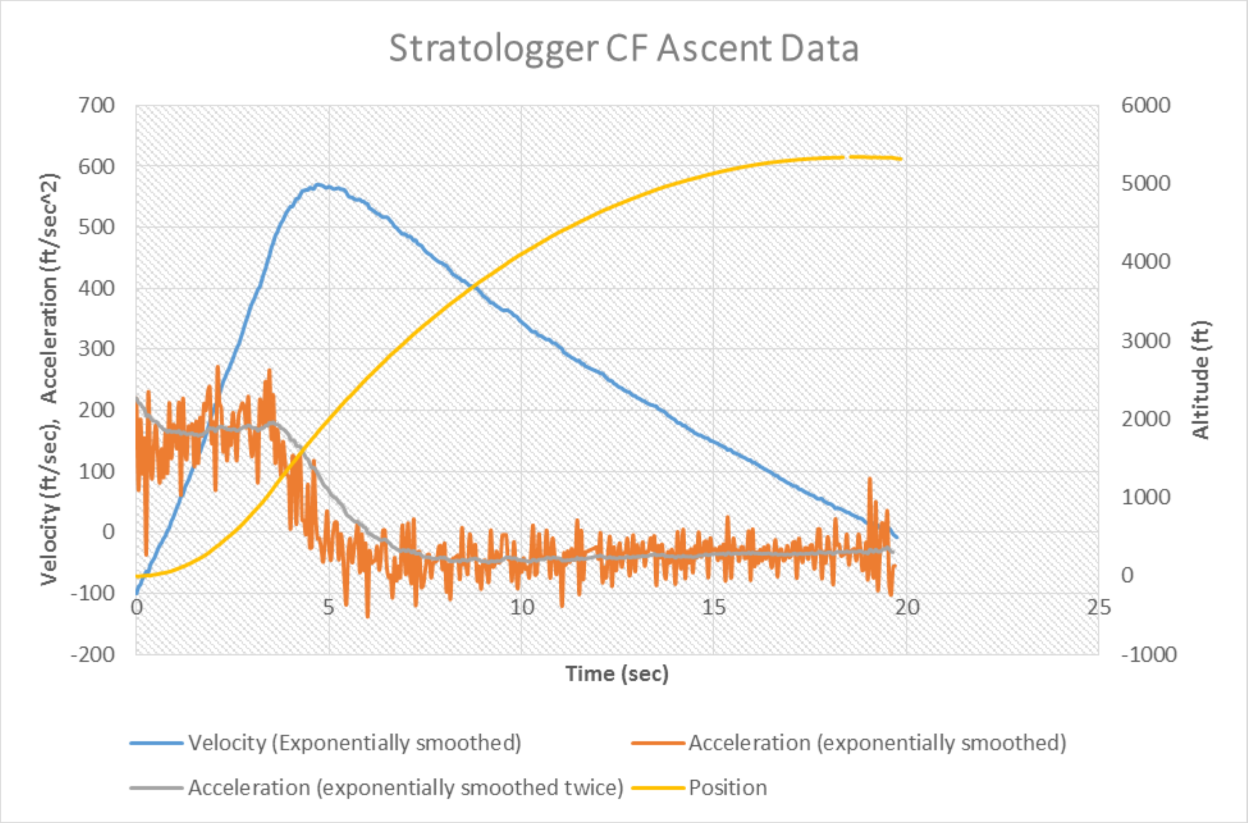


Figure 18 StratoLogger CF Ascent Data

3.2. Recovery Subsystem

3.2.1. Robustness of Recovery System

3.2.1.1. Structural Elements

The parachutes of for the recovery system are all secured to the rocket with 1 inch flat Kevlar harnesses which are rated for 2,000 pounds of tension. The quick links securing the parachutes to the harnesses and the harnesses to the U-bolts are 5/16 inch zinc-plated steel rated for 1,760 pounds. The 5/16 inch zinc-plated steel U-bolts attached to the bulkheads have a calculated working strength of 3,125 pounds based on A36 steel having a minimum yield strength of 36,000 pounds per square inch. The bulkheads to which the U-bolts are attached in the airframe of the launch vehicle are 0.75 inches thick aircraft grade birch plywood with the bulkhead in the nosecone being 0.375 inches thick. Based on past experience with 0.375 inch thick bulkheads of the same material and construction method, the team is confident that these bulkheads are more than sufficient for the stresses they will be exposed to. The nosecone bulkhead is secured with epoxy, the bulkheads in the forward and aft airframes are secured with #6-3/4 inch wood screws, and the fin section bulkhead is secured with both. All bulkheads are seated flush with a section of coupler which braces the bulkhead in the direction in which the recovery system will pull when deployed.

The drogue parachute is attached to the aft bulkhead of the forward airframe with a Rattworks Advanced Retention Release Device (ARRD). The ARRD is an explosive bolt composed of an aluminum shell and a steel eye-bolt. A 0.2 gram black powder charge is placed inside of the ARRD to separate the parts at 1,100 feet AGL. When the ARRD separates, the drogue stays attached to the aft half of the rocket while the forward half falls until the main is released at 1,000 feet.

Each of the three breaks in the launch vehicle will be held together by four removable #4-40 shear pins which were tested during ground ejection tests and the full scale flight to ensure that they would shear when the parachutes are deployed.

3.2.1.2. Electrical Elements

The launch vehicle has two avionics bays. The forward avionics bay will contain two Entacore AIM 3.0 altimeters. Each of these altimeters will be independently powered by a 9 volt battery and each will be controlled by a dedicated switch. These altimeters will be wired to terminal blocks mounted on the bulkheads with 20-gauge wire. The terminal blocks will connect the wires from the altimeters to the e-matches.

The aft avionics bay will contain two Stratologger altimeters, one CF and one SL100. Each of these altimeters will also be independently powered by a 9 volt battery and each will be controlled by a dedicated switch. They will be wired to terminal blocks mounted on the bulkheads with 20-gauge wire. The terminal blocks will connect the wires from the altimeters to the e-matches.

3.2.1.3. Redundancy Features

There are a total of four events for the flight, each with a redundancy plan. Each redundant black powder charge is 115 percent of the primary charge. At apogee, the Stratologger CF will trigger a 2.1 gram black powder charge to deploy the drogue. After a 1 second delay, the SL100 will trigger the larger 2.3 gram redundant charge. At 1,100 feet AGL, the primary Entacore altimeter will trigger the first e-match to separate the ARRD. The redundant Entacore altimeter will trigger the second e-match at 1000 feet. Due to the structure of the ARRD, it is impossible for the redundant e-match to trigger a larger charge, but testing has shown that the 0.2 gram charge that fits inside of the ARRD is sufficient to separate it. The ARRD is also not mission critical as the launch vehicle will descend with the same kinetic energy whether or not it deploys as planned. At 1,000 feet AGL, the primary Entacore will activate a 3.3 gram charge to deploy the 48 inch forward main parachute. The secondary Entacore will activate a redundant 3.6 gram charge at 900 feet. At 700 feet AGL, the Stratologger CF will ignite a 2.2 gram black powder charge to deploy the 84 inch aft main parachute. At 600 feet, the SL100 will activate the redundant 2.4 gram charge.

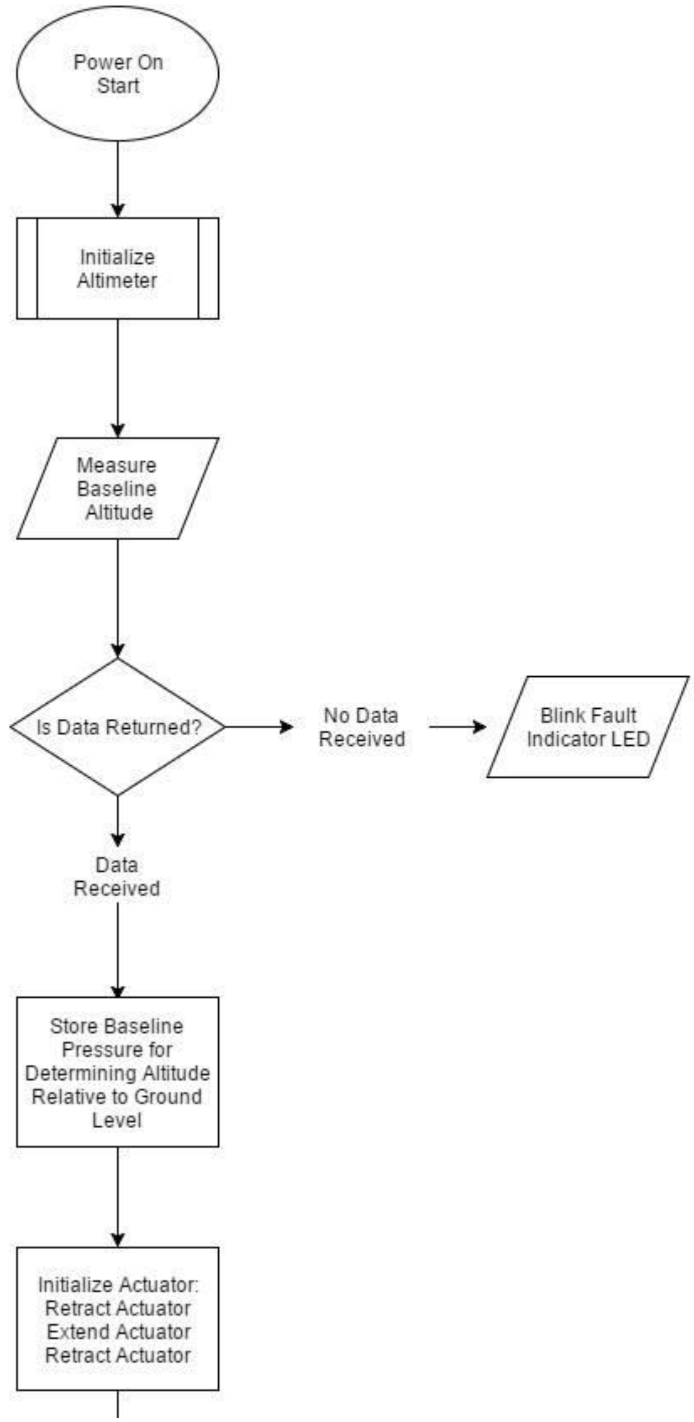
3.2.1.4. Parachute Sizes and Descent Rates

Table 6 Parachute Sizes, Descent Rates, and Kinetic Energies

Parachute	Velocity (ft/s)	Kinetic Energy (ft-lbs)
18” Drogue	92.9	3758
48” Forward Main	20.2	60.2
84” Aft Main	14.6	61.8

3.2.1.5. Drawings and Schematics of Electrical and Structural Assemblies

Figure 19 below shows the flow of events as it pertains to the airbrake system.



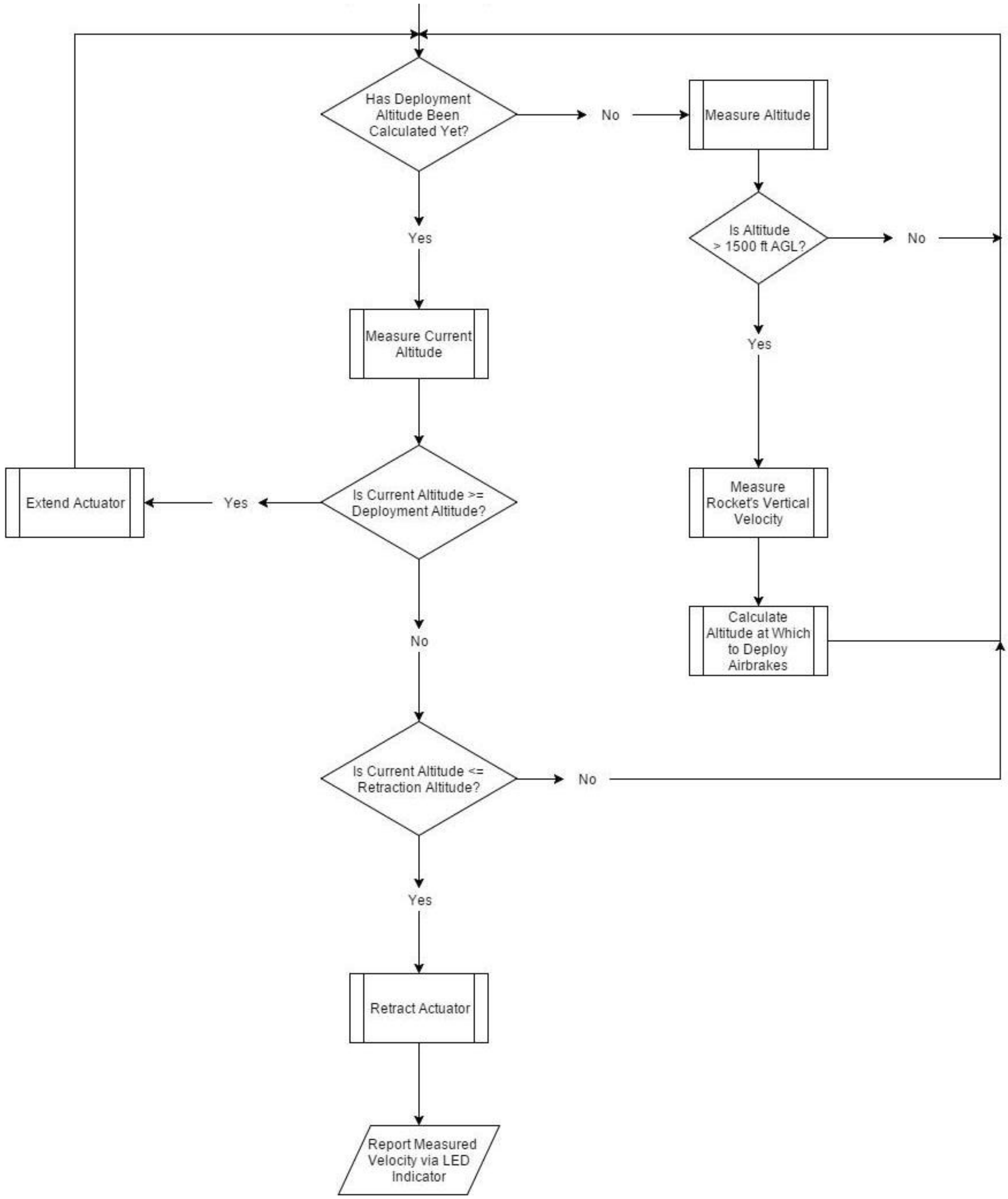


Figure 19 Airbrake Code Flow Chart

Figure 20 below shows a basic layout of how the launch vehicle airbrake system works. An Arduino Mega 2560 will be the primary computer which determines when to deploy the airbrakes. A Firgelli linear actuator will be used to deploy the airbrakes. An Adafruit BMP180 altimeter will be used to tell the Arduino what altitude it's at. The BMP180 has a sampling rate of 20Hz, which is sufficient for this feature. An SD card data logger will be used to record the samples altitude and determine at what altitude the airbrakes were deployed once the launch vehicle is recovered.

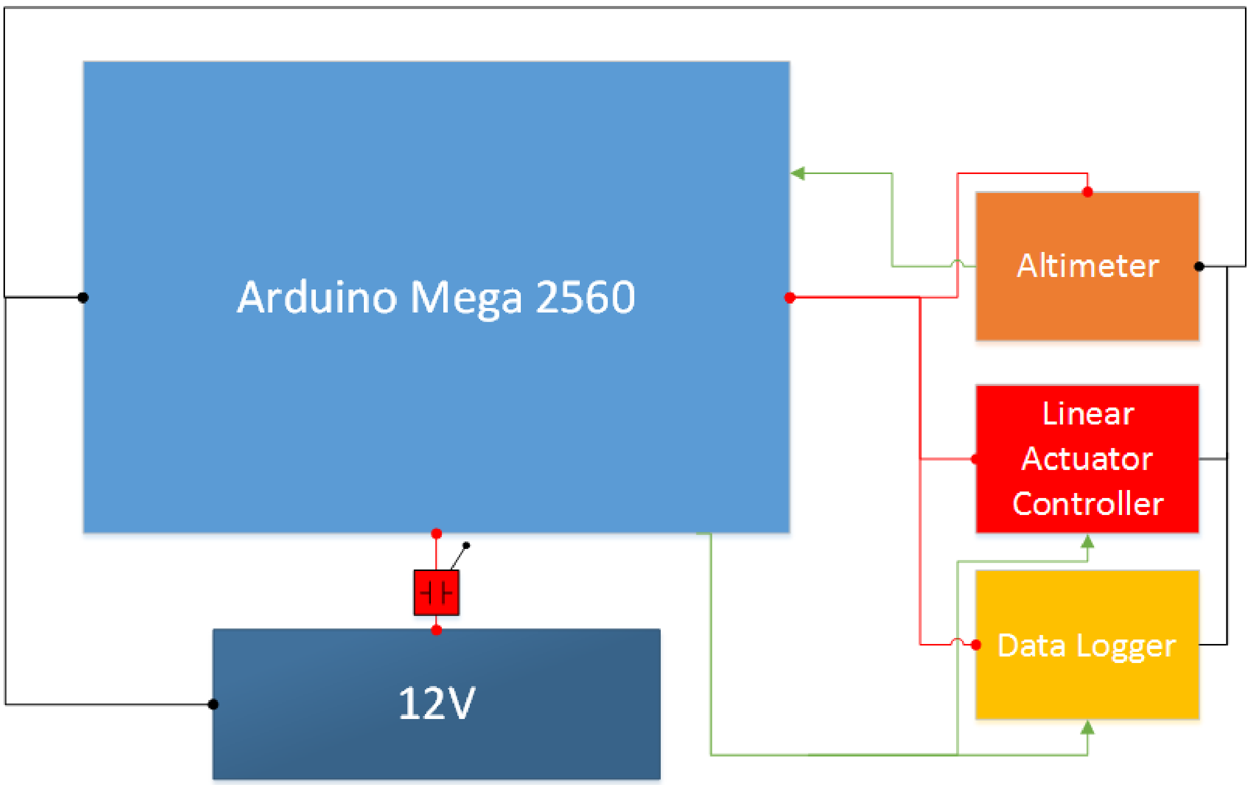


Figure 20 Schematic of Airbrake System

The layouts of the forward and aft avionics electronics are shown below in Figure 21 and Figure 22 respectively.

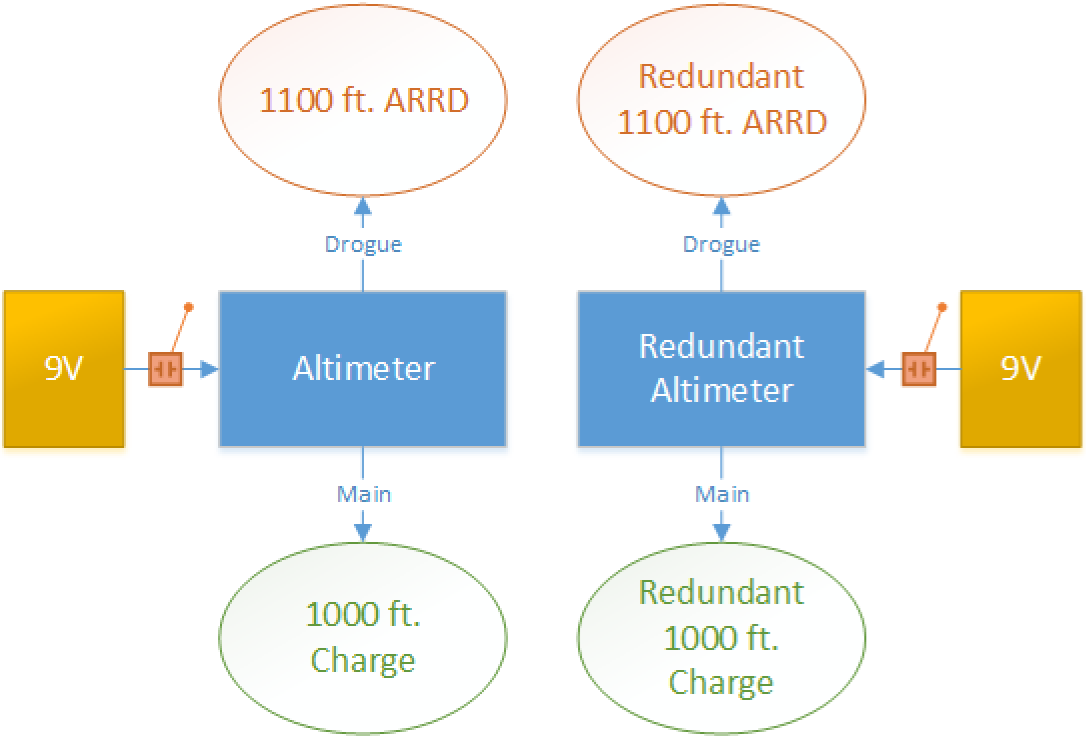


Figure 21 Schematic of Forward Avionics Electronics

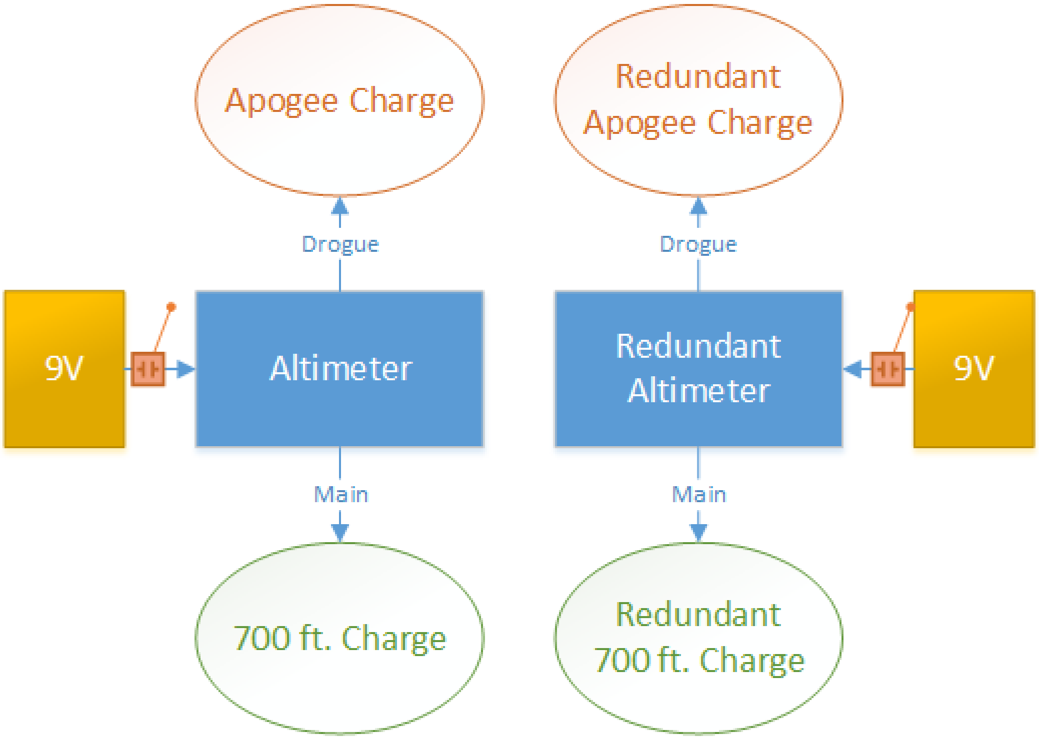


Figure 22 Schematic of Aft Avionics Electronics

3.2.1.6. Rocket-Locating Transmitters

The launch vehicle will contain two independent BigRedBee GPS units, shown in Figure 23, in order to track its whereabouts. The GPS's will be fitted into both the forward and aft avionics bays since those sections fall independently of each other. The GPS's transmit at 900MHz to a ground receiver which feeds data to Google Earth. Google Earth is used since it provides a detailed map of the launch site, has support for pinning GPS coordinates, and does not require a live internet connection.

Figure 23 BigRedBee 900 MHz GPS Units and Receiver

3.2.1.7. Sensitivity of Recovery System to Onboard Electromagnetic Fields

The BigRedBee GPS units (talked about in section 3.2.1.6) will be the only devices on the launch vehicle which transmit high-frequency EM waves. In order to prevent any interference between the vehicle avionics and the GPS units, an aluminum foil barrier will be placed in each avionics section. The barrier will isolate each GPS from the altimeters used to deploy the launch vehicle parachutes. A test will be performed to make sure that the barrier works by powering on the altimeters and GPS and seeing if the altimeters react in any way. In the event that the barrier doesn't work, the GPS units will be moved outside the avionics bays and can be easily mounted to a bulkhead, such that it is not in the same compartment as the avionics.

3.2.2. Suitable Parachute Size for Mass, Attachment Scheme, Deployment Process, Test results with Ejection Charge and Electronics

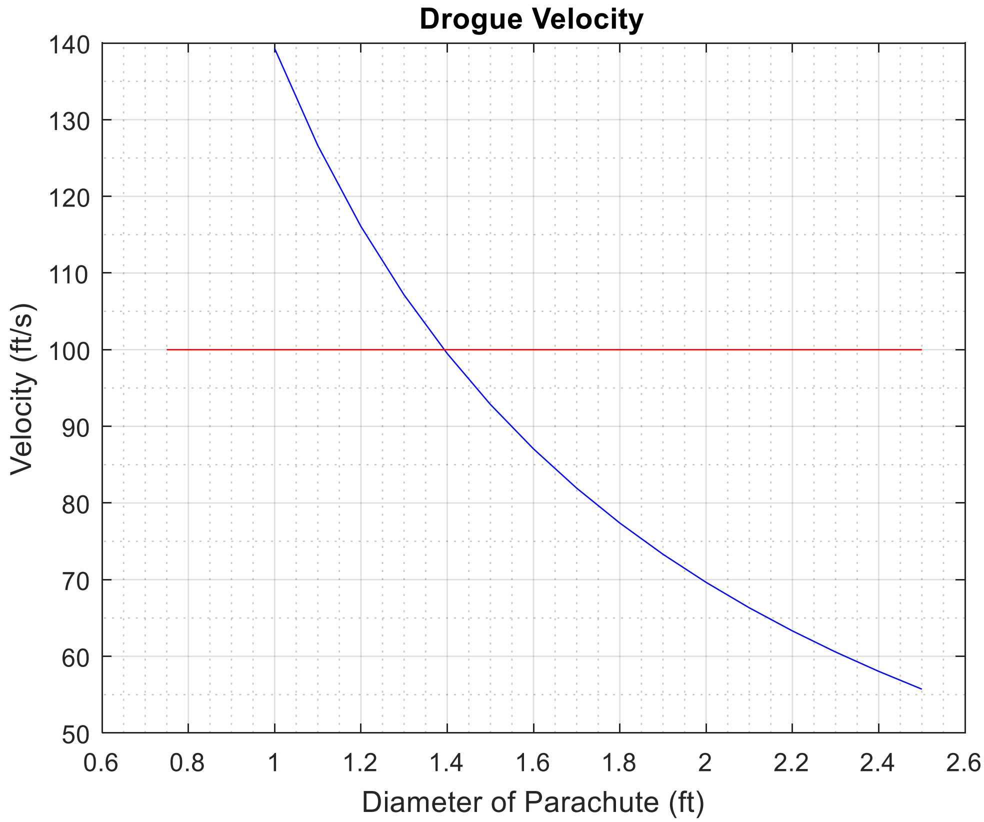


Figure 24 Velocity Under Drogue Parachute

Figure 24 shows the velocity of the launch vehicle under the 18 inch drogue parachute. The drogue parachute deploys at apogee and keeps the terminal velocity of the launch vehicle to 92.9 feet per second during its descent. The kinetic energy of the launch vehicle at this time is 3,758 foot-pounds. The rocket weight after burnout was used to calculate these values. The packing volume of the drogue is 6.4 inches cubed and the compartment for it is 237.6 inches cubed, providing ample room for the recovery harnesses and hardware.

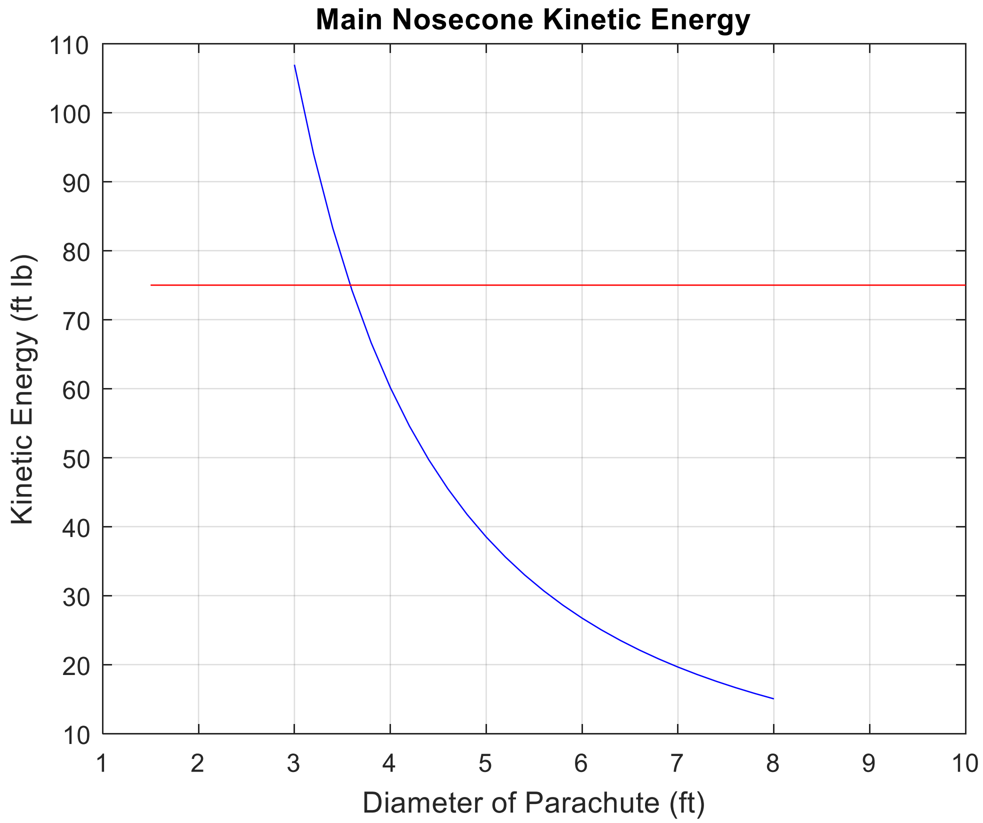


Figure 25 Kinetic Energy of Forward Section Under Main Parachute

At 1,000 feet, the main parachute will deploy from the nosecone and payload section of the vehicle. This section must hit the ground with a kinetic energy below 75 foot-pounds. In order to accomplish this, a 4 foot main parachute was chosen, as shown in Figure 25. This will slow the forward section down to 20 feet per second. The rocket weight, determined after ARRD separation, was used to calculate these values. The packing volume of the 48 inch parachute is 37.3 inches cubed while its compartment is 308.9 inches cubed.

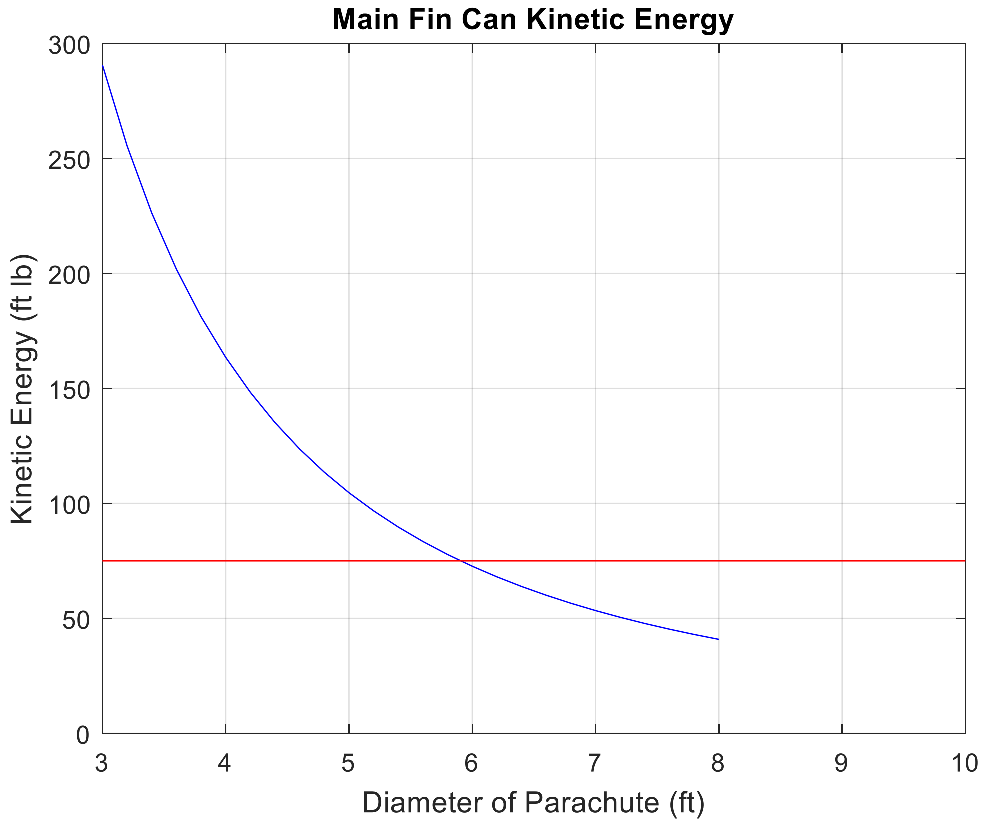


Figure 26 Kinetic Energy of Aft Section Under Main Parachute

Once the fin section reaches 700 feet AGL, the main parachute will come out of that section. This section also has the requirement to land with less than 75 foot-pounds of kinetic energy. Using Figure 26 above, a 7 foot diameter parachute was chosen to allow the fin section to also land safely to allow for reusability. This parachute will slow the fin section down to 15 feet per second. The rocket weight, determined after separation and propellant burn, was used to calculate these values. The compartment for the 84 inch parachute is 261.3 inches cubed while the advertised packing volume is 74.1 inches cubed.

3.2.3. Safety and Failure Analysis

A complete list of FMECAs can be found in Appendix C Failure Mode Effects and Criticality Analysis

3.3. Mission Performance Predictions

3.3.1. Mission Performance Criteria

The first objective to accomplish is the altitude requirement of 5,280 feet AGL. Based on the simulations and calculations, the L1150R motor is sufficiently powerful to carry the vehicle past the goal at the current projected weight. The additional drag provided by the airbrakes will lower the apogee to the target.

One of the altimeters has to be designated as the officially scored competition altimeter. All of the altimeters will be calibrated carefully to ensure accuracy and programmed to read the correct altitude for the elevation at the launch site

The launch vehicle must be recoverable and reusable. The vehicle will be constructed from sturdy materials which will easily withstand the gentle landing. The staged recovery system will ensure that the landing is low force. The two, independent sections will each contain a GPS tracking unit to aid in the recovery of the vehicle after landing.

The vehicle shall have a maximum of four independent sections. These sections at landing will be the nosecone, forward airframe, aft airframe, and fin section.

The launch vehicle will be limited to a single stage. The vehicle will be flying on a single stage L1150R motor.

The launch vehicle shall be capable of being prepared for flight at the launch site within 2 hours. Through proper use of a launch checklist and rehearsed assembly of the vehicle, the team will be able to prepare the vehicle for flight within this time constraint.

The launch vehicle shall be capable of remaining in launch-ready configuration at the pad for a minimum of 1 hour without losing the functionality of any critical on-board component. Each electrical component will be independently powered by either a fresh 9 volt battery or a fully charged LiPo battery to minimize the drain on each battery thereby increasing its life. Furthermore, the altimeters will have switches which will not be activated until the vehicle is in launch configuration on the pad, which will further decrease the drain on the batteries.

The launch vehicle shall be capable of being launched by a standard 12 volt direct current firing system. The standard igniter used to ignite the motor being used to launch the vehicle can be triggered by a standard 12 volt direct current firing system.

The launch vehicle shall use a commercially available solid motor propulsion system using ammonium perchlorate composite propellant (APCP). This motor shall not exceed 5,120 Newton-seconds of total impulse (L-class). The vehicle will be flown on an AeroTech L1150R motor, which is approved and certified by the National Association of Rocketry (NAR) and has a total impulse of 2517 Newton-seconds.

3.3.2. Flight Profile Simulations

Figure 27 shows the predicted flight profile for Huntsville, AL. Using the data received from the full scale test flight and transferring that to the warmer climate of Huntsville, AL, the predicted altitude is 5,391 feet. The maximum velocity will be 732 feet per second, with a maximum acceleration of 287 feet per second squared. This flight profile also uses our total vehicle weight and correct stability margin.

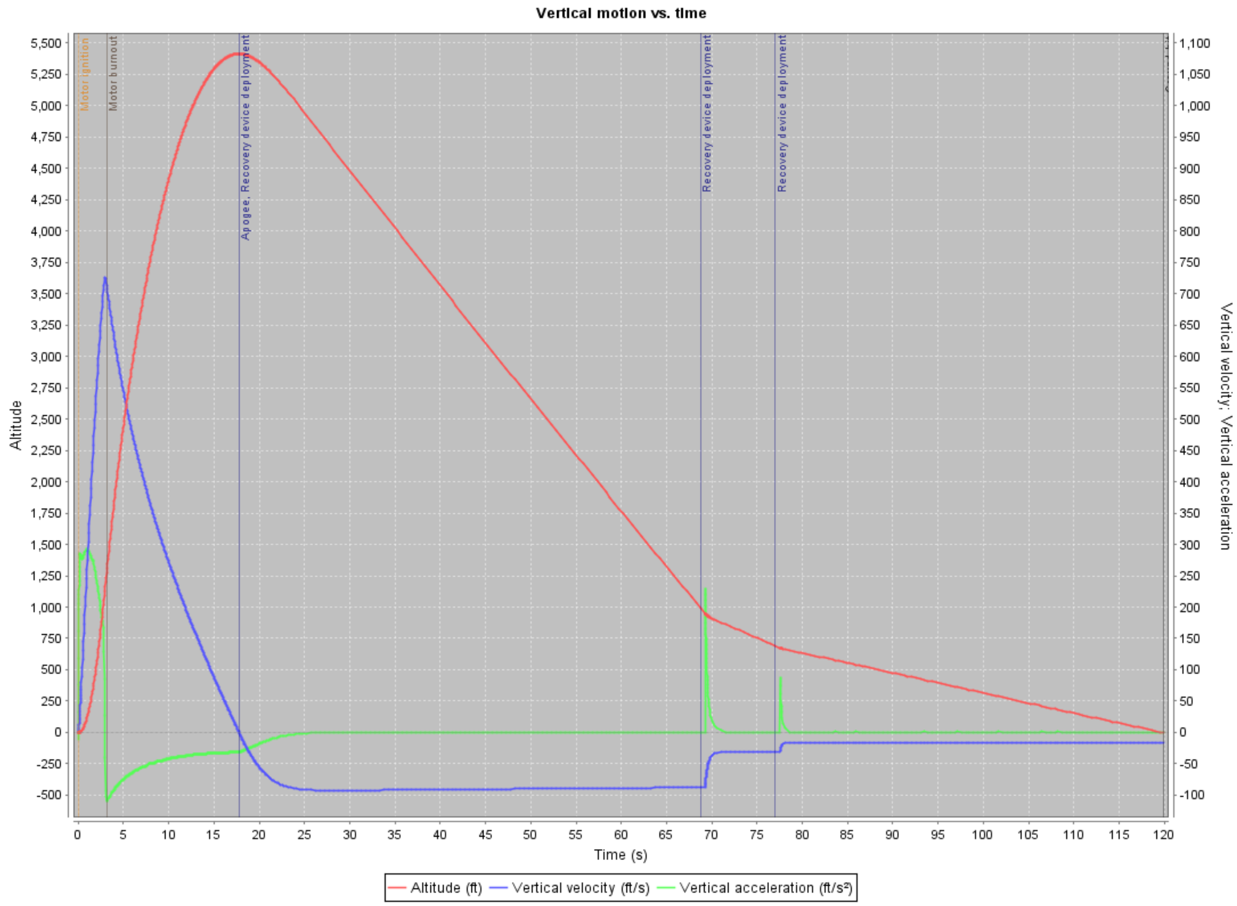


Figure 27 OpenRocket Simulation of the Full Scale Launch in Huntsville, AL

The thrust curve for the AeroTech L1150R is given in Figure 28. This gives a maximum thrust of 302.6 pounds and an average thrust of 258.3 pounds.

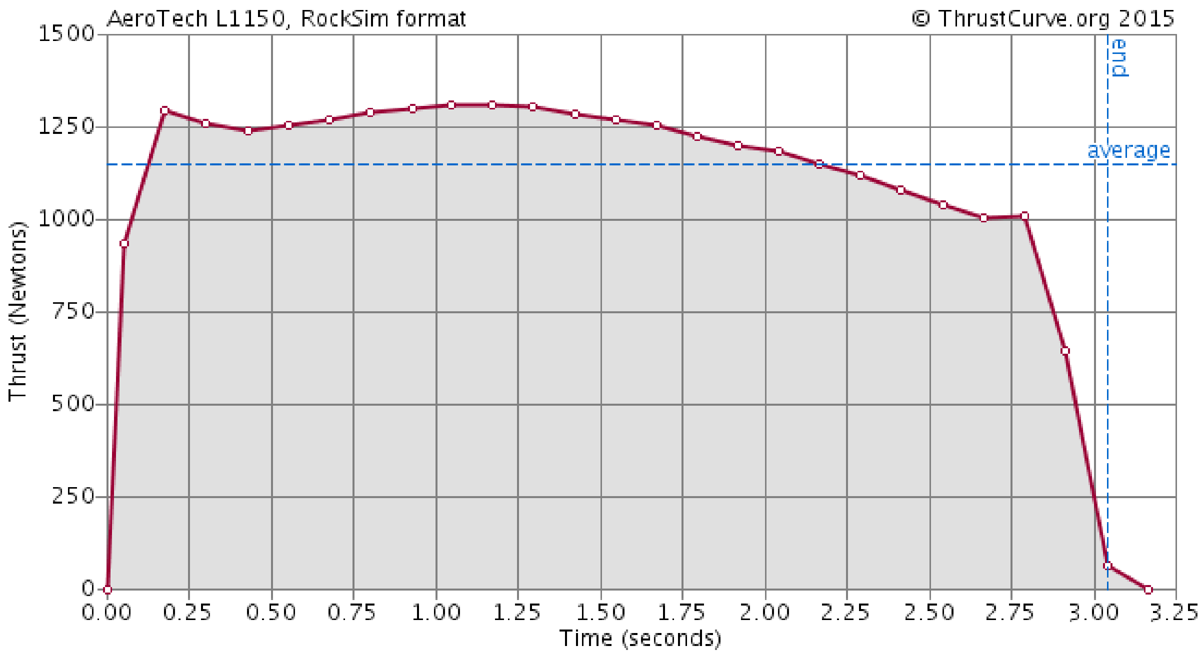


Figure 28 Thrust Curve for the AeroTech L1150R

3.3.3. Thoroughness and Validity of Analysis

The analysis of the rocket so far has included many different calculations and computer analyses. The rocket was originally created with OpenRocket which gives a calculation of centers of pressure and mass, static margin, and stability. The team then used Barrowman's Equation to confirm the center of pressure calculation. With Computational Fluid Dynamics, the coefficients of drag, lift, and moment were able to be determined along with another confirmation of the center of pressure. This CFD analysis was also done with the experimental flaps extended. A SolidWorks model was created of the rocket and from it a mass model was made. All of these analyses together prove the thoroughness of the team's evaluation of the rocket.

3.3.3.1. Drag Assessment

The full scale rocket model was analyzed using computational fluid dynamics in the ANSYS Fluent software package. The vehicle was simulated at zero degrees angle of attack in two different configurations: airbrakes down and airbrakes up. Figure 29 shows the cross sectional area of the two configurations.

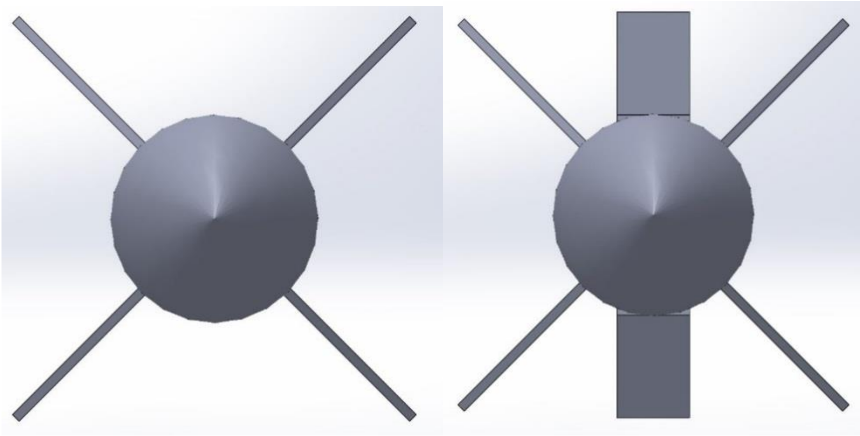


Figure 29 Comparative Cross Sectional View of the Launch Vehicle without the Airbrakes Engaged and then with the Airbrakes Engaged

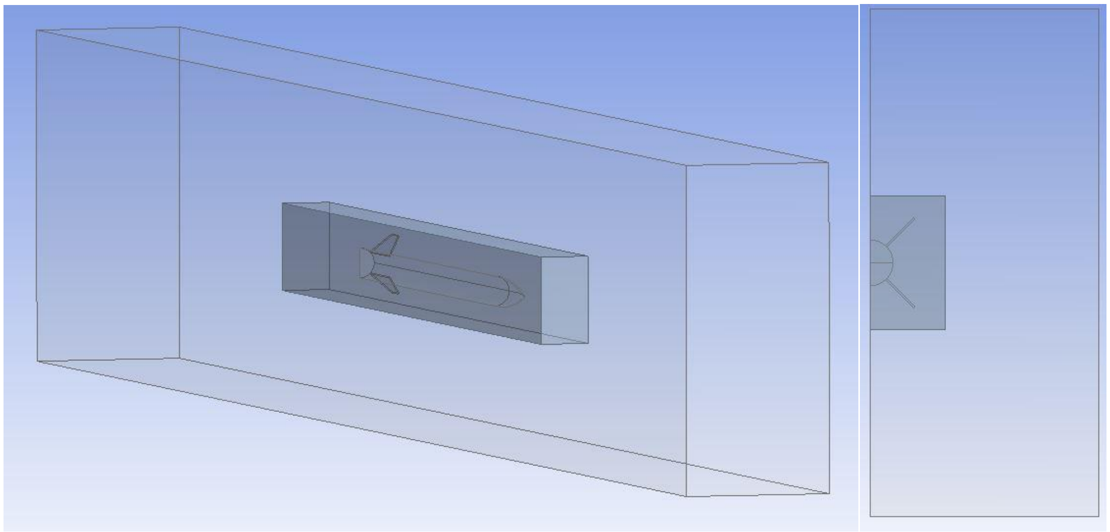


Figure 30 Inner and Outer Domain Model in ANSYS

In order to run the simulation, the vehicle faces were modeled as walls and the two domains were modeled as fluids. Two domains were used so that the model could be meshed finer close to the vehicle and coarser farther away. This was necessary to reduce the computational time required. To further reduce computational time, a symmetry plane was created that split the model in half. This resulted in a mesh that consisted of around 1.4 million elements for both configurations. The maximum element size for the outer domain was 3 inches, 0.75 inches for the inner domain, and 0.25 inches for the faces of the vehicle. Figure 30 shows the tetrahedral element mesh with the transitions between the vehicle, inner, and outer domains.

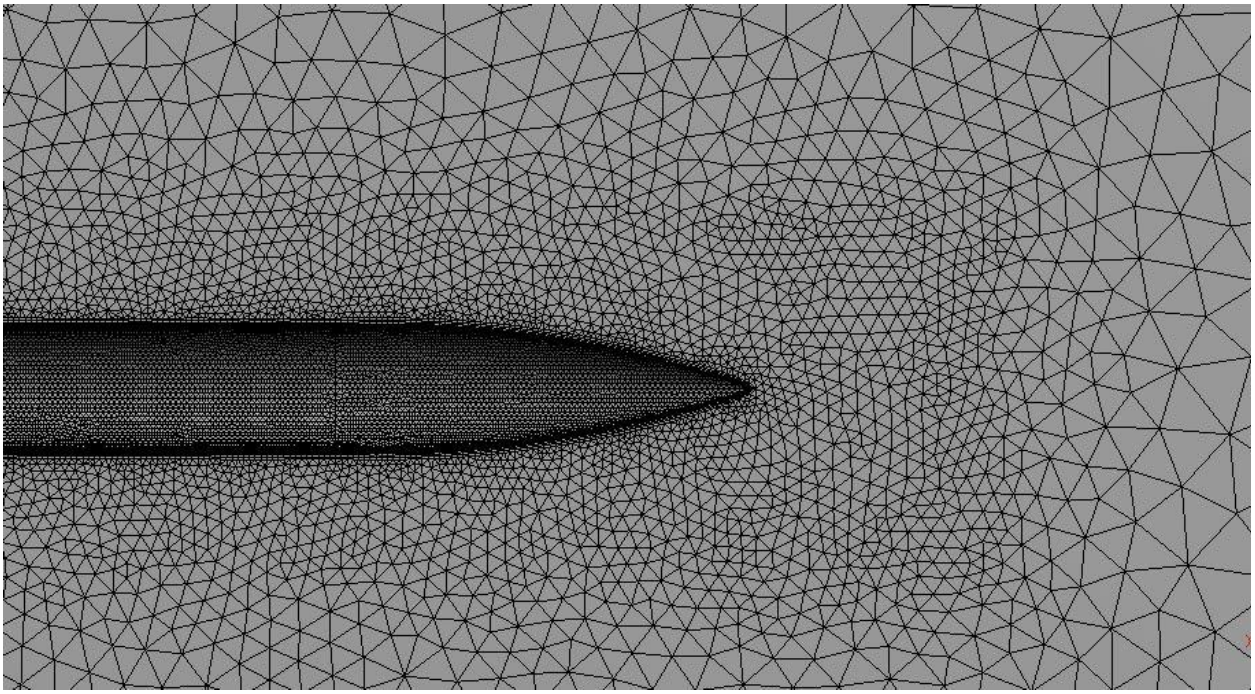


Figure 31 Tetrahedral Element Mesh for Simulations

The meshed model was then run using a realizable k-epsilon model, which is the most common turbulence model. The model used two transport equations to represent turbulent properties of the flow. Using this model allows the simulation to accurately represent realistic conditions. To further increase simulation realism, the reference values used were the cross sectional areas as shown in Figure 31 and 102 inches for the length. With the simulation completely set up, hybrid initialization was used to obtain a starting point and 600 iterations was set as the limit for convergence. The residuals, drag coefficient, lift coefficient, and the moment coefficient were monitored to make sure they had an absolute convergence of 0.00001. All of the monitored cases converged by the 600 iteration limit which gave confidence in the results.

The results were then visualized in the ANSYS Fluent graphics solutions package. Figure 32 shows the pressure contour across the body of the vehicle. The high pressure zones at the tip of the nosecone and along the leading edge of the fins experienced 281 pounds per feet squared. The symmetry of the pressure contours along the vehicle invokes confidence in the aerodynamic design of the vehicle.

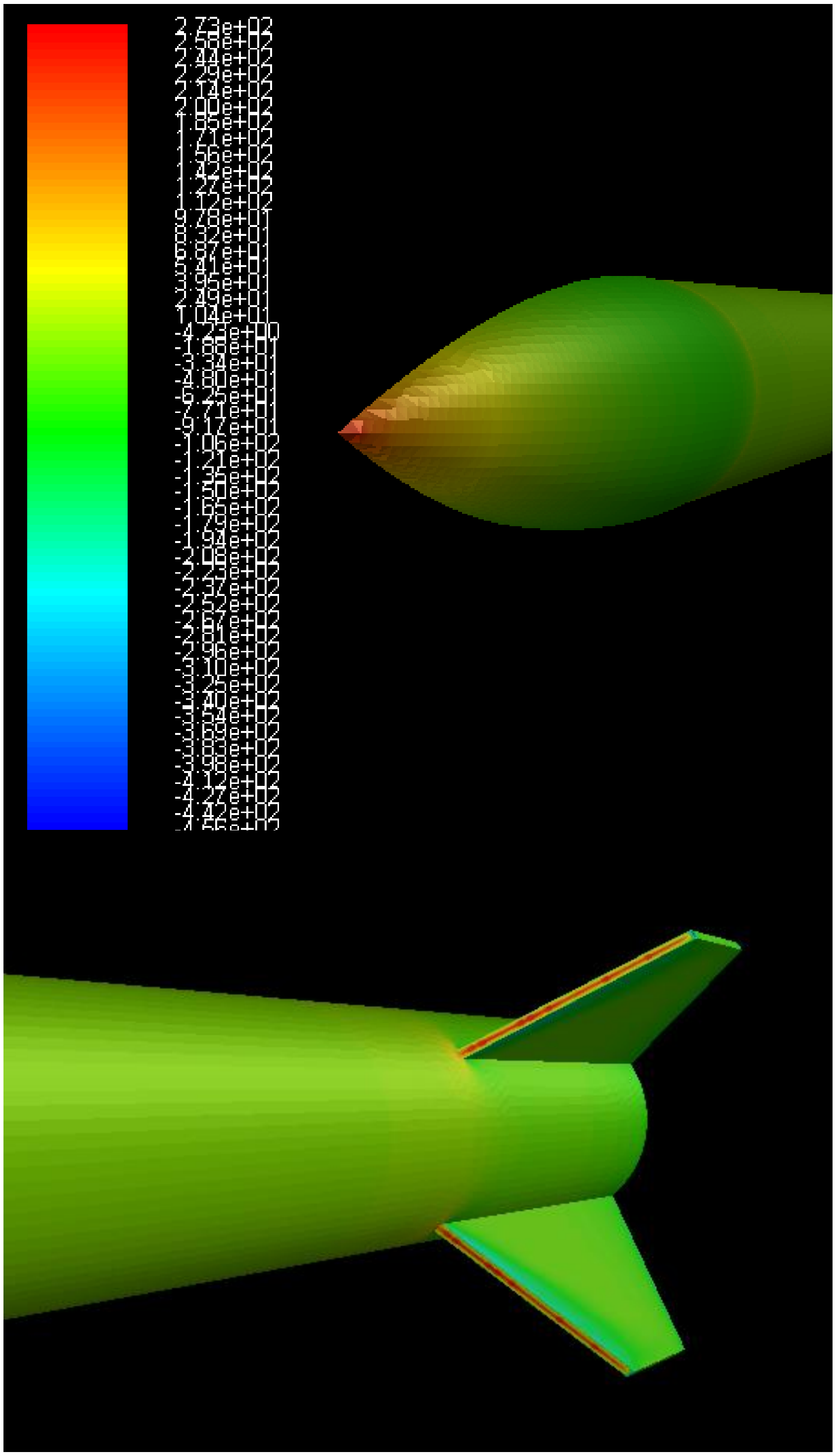


Figure 32 Airbrakes Undeployed Model of the Pressure Contour at 700 Feet per Second

The model was then analyzed again with a pressure contour along the body of the vehicle using the ANSYS Fluent post-processing software. Figure 33 shows the resulting pressure contour; inspection of the results reveals that the pressure contour is the same as in the first analysis. As a result, the accuracy of the simulation was verified. In addition to the pressure contour, the model was analyzed with a volume rendering of the velocity streamlines along the body of the vehicle. As it can be seen in Figure 34, the velocity stayed fairly consistent at 700 feet per second except at the nose of the vehicle and the wake region. This result was anticipated and further verifies the accuracy of the simulation.

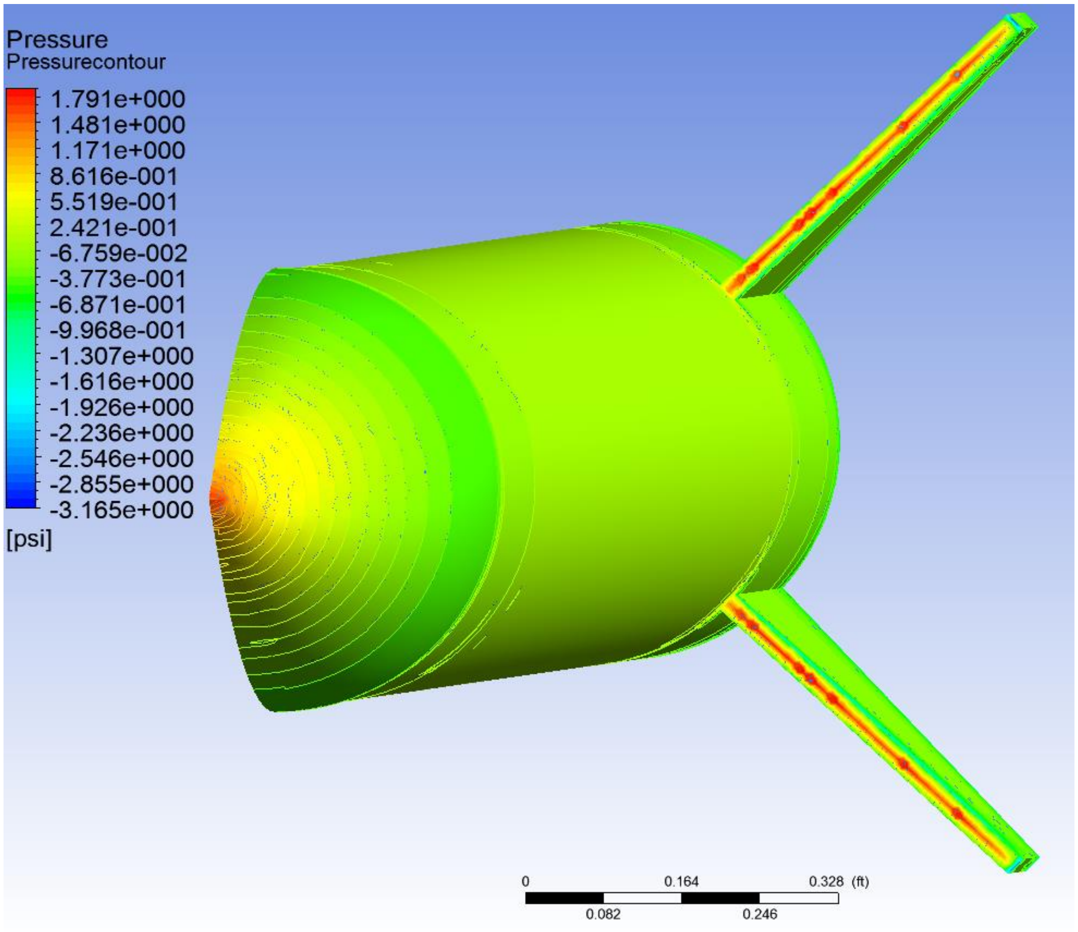


Figure 33 Airbrakes Undeployed Post-Processing Model of the Pressure Contour at 700 Feet per Second

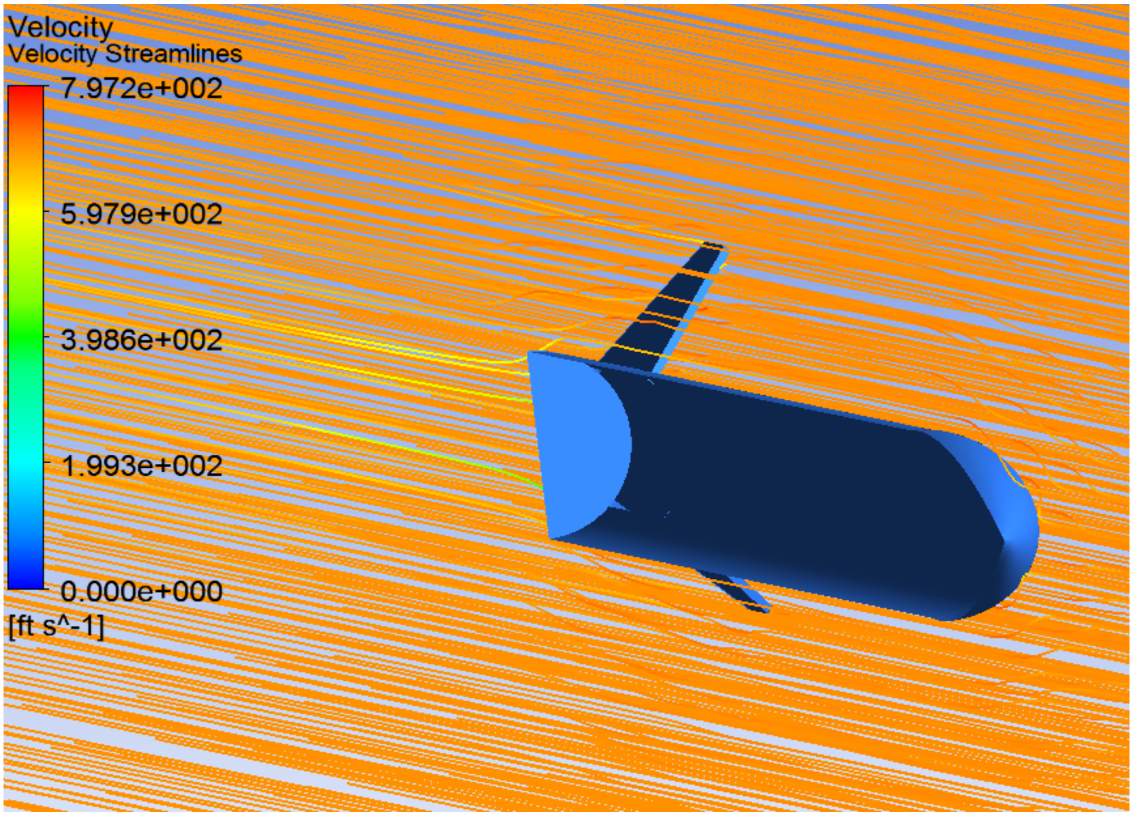


Figure 34 Airbrakes Undeployed Post-Processing Model of the Velocity Streamlines at 700 Feet per Second

These same three cases were then run for the airbrakes-up configuration of the model. These results can be seen in Figure 35, Figure 36, and Figure 37.

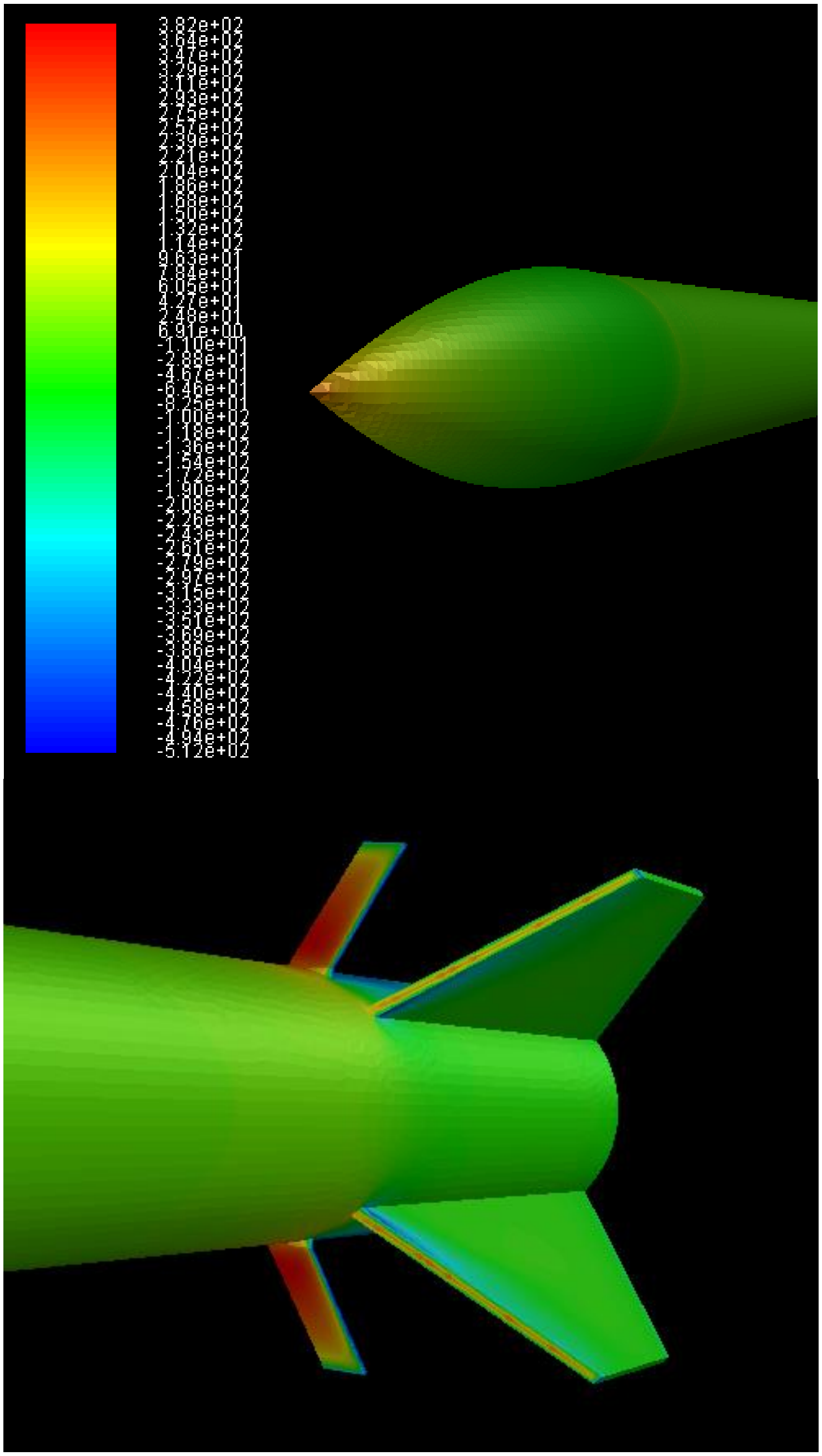


Figure 35 Airbrakes Deployed Model of the Pressure Contour at 700 Feet per Second

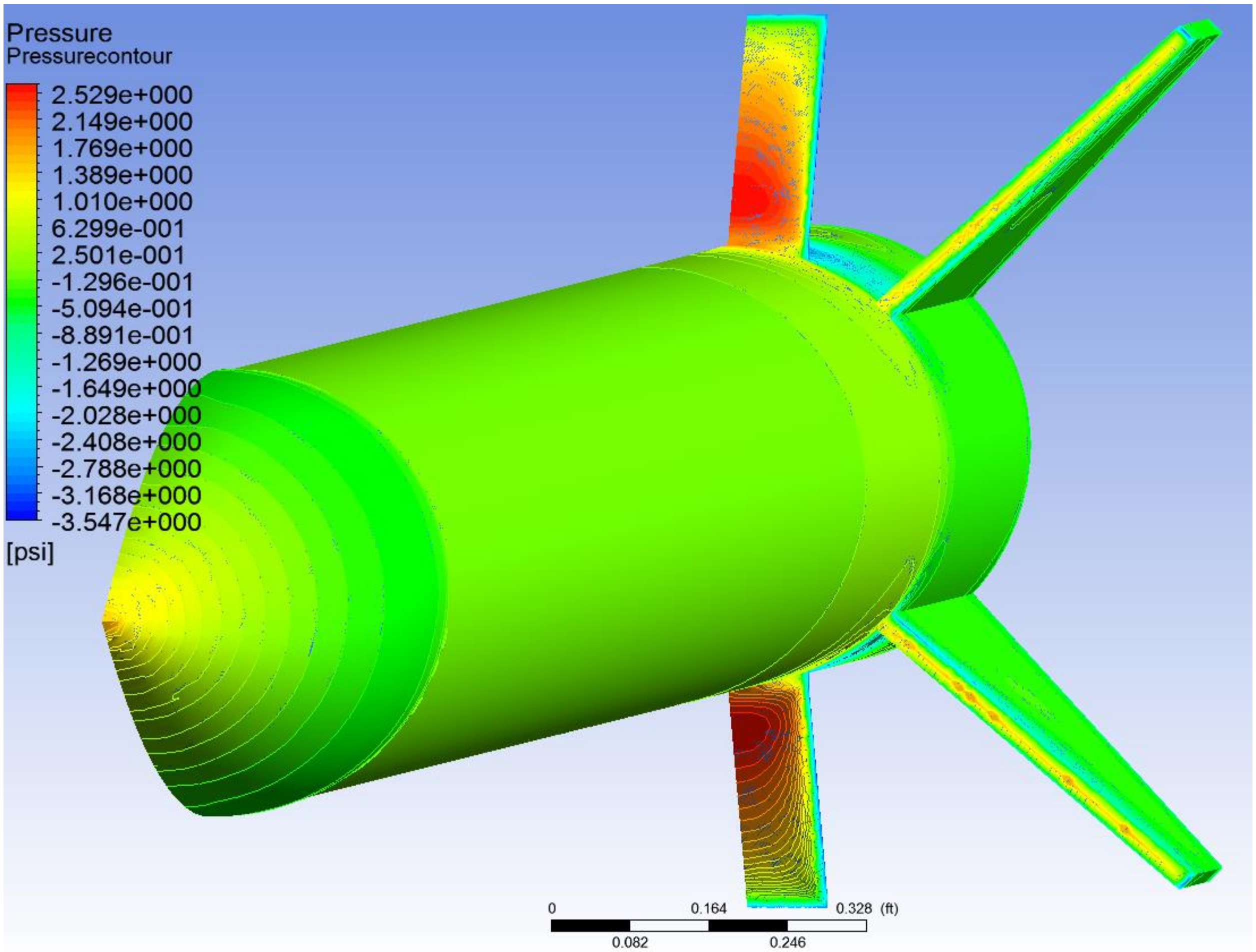


Figure 36 Airbrakes Deployed Post-Processing Model of the Pressure Contour at 700 Feet per Second

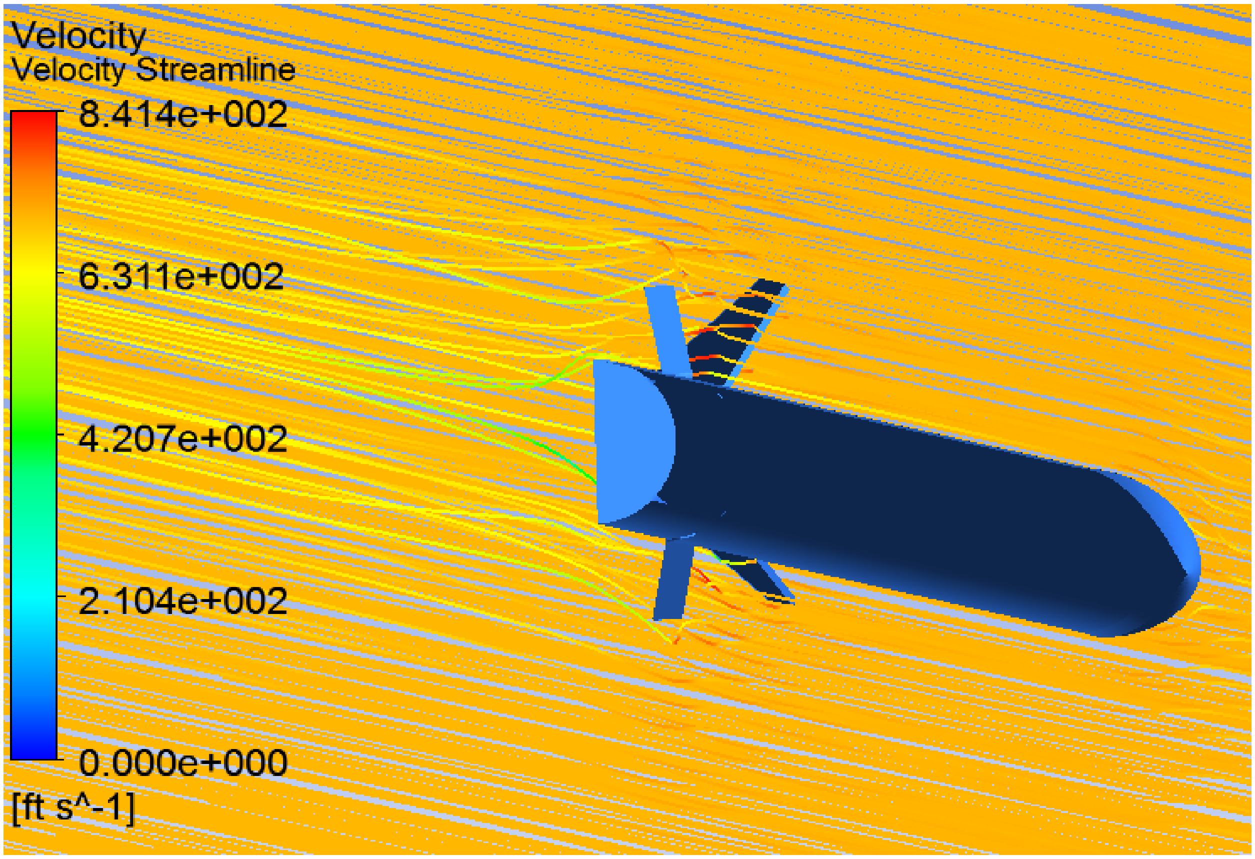


Figure 37 Airbrakes Deployed Post-Processing Model of the Velocity Streamlines at 700 Feet per Second

In addition to the visualizations from the post processing software, the ANSYS results also gave the drag coefficient, lift coefficient, and the moment coefficient of the vehicle. These coefficients can be seen in Table 7 below.

Table 7 Comparison of Aerodynamic Coefficients Before and After Airbrakes Engage

Coefficients	**Airbrakes Unengaged**	**Airbrakes Engaged**
C_D	0.3848	0.54387
C_L	0.001390	-0.00003318
C_M	0.00003330	0.00004478

The drag force experienced by the vehicle when the airbrakes are down is 22.67 pounds force and 44.58 pounds force when the airbrakes are engaged. The center of pressure was also calculated from the simulation results and the coefficients. The center of pressure was located 6.44 feet (77.28 inches) from the tip of the nosecone. This gives a static margin of 2.37 caliber. Barrowman's equation and OpenRocket gave a static margin of 2.19 caliber. This slight difference in the static margin can be attributed to the refinement of the Fluent model. The most accurate results come from a mesh with very small element sizes and that means more computational power required. Even though this model can be further refined to be more accurate, the results from the model give confidence in the design of the vehicle. As such, the cost of implementing more-refined computations is not justified for this analysis.

3.3.4. Stability Margin

From OpenRocket software, the simulated CG and CP locations were 64.75 and 76.32 inches aft of the tip of the nose. This makes for a stability margin of 2.1 caliber at takeoff which satisfies the minimum value of 2.00 recommended by the NASA reviewers during the PDR presentation. As the motor burns out and the CG is moved farther forward, the stability will increase to 2.98 caliber. The overall rocket with CG and CP locations marked can be seen in Figure 38.

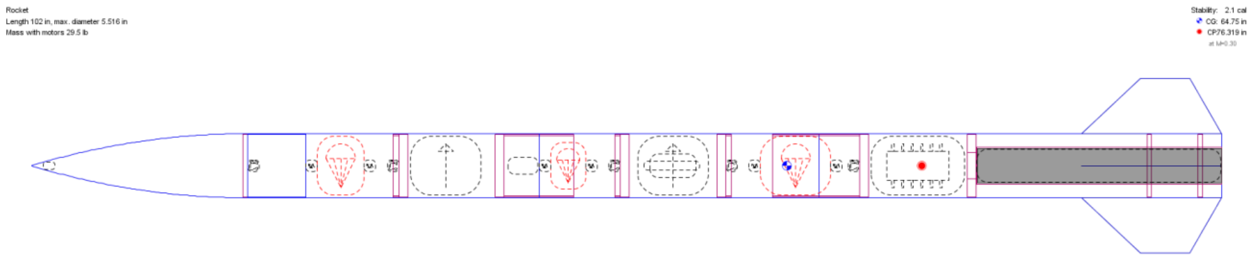


Figure 38 OpenRocket Model with CG and CP Marked

3.3.5. Management of Kinetic Energy

The kinetic energy of each part of the rocket during different stages in the recovery operation was found by squaring the velocity of the component and then multiplying it by half of the mass. This yielded the results in Table 8.

Table 8 Kinetic Energy and Descent Rates for Parachutes

Stage #	Forward Airframe Kinetic Energy (foot-pounds)	Aft Airframe Kinetic Energy (foot-pounds)	Descent Rates of Forward Airframe (Feet/second)	Descent Rates of Aft Airframe (feet/second)
Stage 1 (Apogee-1100 feet)	3765	3765	92.9	92.9
Stage 2 (1100 – 1000 feet)	2223	--	123	--
Stage 3 (1100 – 700 feet)	--	1651	--	75.6
Stage 4 (1000-0 feet)	60.2	--	20.2	--
Stage 5 (700-0 feet)	--	61.6	--	14.6

*Note, because the upper and lower airframes are connected during stage 1 of the recovery sequence, the kinetic energy and descent rates of the two connected pieces is shown in both columns.

3.3.6. Altitude of Launch Vehicle and Drift

The maximum altitude for all components (upper airframe, middle airframe, and fin section) will be at the projected apogee of 5350 feet.

A MATLAB code was written to determine the lateral drift of the two parts of the rocket that come down separately. This drift would be caused by wind, or by both wind and a launch angle of 5° upstream or downstream of the wind. Wind speeds of 0, 5, 10, 15, and 20 miles per hour. Using the C_d of the various parachutes (1.55 for the drogue and 48 inch main, 1.9 for the 84 inch main) assuming that the density of air stays constant at 0.002377 slugs/feet^3, and assuming that drag equals weight, the terminal descent velocity was obtained by utilizing the equation

$$V_{Term.} = \sqrt{\frac{2 * Drag}{C_d * \rho * Area}}$$

Equation 2

The terminal velocities of the different parachute set-ups were as follows:
-92.9 feet per second for the drogue slowing the rate of the entire rocket at apogee
-75.6 feet per second for the drogue slowing the rate of only the lower airframe
-20.2 feet per second for the 48 inch main slowing the upper airframe
-14.6 feet per second for the 84 inch and drogue slowing the lower airframe

Using these descent velocities of the various configurations that the rocket undergoes after apogee, the amount of time that the descent would take was derived; this time was multiplied by the hypothetical wind speed to get an approximate drift radius for the two parts of the rocket that come down separately. These distances are shown in Table 9.

Table 9 Zero Degree Launch Angle Wind Drift Distances

Wind Speed (Miles per Hour)	Lateral Drift of Upper Airframe (feet)	Lateral Drift of Lower Airframe (feet)
0	~0	~0
5	829	1712
10	1658	1712
15	2487	2569
20	3316	3425

Once the 0° Launch Angle drift radii were found, it was necessary to determine the drift distances with the Launch angle of 5°. A simulation was run in OpenRocket where the wind conditions were set to zero, and the launch angle was set to 5°. The lateral distance shown (roughly 460 feet from launch rail) was then added to the wind drift values found above to get a total drift radius once wind and launch angle were taken into account. These values are shown in Table 10.

Table 10 Five Degree Launch Angle Wind Drift Distances

Wind Speed (Miles per Hour)	Downstream Lateral Drift of Upper Airframe (feet)	Downstream Lateral Drift of Lower Airframe (feet)
0	460	461
5	1289	1317
10	2118	2174
15	2947	3030
20	3776	3887

Variations in wind also affect the apogee of the rocket. Using simulations in OpenRocket, we were able to predict how wind speed effects the apogee of the rocket launching with a launch angle of 5°. The results of these simulations are shown below in Table 11.

Table 11 Comparison of Wind Speeds at Launch and Subsequent Apogees

Wind Speed (Miles per Hour)	Apogee (feet)
0	5519
5	5463
10	5415
15	5357
20	5305

3.4. Verification

The verification matrices for the vehicle can be found in Appendix D Vehicle Verification Matrix.

3.5. Safety and Environment

3.5.1. Safety and Mission Assurance Analysis

The FMECA diagrams can be found in Appendix C Failure Mode Effects and Criticality Analysis

In terms of structures, the nosecone separating prematurely from the vehicle may result in the parachutes being deployed too early. If the vehicle is still in the thrusting phase, then the parachutes or other structural components may be damaged if the parachutes deploy prematurely as well. Because this error will most likely occur as a result of poor handling or maintenance, this error is unlikely if the team properly handles the nosecone.

As for the recovery system, a malfunction in the avionics due to a dead battery has some of the worst consequences. If the altimeters do not function, then the black powder charges will not go off, resulting in a failure of the parachutes being deployed. As a result, the vehicle may be destroyed or it may damage other objects as it falls back to the ground. Using new batteries for every launch is standard team practice, however, so dead batteries are extremely unlikely.

A third significant failure mode is the separation of the vehicle from a parachute due to a failure in the bulkhead and/or U-bolt. Similar to the failure in the altimeters, the vehicle separating from a parachute may result in significant damage to the vehicle or other objects (including personnel). Because the team thoroughly tests all epoxied joints and U-bolts for this failure, this is unlikely to occur during the competition.

Furthermore, the motor breaking through the bulkhead would cause catastrophic failure of the vehicle. If the propellant escapes the motor housing, then the vehicle will most likely be destroyed. The team realizes this risk and will ensure that the motor block is structurally sound.

Another possible failure involving the motor is the chance of catastrophe at takeoff. While this is an extremely serious failure mode, the likelihood is low provided that the team takes care to meticulously follow the procedure for correctly assembling the motor.

Buckling of the body tube at any of the hatch locations would result in catastrophic failure of the vehicle. This is a very unlikely failure as each of the hatches are screwed into the bulkheads on either side of each hatch. Due to this, the compressive forces encountered during launch will be transferred through the hatches as well as the body tube surrounding them.

Another possible failure that could occur would be non-deployment of the airbrake system, that the airbrakes would only partially deploy, or that only one airbrake would deploy. This failure mode would not result in any damage to the launch vehicle and would not pose any threat to the safety of the mission. These failures would only result in a higher apogee and a lower overall score.

3.5.2. Personnel Hazards

As more construction occurs, the team will be exposed to potentially-dangerous machines. An outline of these construction hazards is located in Table 12. In building the vehicle, the team will also be exposed to hazardous materials such as black powder and epoxy. The MSDS sheets for such materials are included in Appendix B MSDS**.** In order to mitigate the risks associated with these materials, the team will follow the procedures outlined within the documentation. Furthermore, the personnel hazards on the launch site are described below in Table 13.

Table 12 Construction Personnel Hazards

Safety Concern	Mitigation	Confidence
Drill Press	All personnel in the lab space are notified before powering on the drill press. Safety glasses and earplugs are to be worn by persons operating the press. Precise set up of the drill press and retention of the material being drilled will ensure the press is operated smoothly and within operating limits.	The drill press is a safe piece of machinery. Team members are trained on how to use the press safety and are supervised until proficient. Proper PPE will be worn at all times during operation.
Band Saw	All personnel in the lab space are notified before powering on the band saw. Safety glasses and earplugs are to be worn by persons operating the band saw. Saw calibration and setup are checked prior to use. Only select materials and thickness will be used on the band saw.	Proper setup (tightness and alignment of band) is the most important part of safe operation of the band saw. Team members are trained on the band saw and supervised until proficient. Proper PPE will be worn at all times during operation.
Belt Sander	All personnel in the lab space are notified shortly before powering on the belt sander. Safety glasses and earplugs are to be worn by persons operating the belt sander.	The belt sander will be checked for proper tightness before use. Proper PPE will be worn at all times during operation.
Manual Mill	For any items that need the manual mill, the team goes to the director of the Mechanical Engineering Shop. The director of the shop is a professional machinist hired by NC State.	The shop director ensures the safety of his lab and helps teach those concerns to team members. All shop procedures are followed when the manual mill is used.
Chop Saw	For any items that need the	The shop director ensures

	chop saw, the team goes to the director of the Mechanical Engineering Shop. The director of the shop is a professional machinist hired by NC State.	the safety of his lab and helps teach those concerns to team members. All shop procedures are followed when the chop saw is used.
Black Powder	Black powder is handled in an isolated location, premeasured, and placed into vials before taking it out to the launch site. The black powder is stored separately in a safe environment away from potential ignition sources.	Black powder is one of the more dangerous substances handled by the club, so extreme caution is taken when handling. There is minimal chance for problems with black powder.
Epoxy	Epoxy is applied in ventilated areas. Persons using epoxy wear gloves and eye protection.	Safety procedures and observers ensure epoxy is a minimal safety concern in the lab.
Power Supply	Power supplies are left unplugged when not in use. They are not used near water and cords are inspected for bare wires before use. Circuitry is checked prior to use to ensure they can handle the applied loads.	Relatively low power uses with stringent safety requirements ensure proper use and safety when using electrical equipment.
Soldering Iron	Soldering irons are left unplugged when not in use. They are not used near water and cords are inspected for bare wires before use. User ensures proper spacing during operation.	Primary concerns with soldering irons focus around electrical safety and minimizes misplacement of the heat source. Keeping these two risks in check ensures the safety of the equipment operation.

Table 13 Launch Site Personnel Hazards

Safety Concern	Mitigation	Confidence
Assembly of Rocket Motor	The rocket motor is carefully carried from the car to the rocket assembly point under close supervision by other team members and Team Advisor Charles Hall. During assembly, all points specified by the manufacturer's instructions are followed step by step.	Assembling the rocket motor is a critical procedure to ensure the safety and success of the launch. Special attention to manufacturer's as well as advisor's instructions ensures the motor ignites and burns properly.
Handling of Vehicle	Two hands are used to transport each component when taking the rocket from the car to the assembling area. Electronics and blast caps are armed and filled shortly before launch during the onsite assembly.	Cautious handling protects the rocket from falls that could damage components and harm the launch. Keeping the black powder and E-matches separate during transport of the rocket keep the chances an explosion low
Launch Vicinity	Monitoring the location of everyone that is in attendance on the launch site and preventing them from getting to close will be a simple task by giving warnings prior to launch.	This concern is mitigated by having set distances specified by launch officials and by being able to identify team members by their team uniforms
Weather	For every launch we make sure that the conditions such as wind speed, precipitation, and temperature are within safe limits of operation. If conditions are unsafe the team will not launch the vehicle	Proper weather forecast monitoring and monitoring the weather at the launch site will eliminate the risk of weather.
Location	Launches are only done at locations specified by the North Carolina Rocketry Association or NASA Student Launch.	We are confident in these organizations to choose proper locations for launches.

3.5.3. Environmental Concerns

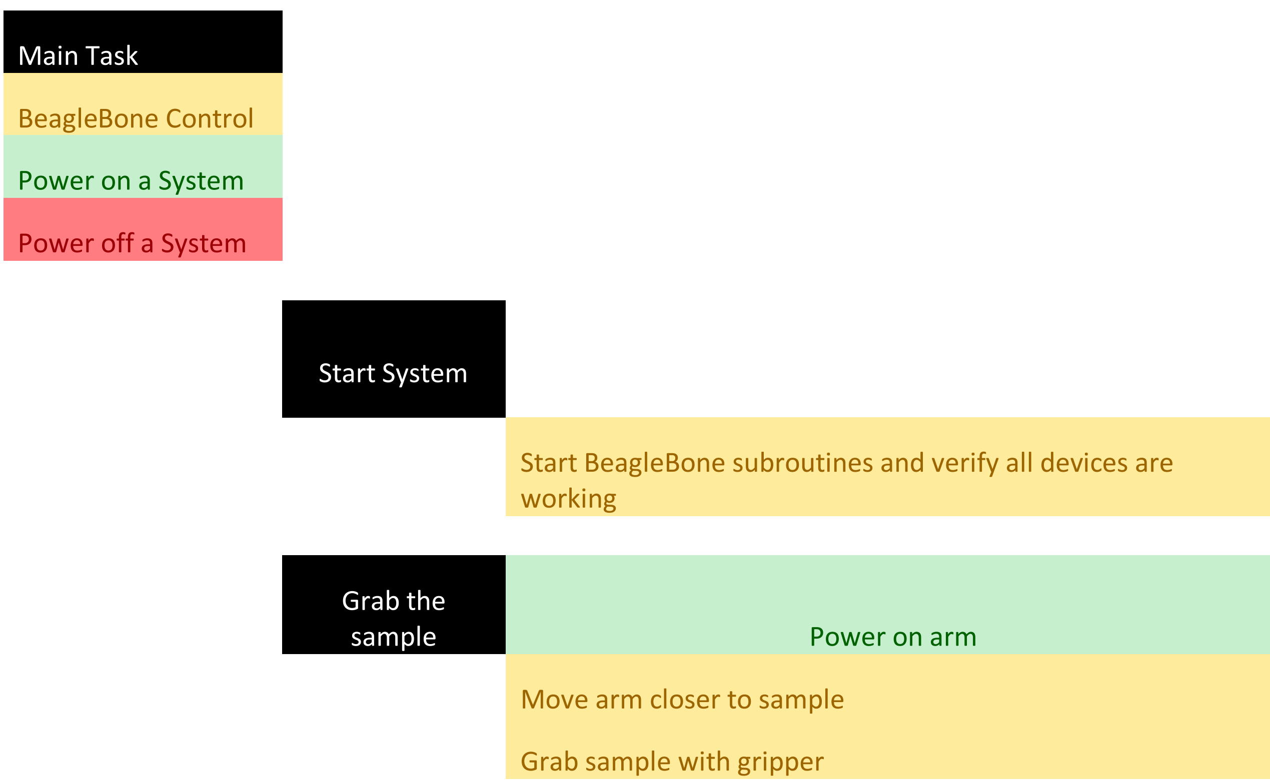
A thorough discussion of the environmental concerns of the project are described in section **Error! eference source not found.**.

3.6. AGSE/Payload Integration

3.6.1. Integration of AGSE/Payload into Launch Vehicle

In terms of static integration, the launch vehicle will integrate with the AGSE through two launch rail buttons and a rear fin section support. The large rail buttons, purchased from Apogee Rocketry, match the profile of the 80/20 t-slot aluminum launch rail. The rear fin section support will serve two functions. First, it will prevent the vehicle from sliding down the launch rail during the raising process. Second, the rear support will reduce side to side movement of the vehicle on the launch rail during sample insertion and closing of the payload door.

Moving on to dynamic integration, the AGSE begins by knowing the sample location. The robotic arm will move to this position and grasp the sample at its center. The arm movement calculations are done on the BeagleBone Black in real time. With the sample in the arm's gripper, the sample will be placed in a foam inside the opened door of the vehicle. The arm will then close the door which locks into place using two neodymium magnets. This progression can be seen in Figure 39 *AGSE Task Progression***Error! Reference source not found.** below.



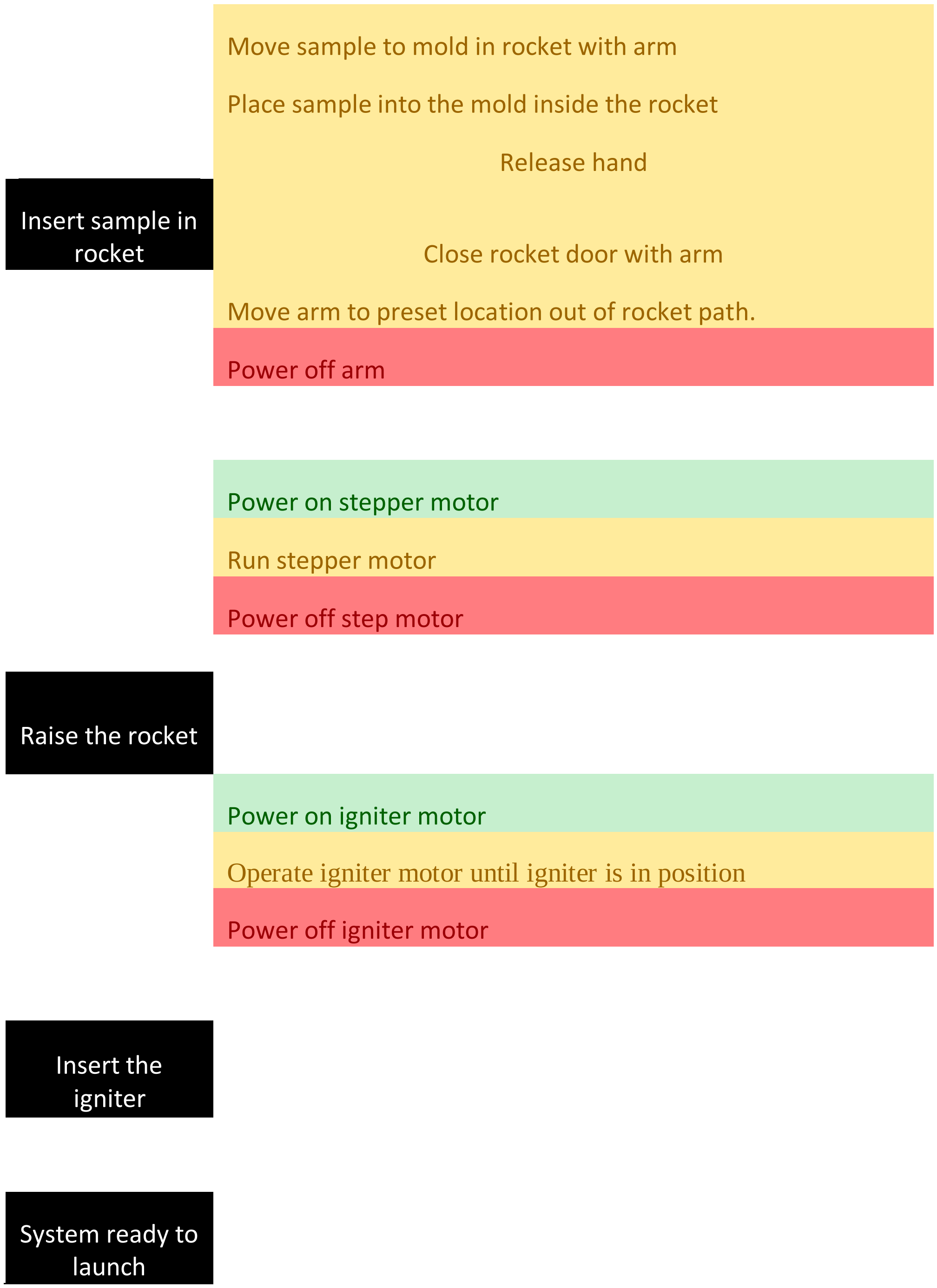


Figure 39 AGSE Task Progression

Once the sample is secured, the vehicle will be raised using the gearing system on the AGSE. The stepper motor used to raise the vehicle will stop when the vehicle has reached 5° from vertical. Ratcheting stops on the base of the AGSE will prevent the launch rail from falling down which could potentially damage the vehicle or the AGSE and cause harm to any ground personnel. The AGSE will then insert the igniter into the motor autonomously using a 1/8 inch wooden dowel and linear actuator system.

3.6.2. Compatibility of Elements

Dimensionally correct CAD models of the RobotShops robotic arm and LynxMotion gripper were used to ensure that the real robotic arm will interface properly with the payload compartment and launch vehicle. In Figure 40 below, the gripper is shown placing the sample into the payload compartment. In this configuration, the robotic arm has sufficient space to clear the open payload compartment and door. The Polyurethane Pick ‘N Pluck foam padded payload section is molded to the cross sectional area of the sample and the gripper, with sufficient room so that the gripper can release the payload and retract from the payload bay.

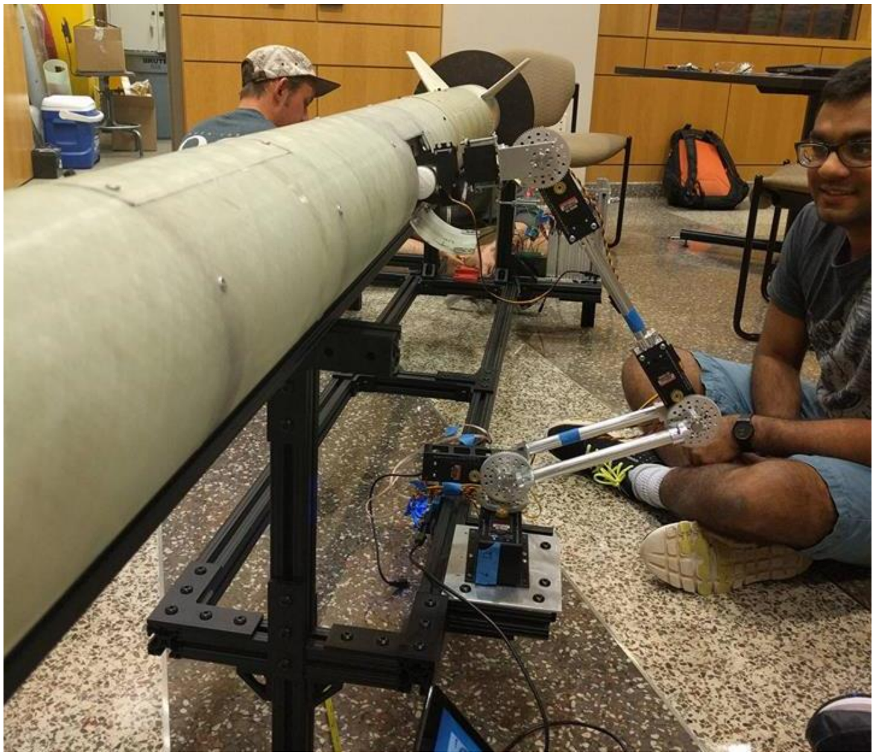


Figure 40 Picture of Robot Arm Placing Sample in Payload Bay

Testing has been done to prove that the robotic arm can move such that the door can close. The payload bay door seals with magnets, so the arm needs only to lift the door to an almost closed position and the magnets will engage and seal the door.

3.6.3. Payload Housing Integrity

A thorough description of the payload compartment construction process can be found above in section 3.1.1. Due to the fact that this section of the vehicle underwent thorough design review and had a small team involved in its accurate and meticulous construction, we can ensure that it is of sound integrity. To ensure that the compartment door remained attached during the entire flight and recovery process, the hinges were secured using screws. Strong Neodymium magnets are used to hold the compartment door shut during the entire flight and both static and flight tests have confirmed that the magnets are strong enough to hold the door shut. These tests have also confirmed that these magnets do not cause any interference with the onboard electronics. The profile of the sample was removed from polyurethane Pick 'N Pluck foam and the foam was attached to the inside of the payload bay using epoxy. The foam also has room for the gripper to fit in when placing the payload and room for it to open and retract from the payload bay doors. Foam is also located on the door such that it will sandwich the sample when the door is closed. The full-scale flight test has proven the integrity of the payload housing and the team is confident in the integrity of the design.

4. AGSE Criteria

4.1. Experiment Concept

4.1.1. Creativity and Originality

Although all of the individual subsystems have been done before in other projects, they are all put together in a way that makes the design unique. For example, the rocket will be raised for launch using a large gear system and the igniter will be inserted with a threaded rod system. There is also the use of ratchets to hold the rocket and rail in case of motor failure. These systems provide an effective mechanical means of preparing the vehicle for launch without increasing the number of potential modes of failure inherent to a complex electrical system of motors and actuators.

4.1.2. Uniqueness or Significance

This AGSE design differs from others the team has seen in several aspects. First is the shape of the AGSE frame. In order to decrease the volume and weight while maintaining ease of assembly, the shape of the AGSE is that of a T. The AGSE is also utilizing a tripod leg design which will greatly reduce the possibility of tipping as three points always form a plane. The feet of the AGSE also have terrain-gripping spikes protruding from the bottoms to further improve stability and decrease the chance of tipping in high winds or shifting as the thrust of the rocket taking off acts on it.

4.2. Science Value

4.2.1. AGSE Objectives

The goal of the AGSE is to retrieve a sample and insert it into the rocket. On Mars, or any other distant body, a similar process will need to be done so that the soil sample can be processed on Earth. Therefore, the processes investigated in the AGSE portion of the project have a direct correlation to actual systems that can be used. Having a robotic arm obtain and secure the sample in the rocket is a feasible system. The AGSE must also erect the rocket into launch position 85 degrees from vertical and insert an igniter into the motor.

4.2.2. Mission Success Criteria

The AGSE will be successful if it can identify, capture, and retain the sample. It must also accomplish all of this autonomously within 10 minutes. Current predictions for the robotic arm to grapple the sample, place it in the payload compartment, close the door, and move away from the rocket are to accomplish those tasks within 45 seconds. After these tasks have been completed, the vehicle will then be erected for launch. Tests performed on the launch rail raising gear indicate that the rail can be raised in as little as 15.49 seconds. The insertion system with a 5 thread per inch 21 inch long rod will be able to insert the igniter in as little as 24.66 seconds. Success for the AGSE will only be obtained if these tasks are completed. Overall, the system will be capable of performing its tasks within 90 seconds. Success with the AGSE will prove the viability of the system as a whole to be implemented in other tasks, such as missions to Mars. The AGSE should be able to perform these tasks as many times as needed, provided it is supplied adequate power.

4.2.3. Experimental Logic

As described above in Section **Error! Reference source not found.**, the experiments were carefully onducted so that accurate results could be obtained. Careful experimentation preserves the scientific value of the experiments and keeps the results indicative of the project. Each experiment followed the general guidelines of any scientific study; a problem was present that needed to be investigated or solved. Next, an experiment was formed that tested possible solutions to the problem or provide more insight into the issue. The experiments were designed to account for any issues that might arise and to test the capabilities of the design. The experiments were then carefully conducted so as to not corrupt the results and to preserve their legitimacy. The results were then analyzed to make sure that the initial requirements were met and that the data received was accurate. This process of experimentation is valid for any scientific study, and thus the experimental process procedures have scientific value.

4.2.4. Explain Meaningfulness

The tests conducted were done to verify the potential of each component of STORM to complete its portion of the mission criteria. Tests were also done to ensure that STORM could operate safely and reliably.

4.2.5. Relevance of Expected Data

The data collected during the experiments will show if the current plan will work. The data is critical to the success of the project, and is thus relevant to the tasks at hand.

4.2.6. Detailed Experiment Process Procedures

Robot Arm Experiment

To operate, the robotic arm must be able to lift the sample, raise the sample to the payload bay, deposit the sample in the bay and finally close the door. The arm must be able to complete these tasks consistently and in a timely manner. Two experiments were conducted with the robotic arm, one to determine the best way to arrange the gears and operate the arm, and one to check the power, accuracy and precision of the arm.

The first experiment that was done was to simply determine the most effective way to arrange the servo motors, gears and servo controller to provide the most power, speed and control. The servo arm had come with three HiTec 785HB stock servos which had a 5:1 gearing ratio and had 212 degrees of rotation. Three new HiTec HS-7950TH servos were bought as a potential replacement for the stock servos after reading some negative reviews about the arm. The HS-7950TH servos had a 2:1 gearing ratio and had 90 degrees of rotation. The club already had a Lynxmotion SSC-32 servo controller, and a Lynxmotion SSC-32U servo controller was bought to compare.

For the test, the robotic arm was set up first using the SSC-32 servo controller and a 785HB stock servo placed at the shoulder joint. The arm was tested at four voltages by raising the arm and sample fully extended and the results were recorded. The first test was done to give a baseline performance. The second and third tests were done with the SSC-32U servo controller due to its increased processing power and its ability to move multiple servos at one time. The following table shows the results of the test.

Table 14 Servo and Servo Controller Test Results

Servo Voltage	SSC-32 Servo controller 785HB Servo	SSC-32U Servo controller 785HB Servo	SSC-32U Servo controller HS-7950TH Servo
10.4 Volts	Slowly raises arm	Raises arm	Doesn't raise arm
12 Volts	Raises arm	Quickly raises arm	Raises arm to 30 degrees
13 Volts	Raises arm, motors increase in temperature swiftly	Quickly raises arm	Raises arm to 30 degrees

It was evident from the testing that the SSC-32U servo controller and the HiTec 785HB Servos together made the most effective arm based on their speed, holding torque, power and computing speed. Once the servo motor and servo controller had been chosen, the arm was tested with all of the servos in use to determine how much voltage would be needed to operate the arm. The following table shows the experimentally determined voltages needed to operate each quantity of servos.

Table 15 Number of Servos vs. Required Voltage

Number of Servos	Required Voltage (V)
1	6.4
2	7.0
3	8.6
4	10.4
6	11.4

The second experiment that was conducted was done to check the power, accuracy and precision of the robotic arm. The experiment was done using the 785HB servos on the entire arm and with the SSC-32U servo controller. The sample was placed at two measured distances from the servo base and using pulse widths calculated using a MATLAB code the arm was moved to position the gripper at those two locations three times each. The arm was able to enclose the sample in the gripper each time, which validated the MATLAB code, servo controller and servo motors. By pressing down on a gram scale with the arm it was determined that the arm could produce 3.5 pounds of force, which is sufficient to close the payload bay door. The holding power of the gripper was tested by closing the gripper around the sample and quickly moving the arm in a jerking motion. The sample was retained in the gripper and moved less than ¼ of an inch.

For operating the arm as part of the autonomous operation of the AGSE, the robotic arm will be operated by the BeagleBone Black. A code has been written to operate the arm and was tested successfully, as seen in Figure 41.

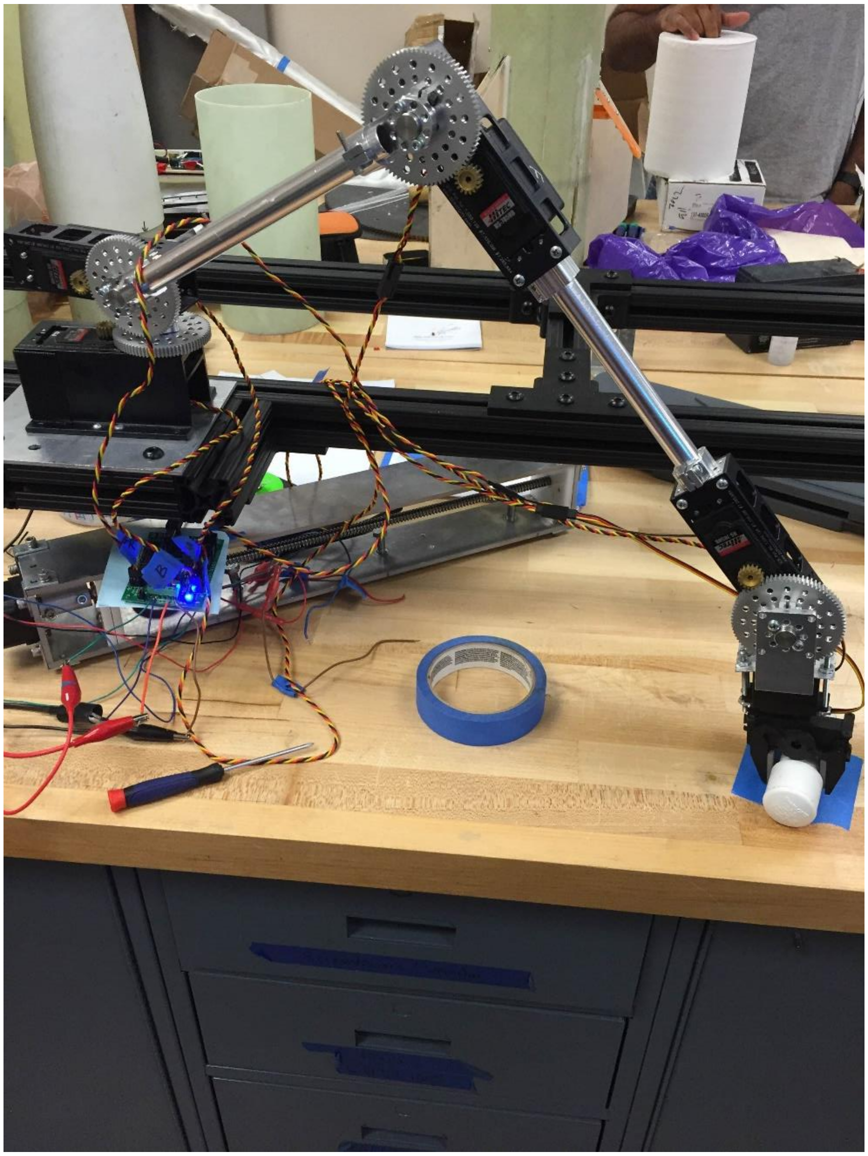


Figure 41 Photo of Robotic Arm Grappling Sample at Programmed Location

Launch Rail Raising Experiment

The goal of the launch rail raising experiment was to determine if the launch rail stepper motor would be able to meet the required torque and speed values. Using a vehicle weight of 35 pounds, a 120 inch launch rail, and launch rail sector gear and drive gear radii of 8 inches and 1 inch respectively, the required stepper motor holding torque was 19.5 foot-pounds. In addition, a launch rail rise time of 45 seconds or less was desired to allow sufficient time for other AGSE processes. Lacking a completed AGSE for the experiment, the torque load was simulated with three weights totaling 19.5 pounds hanging vertically from a rope attached to the perimeter of a 24 inch diameter plywood pulley. The resulting torque of 19.5 foot-pounds is well below the stepper motor's 30 volt maximum holding torque. The pulley attached to the 23HS22-2804-PG47 planetary gear stepper motor and weights can be seen below in Figure 42.

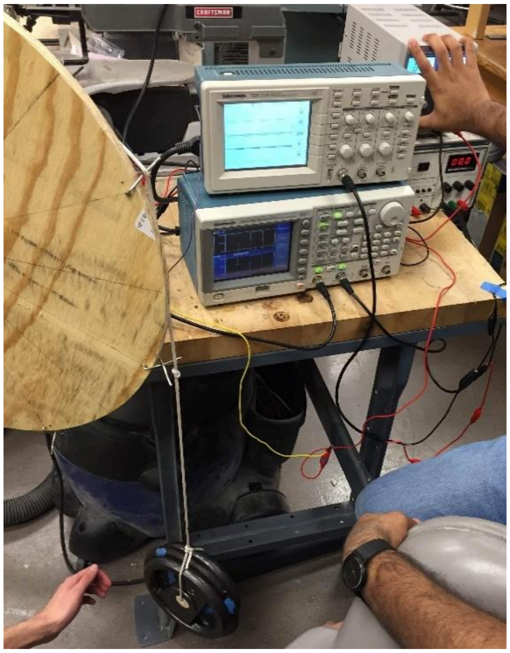


Figure 42 Launch Rail Stepper Motor and Pulley Apparatus

The system used to power and control the stepper motor can be seen below in Figure 43. Attached to a Leadshine M542 stepper motor driver is a Mastech HY5003D DC power supply (in the upper right corner) set at 37 Volts and 3.0 amps to approximate the 37 Volts 5000 milliamp-hour Thunderpower battery. The power supply powered both the driver and stepper motor. Beside the power supply is a Textronix AFG 3022B function generator. This acted as the stepper motor controller, generating a 5 volt amplitude square wave. In the future, this square wave will be generated using the Beaglebone Black. For each square wave cycle, the stepper motor was set to rotate by one step. The rotation rate of the stepper motor was adjusted by varying the square wave frequency. Above the function generator is the Tektronix TDS210 oscilloscope. In the bottom left of the picture is a power supply supplying 5 volts to the stepper motor driver used to control the stepper motor's rotation direction. Completing the battery circuit yielded counterclockwise stepper rotation and disconnecting it yielded clockwise rotation when viewed from the front of the pulley.

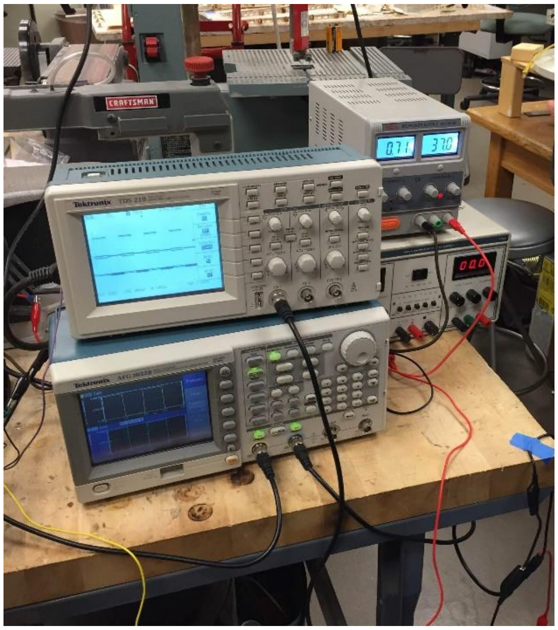


Figure 43 Tektronix Function Generator and Oscilloscope

To conduct the test, the time required for the pulley to rotate 90 degrees under the 19.5 foot-pound load was recorded for different square wave frequencies. A 90 degree rotational angle was chosen to keep the hanging weights from touching the ground during the test. The 90 degree rotation time could then be easily converted to the total launch rail rise time knowing the required rotations of the stepper motor output shaft (1.889 rotations for an 85 degree launch rail angle). The results are shown in Table 16 below. This table illustrates that launch rail rise times as low as 15.49 seconds were achieved, well below the desired value of 45 seconds. The surprising ease and speed at which the stepper motor rotated under the 19.5 foot-pound load at all tested frequencies clearly demonstrated its ability to accomplish the required task.

The other requirements and the means by which they were verified are outlined in **Error! Reference ource not found.**.

Table 16 Square Wave Frequencies and Resulting Launch Rail Rise Times

Function Generator Square Wave Frequency (Hz)	90 Degree Rotation Time (s)	Calculated Launch Rail Rise Time (s)
400	13.24	100.04
500	9.54	72.08
600	7.74	58.48
700	6.67	50.39
800	5.58	42.16
900	4.87	36.80
1000	4.31	32.56
1250	3.13	23.65
1500	2.82	21.31
1750	2.41	18.21
1900	2.05	15.49
2000	N/A	N/A

Igniter Insertion Experiment

The goal of the igniter insertion experiment was similar to that for launch rail stepper motor. Verification that the igniter insertion stepper motor could translate the threaded igniter plate vertically in 45 seconds or less was desired. Before insertion, the igniter will sit just behind the vehicle's base. Therefore, the translation distance required for the linear stepper actuator is the internal length of the rocket motor, approximately 21 inches for the AeroTech L1150R. So this experiment was designed to time a 6 inch vertical translation along the threaded rod at different stepper motor frequencies and then the times were scaled up for the needed 21 inches. The experiment setup can be seen below in Figure 44. The setup consisted of the 17HS15- 0404S stepper motor attached to an 8 turn per inch ACME threaded rod via a coupler, the igniter plate, and two parallel rods to prevent igniter plate rotation. Because the wooden dowel and igniter wire are quite light, their weights were neglected for this experiment. The igniter plate was made out of two quarter inch white Delrin plates bolted together with an ACME nut mounted in the lower plate. Delrin was chosen for its low friction coefficient. The power and control system was the same as for the launch rail raising experiment except that the smaller StepperOnline ST-6128 driver was used instead of the Leadshine M542.

Figure 44 Igniter Insertion Stepper Motor Experiment Setup

In Table 17 through 20 below can be seen the testing for different voltages from the power supply applied to the igniter insertion stepper motor. The tests were done at multiple increasing frequencies at 12, 15, 18, and 21 volts. In all of the tables is a point where the frequency was too great for the motor to move the Delrin block. The motor would just grind and not move the block at all. As the voltage increased in each test, the motor was able to increase its pulse frequency which peaked at 1800 Hz at 21 volts. Because there was still a small amount of grinding at 1800 Hz, the team has decided to operate the motor at 1700 Hz at 21 volts to achieve the best insertion time. At 39.45 seconds, this is still under our desired igniter insertion time of 45 seconds and will allow the team to stay in the allotted time.

Table 17 12V Test of Igniter Insertion Stepper Motor

Function Generator Square Wave Frequency (Hz)	6 inch Rise Time (s)	21 inch Rise Time (s)
300	63.70	222.95
450	42.13	147.46
600	31.95	111.83
750	24.97	87.395
900	21.37	74.80
1050	17.95	62.83

1200	15.95	55.83
1350	14.12	49.42
1400	13.79	48.27
1500	N/A	N/A

Table 18 15V Test of Igniter Insertion Stepper Motor

Function Generator Square Wave Frequency (Hz)	6 inch Rise Time (s)	21 inch Rise Time (s)
500	38.07	133.25
750	25.53	89.36
1000	19.08	66.78
1250	15.55	54.43
1500	12.69	44.42
1600	N/A	N/A

Table 19 18V Test of Igniter Insertion Stepper Motor

Function Generator Square Wave Frequency (Hz)	6 inch Rise Time (s)	21 inch Rise Time (s)
1000	19.06	66.71
1250	15.45	54.08
1500	12.84	44.94
1600	12.13	42.46
1700	11.61	40.635
1800	N/A	N/A

Table 20 21V Test of Igniter Insertion Stepper Motor

Function Generator Square Wave Frequency (Hz)	6 inch Rise Time (s)	21 inch Rise Time (s)
1500	12.82	44.87
1600	11.86	41.51
1700	11.27	39.45
1800	10.87	38.05
1900	N/A	N/A

AGSE Ratchet Holding Torque Test

This test was used to ensure that the ratchets holding the launch rail can hold the necessary amount of torque. These ratchets are used to ensure that if power is lost that the launch rail holding the rocket will not rapidly return to its horizontal position. The maximum torque that will be experienced at the pivot point will be 120 foot-pounds. The test that was carried out was initially supposed to be preliminary in nature, and was to be followed out by a more complete destructive testing of the ratchets. The test involved placing the half inch square drive of one of the ratchets (an extra that was identical to the others purchased and designated to be used for testing only). A five foot long hollow metal rod was then used to extend the length of the moment arm to about five feet. Weight was increased until about 45 pounds had been applied at which point the solid metal vice sheared as shown in Figure 45. This test demonstrated that the ratchets could hold at least 225 foot pounds of torque. This is significantly more than the expected 120 foot pounds of torque that the two ratchets are expected to have to hold together, assuring the team in a factor of safety of the holding system of at least 3.75.

Figure 45 Sheared Vise Following Ratchet Test

4.3. AGSE Design

4.3.1. Design and Construction of AGSE

The AGSE was designed in a T shape to decrease the volume and weight while maintaining overall structural strength and ease of assembly. It was also designed with three legs, similar to that of a tripod, as to reduce the possibility of tipping. Removable feet with cleating have also been designed in order to provide stability in high wind situations and to provide all around terrain gripping capabilities.

The AGSE has been constructed out of 1.5 inch squared T-slotted 80/20 Aluminum Railing. With the launch rail itself being 120 inches long, a total of almost 360 inches of aluminum railing has been used to construct the AGSE. To hold the pieces of aluminum together, many assorted shape brackets were bought along with special screws and nuts that fit in the T-slots of the railing. Ratchets were affixed to the aluminum railing on either side of the pivoting rod in the event of motor failure while lifting the rocket and launch rail. The sector gear of the erection system was cut from 3/8 inch thick steel entirely for strength and resistance to warping. The igniter insertion system was constructed out of aluminum for its strength and relative light weight. All of the parts were put together to construct a strong, yet light weight, ground support system.

4.3.2. Computer and Electronics

The AGSE will consist of several electronic devices to accomplish the mission tasks. Figure 46 shows the general physical layout of how the electronics will communicate with each other.

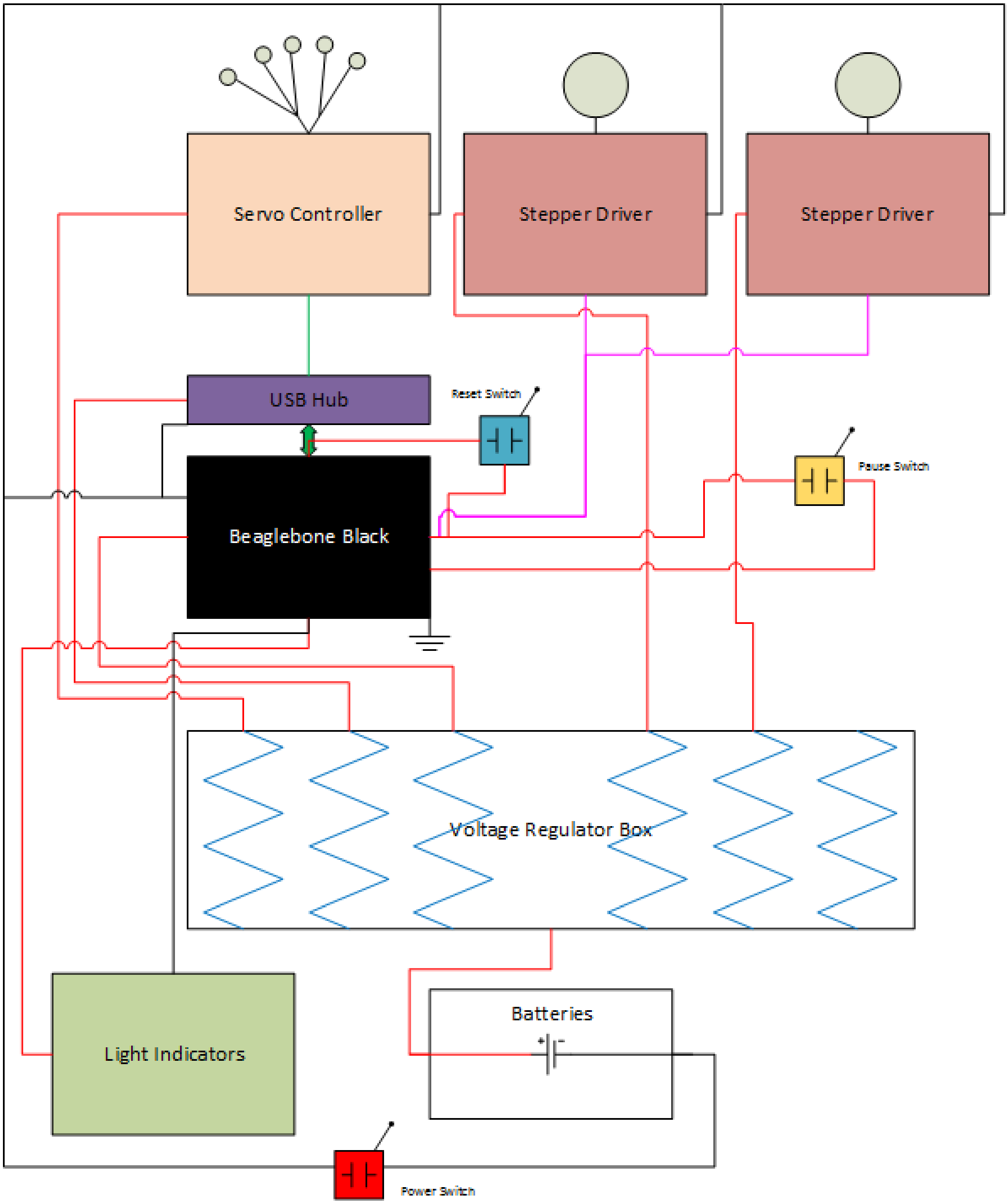


Figure 46 AGSE Electrial Schematic

The AGSE will be controlled by one central computer which will use a series of controllers to manage all the subsystems. The team will be using a Beaglebone Black (BBB) as the central computer. It has 512 MB of RAM, 1.2 GHz Processor, and 36 GB of flash memory which should be sufficient for any computations needed to achieve the desired tasks. The team will be using an SSC- 32U servo controller to control all the servos on the robotic arm. The arm will be used to pick up the sample and load it into the rocket. Stepper motor controllers will be used to control the motors used for erecting the rocket and inserting the igniter. The schematic below shows the relationship between the BBB and all other subsystems that interact with it. Legend: • Black Wire: Ground • Red Wire: Power • Pink Wire: Digital Association • Green Wire: USB Association

4.3.3. Precision of Instrumentation

The team strives to use the most accurate tools available for measurements. For example, the gram scale used by the team is accurate to 0.01 grams, and the digital calipers are accurate to 0.001 inches. As described above in Section 4.2.6, the arm was calibrated and verified using several experiments. The arm is accurate to 0.125 inches based on the experiments conducted by the team. The repeatability of the stepper motors were also tested in the experiments described above. Conducting these experiments several times proves the repeatability of measurement with the arm, and stepper motors. As a result, the data obtained in the experiments was verified.

4.3.4. Approach to Workmanship

Quality of workmanship is the foundation for success in any mission and improper construction can lead to mission failure. For this reason, all possible steps were taken to ensure that quality was held above all during AGSE construction. For one, the total amount of railing was determined before it was ordered to ensure that there would be no missing parts. Also, all distances were measured twice during construction to guarantee that the final product would be just as the design specified. Railing was ordered from 80/20 Inc. which ensures that STORM will be easy to assemble and disassemble as needed and will remain rigid during all procedures. Finally, all senior members with experience in construction and design were the primary contributors with guidance given to younger members whenever necessary.

4.3.5. Test and verification plan

Testing of the subsystems of the AGSE can be seen in detail in Section 4.2.6.

4.4. Verification

The verification matrices for the AGSE can be found in Appendix E AGSE Verification Matrix.

4.5. Safety and Environment

4.5.1. Safety and Mission Assurance Analysis

The FMECA diagrams can be found in Appendix C Failure Mode Effects and Criticality Analysis.

Of all of the failure modes listed, the gearing slipping out of plane has one of the worst consequences. Not only will the vehicle not be in the proper position for launch, but the vehicle may fall and damage other components. If the processes are not stopped early enough, then the gears may damage themselves or other components, preventing the AGSE from operating again. However, this failure is unlikely because the team is bolting the gear to the launch rail and has the ratcheting stops that will prevent the vehicle from falling back down onto the AGSE.

Structural failure of the gearing system would render the AGSE functionless. As a result, it would not be able to accomplish its mission. Because the team is manufacturing the gears out of steel, this failure is unlikely.

A third significant error is the robotic arm failing to retrieve the sample and place it in the payload compartment. This would defeat the central purpose of the AGSE, which is to retrieve the sample. This failure possibility is mitigated by the rigorous testing of the robotic arm code and the correct calibration of the servos.

4.5.2. Personnel Hazards

As the competition gets closer, more construction will need to be done. Consequently, the team will need to use more power tools and machines, such as the drill press and band saw. These machines pose significant risks to the team if they are misused. Although a majority of the construction on the AGSE has been completed, there will still be work done after submission of the FRR. Therefore, these safety hazards will exist after the FRR. The table in 3.5.1. outlines the hazards the team is exposed to and the mitigations they will use in constructing the AGSE.

4.5.3. Environmental Concerns

In addition to the environmental concerns expressed in section 5.2.3., the proximity of personnel and other objects to the AGSE during operation is an important concern as well. If personnel are too close to the AGSE, then they may be injured during processes. Furthermore, the AGSE may be prevented from fully performing its tasks. In theory, there is the potential that the AGSE will tip over due to high winds. However, hand calculations have shown that the AGSE will only tip over if the winds are in excess of 20 miles per hour. Therefore, the AGSE tipping over is not a concern as the competition would be canceled in such weather.

5. Launch Operations Procedures

5.1. Checklist

5.1.1. Recovery Preparation

1) Retrieve nosecone
2) Retrieve forward airframe
3) Remove access hatch from forward airframe with four screws
4) Carefully pull avionics bay from forward airframe making sure not to pull out wiring
5) Check that altimeter switches are in the off position
6) Insert two fresh batteries into each of the battery trays
7) Connect battery snaps on each battery
8) Secure GPS unit onto sled
9) Plug GPS into battery
10) Pair GPS with handheld device
11) Insert avionics sled back into avionics bay making sure no wires are crossed and the sled is oriented with the sled facing the correctly marked position
12) Attach e-match wiring to terminal block 1 and ensure the wires are secured

13) Insert primary main black powder charge (3.3 g) into cap 1 on top of forward airframe avionics bay
14) Insert e-match into cap 1
15) Insert wadding into cap 1 and cover cap 1 with blue painter's tape
16) Repeat steps 12-15 with redundant main black powder charge (3.6 g) into cap 2 on top of forward airframe avionics bay in terminal block 2
17) Assemble ARRD
    a) Unscrew base then push piston up to remove toggle
    b) With screwdriver push piston out; remove the ball bearings careful not to dislodge spring.
    c) Remove cartridge from base.
    d) Place ball bearings in red anodized body
    e) Place shackle and toggle assembly into red body; push piston into body up to the end of the threads
    f) Place black powder into cartridge; fill cavity. Place 2 e-matches through hole
    g) Place blue painter's tape over the end of the cartridge to retain black powder
    h) Holding base and body; screw together by turning red body until firmly seated
    i) Grasp body and base assembly and firmly pull toggle to ensure correct fit
    j) Insert e-matches into terminal blocks 3 and 4
    k) Tighten the screw securing the ARRD to the bulkhead
18) Replace Access hatch and secure with four screws
19) Check that the four screws securing the forward and aft bulkheads to the body tube are tight
20) Retrieve aft airframe
21) Remove all four screws from aft airframe access hatch and remove access hatch
22) Carefully pull aft airframe avionics bay from aft airframe making sure not to pull out wiring
23) Check that altimeter switches are in the off position
24) Insert two fresh batteries into each of the battery trays
25) Connect battery snaps on each battery
26) Secure GPS unit onto sled
27) Plug GPS into battery
28) Pair GPS with handheld device
29) Insert avionics sled back into avionics sled back into avionics bay making sure no wires are crossed
30) Attach e-match wiring to terminal block 5 and ensure the wires are secured
31) Insert primary main black powder charge (2.2 g) into cap 3 on bottom of aft airframe aft bulkhead
32) Insert e-match into cap 3
33) Insert wadding into cap 3 and cover cap 3 with blue painter's tape
34) Repeat steps 30-33 with redundant main black powder charge (2.4 g) into cap 6 on bottom of aft airframe aft bulkhead in terminal block 6
35) Attach e-match wiring to terminal block 7 and ensure the wires are secured

36) Insert primary drogue black powder charge (2.1 g) into cap 5 on top of forward bulkhead of aft airframe
37) Insert e-match into cap 5
38) Insert wadding into cap 5 and cover cap 5 with blue painter's tape
39) Repeat steps 35-38 with redundant drogue black powder charge (2.3 g) into cap 5 on top of forward bulkhead of aft airframe
40) Replace access hatch on aft airframe and tighten all four screws
41) Retrieve the 48" main parachute and the shock chord for the nosecone and forward airframe
42) Remove the rubber band from the parachute
43) Attach quick link with no blue tape on shock chord to the bottom of the nosecone
44) Have another person verify that the quick link is secure
45) Insert Nomex sheet protector and parachute into forward airframe
46) Attach quick link with blue tape to the forward bulkhead of the forward airframe
47) Have another person verify that the quick link is secure
48) Insert nosecone and parachute assembly into the forward airframe making sure that the shear pin holes are aligned
49) Install four (4) shear pins into the forward airframe to connect nosecone to the forward airframe
50) Retrieve the 18" drogue parachute and shock chord for the forward and aft airframes
51) Remove the rubber band from the parachute
52) Attach quick link with blue tape to forward bulkhead of aft airframe
53) Have another person verify that the quick link is secure
54) Insert Nomex sheet protector and parachute into aft airframe
55) Attach quick link with no blue tape to lower bulkhead of forward airframe
56) Have another person verify that the quick link is secure

62. Insert forward airframe into aft airframe making sure the shear pin holes are aligned
63. Install four (4) shear pins into the aft airframe to connect forward and aft airframes
64. Retrieve 84" main parachute and the shock chord for the fin section
65. Remove rubber band from the parachute
66. Attach quick link with no blue tape to bottom bulkhead of aft airframe
67. Have another person verify that the quick link is secure
68. Insert Nomex sheet protector and parachute into aft airframe
69. Attach quick link with blue tape to bulkhead in fin can section
70. Have another person verify that the quick link is secure
71. Insert mid-section assembly into fin section making sure the shear pin holes are aligned
72. Install four (4) shear pins into fin section to connect aft airframe to fin section
73. Flip airbrakes switch off
74. Unscrew all four screws from fin section access hatch and remove access hatch
75. Ensure that actuator is plugged in correctly to the LAC
76. Ensure that SD card is contained properly in the red OpenLog board
77. Ensure that all connections to hardware and battery are attached
78. Plug in 11.1V LiPo battery to the designated terminal block

79. Install LiPo battery in electronics bay
80. Ensure that all connections to hardware and battery are attached
81. Replace access hatch on fin section and tighten all four screws
82. Check CG location and verify static margin after inserting motor

5.1.2. Motor Preparation

1. Apply a light coat of Synco Super Lube or other grease to all threads and all O-rings.
2. Chamfer both inner edges of the delay insulator with fingernail or small blade
3. Assemble the RMS-Plus delay element, delay insulator, aft delay spacer and delay O-ring
4. Insert the forward delay spacer into the delay cavity until it is seated against the forward end of the cavity
5. Apply a light film of grease to the inner circumference of the delay cavity (but not the forward end of the cavity)
6. Insert the delay charge assembly into the delay cavity, O-ring end first, until it is seated against the forward delay spacer. Case Assembly
7. Install the propellant grains into the liner
8. Push the liner assembly into the motor case until it is approximately equally recessed from both ends of the case
9. Place the forward insulator (1” O.D. fiber washer) into one end of the case, seated against the liner assembly
10. Place the greased forward (3/32” thick X 1” O.D.) O-ring into the forward insulator end of the case until it is seated against the forward insulator
11. With the motor case held in a horizontal position, thread the previously assembled forward closure assembly into the forward end of the motor case by hand until it is seated against the case
12. Place the aft insulator (1” O.D. fiber washer) into the aft (nozzle) end of the motor case, seated against the liner assembly
13. Insert the larger end of the nozzle into the aft end of the case and against the aft insulator
14. Place the greased aft (1/16” thick X 1” O.D.) O-ring into the aft end of the motor case, seated in the groove between the nozzle and the case
15. Thread the aft (gold) closure into the aft end of the motor case by hand until it is seated against the case

5.1.3. Setup on Launcher

1. Carry assembled rocket to launch pad
2. Slide rocket launch lugs onto 15-15 launch rail
3. Erect rocket to vertical position and verify its angle into wind and away from spectators
4. Flip switch 1 on forward airframe and verify continuity
5. Flip switch 2 on forward airframe and verify continuity
6. Flip switch 1 on aft airframe and verify continuity
7. Flip switch 2 on aft airframe and verify continuity

5.1.4. Igniter Installation

1. For full-scale test launch, a certified individual will insert igniter
2. During flight in Huntsville, igniter will be inserted using the automatic insertion system

5.1.5. Launch Procedure

1. Have all team members, officials and onlookers move to a safe distance from the launch site. If there isn't an official safe viewing area, move at least 100 yards away.
2. Check that the range and skies are clear
3. Begin 5 second countdown
4. Launch the vehicle

5.1.6. Troubleshooting

1. Check to ensure that correct launch pad is live
2. Check for continuity between control booth and launch pad
3. Check igniter is fully installed
4. Check connections on igniter
   a. Check connections are not in contact with each other
   b. Ensure igniter leads are securely wrapped around alligator clips
5. Check that altimeters are turned on
6. Check for correct beeps from altimeters

5.1.7. Post-Flight Inspection

1. Ensure that all black powder charges have blown
2. Turn off all four (4) altimeters
3. Inspect vehicle for cracks or other signs of physical damage
4. Inspect parachutes for tears
5. Inspect parachute chords for fraying and tangling
6. Inspect shock chords for fraying
7. Ensure all non-consumable pieces are accounted for (hardware, ARRD parts)
8. Ensure rocket is ready to launch again in the same day

5.1.8. AGSE

1. Inspect STORM for any structural damage to ensure operations can proceed safely
2. Inspect STORM's wiring for any damage to electrical systems to ensure operations can proceed safely
3. Make sure that ratchet switches are forward.
4. With launch rail in the horizontal position, carefully slide launch vehicle's rail buttons into top T-slot of launch rail and slide back until launch vehicle is seated against the rear stops
5. Ensure Beagle Bone Black is not plugged in to avoid power surge
6. Ensure USB cable is plugged into Beagle Bone Black
7. Ensure USB cable is plugged into SSC-32U Servo Controller
8. Join groups A and B on 37 volt LiPo
9. Plug 37 volt LiPo into correctly labeled power cables
10. Plug 11 volt LiPo into correctly labeled power cables

11. Verify pause switch is in down position
12. Verify reset switch is in up position
13. Power on system using master power switch
14. Power on Beagle Bone Black by inserting barrel jack into the proper port
15. Move pause switch to up position to begin AGSE routines
    15.1. Pause switch may be flipped down at any point to halt AGSE procedures
    15.2. Pause switch may be flipped up at any point to resume AGSE procedures

5.2. Safety and Quality Assurance

5.2.1. Demonstrate Risks at Acceptable Levels

The team was able to successfully launch and recover the full scale launch vehicle using the procedures described above. Because the rocket was recovered without injury, this launch shows that the current levels of risk are at acceptable levels.

5.2.2. Risk Assessment for Launch Operations

When working with explosives, attention to safety and mitigating risks is essential. It is important that all personnel are well-versed with the potential dangers that come with working with the vehicle and other hazardous materials. All team members have been educated on the proper handling of black powder and E-matches. Oversight from a senior member of the team is required to handle the black powder or E-matches. Prior to each launch the size of the black powder charges is tested in an on the ground test conducted outdoors. This is to check that the charges are just large enough to separate the sections of the rocket without damaging the vehicle and creating debris that could fall on onlookers. The vehicle is also checked for any loose parts that could fall off and any parts that are loose are either removed or further secured.

The team will default to the LSO to make all final calls on the safety of the launch operations. Furthermore, the LSO will be the one to initiate the launch procedures. For the launch, the igniter will be inserted by a certified individual.

5.2.3. Environmental Concerns

The environment can play a significant impact in preventing a safe and successful vehicle launch. Precipitation is one of the key environmental risks when launching a rocket as it has the potential to short any electronics contained within the rocket or on the AGSE. Moreover, cloud cover has the potential to obscure the rocket at higher altitudes, resulting in a safety concern. When the vehicle or the payload stages float down in the recovery stage, the parachutes can potentially become entangled in the power lines or trees, preventing a safe and total recovery. To account for these potential hazards, the team will check to make sure that there are no power lines or other hazards nearby. This check will be done before the vehicle is launched. However, the vehicle has the potential to impact the environment as well. The most unavoidable impact would be the pollution caused by the combustion products of the motor. This impact cannot be mitigated without entirely scrubbing the launch. Another environmental impact would occur if there was any debris caused by a failed or damaged rocket. If not all collected/recovered after the completion of the launch, any material would become litter. Therefore, the team will check to make sure that there is no debris nearby, and that it collects all pieces of its own vehicle for the safety of others. Fire is a possible environmental impact that could occur if either the motor casing (being hot after full burn of the motor) comes in contact with something flammable or if the rocket impacts something while still under power. Although this risk cannot be mitigated with an item in the checklists, this risk is being mitigated by choosing a long enough descent and by ensuring that the rocket leaves the launch pad at a velocity high enough to prevent it from going off course. The final possible environmental impact would be any damage caused by collision with the rocket. This risk is being mitigated by using redundant charges for each parachute as well as redundant altimeters to lower the risk of the parachutes not deploying. The team's checklists include making sure that these redundancies are implemented.

5.2.4. Identify Individual Responsible for Maintaining Safety, Quality, and Procedures Checklists

Senior Tacho Lycos member Stuart Philpott is responsible for maintaining the safety, quality, and procedures checklists for the team. He will be assisted by two other team members that will be selected on launch day to check that the checklists are being followed. Having three team members monitor the use of the checklists will ensure that all safety precautions and procedures are followed.

6. Project Plan

6.2. Budget Plan

Table 21 Budget Plan

Category	Supplier	Item	Amount	Total Price
AGSE	Digi-Key	BeagleBone Black	1	$45
	Stepperonline	Leadshine M542 Stepper Motor Driver	1	$40
	Stepperonline	Nema 17 Bipolar Stepper	1	$10
	Stepperonline	Nema 23 Geared Stepper Motor	1	$60
	RadioShack	5mm-5mm Couplers	1	$5
	RAdioShack	USB Extension Cable	1	$2
	RadioShack	USB Hub	1	$7
	Thunder Power	Thunder Power 37 V Battery	1	$268
	RadioShack	12 V Step Down to 5V Power Module	1	$10
	RadioShack	2.1 mm Coax Power Plug	1	$5
	RadioShack	48V Step Down to 24V Power Module	1	$24
	RadioShack	12V Step Down to 6V Power Module	1	$10
	Thunder Power	Thunder Power 12V Battery	1	$100
	Digi-Key	Xtend Radio Units	2	$600
	Metals Depot	3/8" A573 Steel Plate	2 sq ft	$48
	Bertelkamp	1515 Aluminum Railing	36.25 ft	$248
	Bertelkamp	1010 Aluminum Railing	8 ft	$18
	Bertelkamp	5/16-18 T-nut	200	$342

	Bertelkamp	1/4-20 T-nut	50	$92
	Bertelkamp	8020 Connectors	58	$288
	Lynxmotion	Lynxmotion Servo Controller	1	$45
	RobotShop	M100RAK V2 Modular Robotic Arm	1	$600
	RobotShop	Gripper for Robotic Arm	1	$40
	RadioShack	22 Gage Servo Connector Wire	100 ft	$32
	Digi-Key	Molex lockable connectors and pins	50	$40
	--	Misc. Hardware	--	$100
	Lowes	1/8" Balsa Wood Dowel	1	$1
	Electronics-Salon	Crystal Oscillator	2	$25
	McMaster-Carr	Threaded Rod	3 ft	$21
	OnlineMetals	Delrin Sheet 12"x12"x1/4"	1	$25
	Home Depot	Acryllic Sheet 12"x24"x1/4"	1	$21
	Amazon	Ratchet Wrench	2	$25
		AGSE Subtotal		**$3,197**
Vehicle	Apogee	1010 Rail Buttons	1	$3
	Apogee	4" Diameter Nosecone	1	$65
	Rocketry Warehouse	4" Fiberglass Tubing	7 ft	$158
	Rocketry Warehouse	4" Fiberglass Coupler	2	$62
	Rocketry Warehouse	38mm Fiberglass Tubing	12 in	$14
	Madcow Rocketry	5.5" Diameter Nosecone	1	$115
	Madcow Rocketry	5.5" Fiberglass Coupler	1	$64
	Madcow Rocketry	5.5" Fiberglass Tubing	8 ft	$330
	Madcow Rocketry	75mm Retainer	1	$44
	West Marine	Epoxy and Hardener	1	$50
	Askew Taylor	Aircraft Birch Plywood (1/8"x1'x2')	10	$63
	Apogee	1515 Rail Buttons	1	$5
	Apogee	Entacore AIM 3.0 Altimeters	2	$230
	Apogee	Stratologger Alitmeters	2	$118
	Home Depot	Paint	--	$30
	BigRedBee	GPS Bee	3	$95
	RadioShack	Wires	--	$30
	Fruity Chutes	Kevlar Shock Cord	3	$78
	Fruity Chutes	18" Elliptic Parachute	1	$58
	Fruity Chutes	48" Elliptic Parachute	1	$119
	Fruity Chutes	84" Irish Ultra Parachute	1	$345
	Bass Pro Shop	Black Powder	1 lb	$20

	RATTworks	RATTworks ARRD	1	$95
	mentor	Igniters	5	$10
	mentor	E-matches	20	$25
	Rocketry Warehouse	3" Fiberglass Tubing	24 in	$40
	mentor	75mm Motor Casing	1	$100
	mentor	38mm Motor Casing	1	$65
	Amazon	Pick 'n Pluck foam	1	$13
	BuyRocketMotors	L1150R Motor	2	$320
	Firgelli	Firgelli P16-50-22-12-P Linear Actuator	1	$45
	Firgelli	Linear Actuator Control Board	1	$20
		Vehicle Subtotal		**$2,829**
Other		Travel Expenses (hotel, rental car, gas)	16 people	$3,000
		Incidentals (replacement tools, hardware, safety equipment	--	$1,000
		Shipping Costs		$750
		Other Subtotal		**$4,750**
Total				**$10,776**
Total of Final Product (Full Scale, AGSE)				**$5,368**

6.3. Funding Plan

The original budget for the 2015-2016 year was largely based off of the NASA SL requirements from the previous year and previous awards from various sources. The current budget is a more refined version of the budget in the CDR, with complete information on what funds the team has received from our student organizations as well as more specific line items. The total budget is currently $10,776 which includes the full-scale competition rocket, AGSE, sub scale rocket, and estimated travel expenses. The total amount that can be spent on the full-scale competition rocket and AGSE is $7,500.

Funding requests from the Engineering Council at NC State and the Student Government at NC State have been processed. The Engineering Council has granted the club $4,500 of the $4,500 that was requested. The Student Government denied the request for funding from the club. Funding from the Engineering Technology Fee Fund from the Mechanical and Aerospace Engineering Department and from Space Grant have also now been processed. The Engineering Technology Fee Fund provided the entire $2,000 that was expected and the NC Space Grant provided the entire $7,000 that was expected. This brings the total amount of funding the club has received to $13,500.

6.4. Timeline

Table 22 Timeline

Event/Task	Start Date	Finish Date
Completed FRR Submission	3/14/2016	3/14/2016
FRR Team Teleconference (Tentative)	3/17/2016	3/30/2016
Full Scale Vehicle Ejection Testing	3/24/2016	3/24/2016
Team Travel to Huntsville, Alabama	4/13/2016	4/13/2016
Launch Readiness Review (LRR)	4/13/2016	4/14/2016
NASA Safety Briefing	4/14/2016	4/14/2016
Rocket Fair and Tours of MSFC	4/15/2016	4/15/2016
Launch Day	4/16/2016	4/16/2016
Backup Launch Day	4/17/2016	4/17/2016
Post-Launch Assessment Review	4/29/2016	4/29/2016
Winning Team Announced by NASA	5/11/2016	5/11/2016

6.5. Educational Engagement Plan and Status

Event: STEM Career Fair for Students with Disabilities

Location: North Carolina Museum of Natural Sciences, Raleigh, NC 27601

When: Friday, October 9th from 11am to 2pm

Andrew M. and John I. represented the High-Powered Rocketry Club at a special career fair designed to aid students with physical and learning disabilities find support from local organizations and individuals who are successful in their field. Andrew and John spoke with many of these students about the opportunities available to them in various fields of engineering as well as courses offered at NC State University. The members brought several static displays of previous competition rockets to better explain how the rockets worked and to talk about the NASA Student Launch competition.

Presentation to NC-MSEN PCP Middle School Students

Location: Centennial Campus Magnet Middle School, Raleigh, NC 27607

When: Wednesday, December 16th from 2:30pm to 5pm

Several members from the High-Powered Rocketry Club travelled to the Centennial Campus Magnet Middle School (CCMMS) to visit an afterschool program as part of the North Carolina Mathematics and Science Education Network Pre-College Program (NC-MSEN PCP). This program is designed to prepare “underserved students at the middle and high school levels for careers in STEM.” The team gave a presentation with information regarding engineering at NC State University, NASA SL & Centennial Challenges, basic rocket physics, rocket design considerations, and comparing the physics of water bottle rockets to high-powered rockets. Following the presentation, the 20 students were able to ask the team an extensive amount of questions regarding rocketry before building their own water bottle rockets. Members from the club were able to help students design their water bottle rockets for a future launch. The afterschool teacher was very impressed with the team's presentation and we have been discussing another future visit during the Spring semester.

Event: Lacy Elementary School STEM Night

Location: Lacy Elementary School, Raleigh, NC 27607

When: Thursday, January 14th, 5pm to 7:30pm

Members of the High-Powered Rocketry Club attended the Lacy Elementary School STEM night to show the students the basics of how rockets work. The team showed videos of their own rocket launches and talked to around 100 parents and students about the competition and how families can build their own rocket. The team also launched some water bottle rockets to give the students a safe, hand-on experience with rockets.

Event: Astronomy Days

Location: North Carolina Museum of Natural Sciences, Raleigh NC 27601

When: January 30th and 31st, 2016

The High-Powered Rocketry Club partnered with Tripoli of Eastern NC to host a booth at the NC Museum of Natural Sciences' Astronomy Days. The event was held to promote awareness of STEM, space exploration, and astronomy. The team showed visitors the inner workings of both low- and high-powered rockets and answered any questions that the over 1000 visitors had about rockets, NC State, and NASA. The team also helped Tripoli promote their rocket launching event at Perkins Field in Butner, NC. Information of Tripoli of Eastern NC can be found at www.ncrockets.org.

Event: Thales Academy Rocket Unit Kick-Off

Locations: Thales Academy 1201 Granite Falls Blvd, Rolesville, NC 2757 &

Thales Academy 1177 Ambergate Station, Apex, NC 27502

When: TBD

Some members of the High-Powered Rocketry Club will travel to both Thales Academy high schools in the Rolesville and Apex areas to discuss high-powered rocketry and aerospace engineering concepts with the students. Some topics that will be discussed include thrust, drag, stability, and recovery systems on both high-powered rockets and water bottle rockets. Team members will then lead the students in the design and construction of water bottle rockets for launch during the same day. Communication with the Thales Academy Director of Development is ongoing to determine a time and date for each visit.

Event: YMCA Kite and Rocket Day

Location: Carter Finley Stadium, 4600 Trinity Rd., Raleigh, NC 27607

When: March 20th, 2016

The High-Powered Rocketry Club intends to continue its tradition of being an integral part of the local YMCA Kite and Rocket Day event which will occur sometime during the Spring semester. Team members will set up an informational booth at Carter-Finley Stadium to assist young rocketeers with assembling and launching their model rockets. Last year's event had over 200 student attendees with even more predicted to attend this year's event. Communication with YMCA representatives is ongoing to determine a time and date for the event.

Event: Sigma Gamma Tau Boy Scout Merit Badge Event

Location: NC State Centennial Campus, Raleigh, NC 27695

When: TBD April

The High-Powered Rocketry Club is planning to partner with NC State's chapter of Sigma Gamma Tau in hosting the annual Boy Scout Merit Badge Event during the Spring semester of 2016. The event will begin with a model rocket launch and recovery for the enjoyment of the Scouts and their families. The Scouts are then shown a presentation by members of Sigma Gamma Tau before receiving their Space Exploration badges. This event will take place on NC State's Centennial Campus and usually involves 30-40 Boy Scouts and their families. The details of this event will be finalized in the coming weeks.

7. Conclusion

With the conclusion of the FRR, the NC State Rocketry Team, Tacho Lycos, feels confident in the successful operation of STORM and in the second launch of the vehicle.

Appendix A Milestone Review Flysheet

Milestone Review Flysheet

Institution	North Carolina State University	Milestone	FRR

Vehicle Properties	
Total Length (in)	102
Diameter (in)	5.5
Gross Lift Off Weigh (lb)	32.1
Airframe Material	Fiberglass
Fin Material	Birch Aircraft Plywood
Drag Coeffficient	0.385

Motor Properties	
Motor Manufacturer	AeroTech
Motor Designation	L1150R
Max/Average Thrust (lb)	302.6 / 258.3
Total Impulse (lbf-s)	790.6
Mass Before/After Burn (lb)	8.10 / 3.91
Liftoff Thrust (lb)	218.3

Stability Analysis	
Center of Pressure (in from nose)	76.3
Center of Gravity (in from nose)	64.3
Static Stability Margin	2.18
Static Stability Margin (off launch rail)	2.25
Thrust-to-Weight Ratio	8.047 : 1
Rail Size and Length (in)	1.5 x 1.5 x 101
Rail Exit Velocity	63

Ascent Analysis	
Maximum Veloxity (ft/s)	745
Maximum Mach Number	0.662
Maximum Acceleration (ft/s^2)	300
Target Apogee (From Simulations)	5569
Stable Velocity (ft/s)	63
Distance to Stable Velocity (ft)	3.71

Recovery System Properties	
Dogue Parachute	
Manufacturer/Model	FruityChutes
Size	18

Recovery System Properties		
Main Parachute		
Manufacturer/Model	FruityChutes	
Size	48	84

Altitude at Deployment (ft)	5280			
Velocity at Deployment (ft/s)	1.9			
Terminal Velocity (ft/s)	92.9			
Recovery Harness Material	Kevlar			
Harness Size/Thickness (in)	0.5			
Recovery Harness Length (ft)	25			
Harness/Airframe Interfaces	ARRD and U-bolt with quick link			
Kinetic Energy of Each Section (Ft-lbs)	Section 1	Section 2	Section 3	Section 4
	3,765			

Altitude at Deployment (ft)	1000	700		
Velocity at Deployment (ft/s)	92.9	75.6		
Terminal Velocity (ft/s)	20.2	14.6		
Recovery Harness Material	Kevlar			
Harness Size/Thickness (in)	0.5			
Recovery Harness Length (ft)	16			
Harness/Airframe Interfaces	U-bolt with quick link			
Kinetic Energy of Each Section (Ft-lbs)	Section 1	Section 2	Section 3	Section 4
	60.2	61.6		

Recovery Electronics	
Altimeter(s)/Timer(s) (Make/Model)	Perfectflite Stratologger SL100, Stratologger CF, Entacore AIM 3.0
Redundancy Plan	Apogee charges will have a 1 s delay. Main redundant charge will be programmed for 600 ft AGL at 125% primary charge size.
Pad Stay Time (Launch Configuration)	1 hour

Recovery Electronics	
Rocket Locators (Make/Model)	Big Red Bee GPS Locator (2)
Transmitting Frequencies	900 MHz on Channel 128
Black Powder Mass Drogue Chute (grams)	2.1
Black Powder Mass Main Chute (grams)	3.3 (top) / 2.2 (bottom)

Milestone Review Flysheet

Institution	North Carolina State University

Milestone	FRR

Autonomous Ground Support Equipment (MAV Teams Only)

Capture Mechanism	Overview A crafted robotic arm based on a previously purchased robotic arm kit with different servos and gears will move the gripper to a predetermined point above the sample and then the gripper will engage to capture the sample.
Container Mechanism	Overview The robotic arm will carefully insert the sample into the pick and pluck foam padded payload bay, attached to the avionics sled bay in the payload compartment. This will secure the sample on three sides. The arm will then close the door to seal the payload bay and a section of foam on the inside wall of the door will fully secure the sample.
Launch Rail Mechanism	Overview The launch rail will be raised by a planetary geared steppermotor. While being raised, the rail will be supported by a double ratchet system in case of a loss of power. The gearing ratio between the sector gear and the driver gear will be 8:1.
Igniter Installation Mechanism	Overview A stepper motor powered linear actuator will raise the electric match igniter into the rocket on a wooden dowel by rotating a threaded rod which drivese a delrin plate that the dowel rests on.

Payload	
Payload 1	Overview The MAV challenge sample. The payload will be made of .75 x 3 inch PVC tubing filled with sand and weigh approximately 4 oz. The payload will be a cylindrical shape with a .75 inch diameter and a 4.75 in length. Ends of the tubing will be secured with domed PVC caps.
Payload 2	Overview

Test Plans, Status, and Results

Ejection Charge Tests	Ejection charges will be sized for each of the compartments to be separated. Charges will be constructed with black powder in a PVC cap with an E-match secured in the cap using paper wadding and tape. Charge ignition for main and drogue charges are capable of being separately fired at the user's input. Both charges are attached to the wire leads of a switch that fires the charges when activated. If the test is a failure, analysis will be conducted to find the cause of the failure with new tests to follow.
Sub-scale Test Flights	The subscale flight test took place on November 28, 2015. The subscale rocket was overly stable which led to weather cocking and an apogee that was significantly lower than expected. Despite that, the drogue successfully deployed at apogee and the main deployed at 700 feet as planned.
Full-scale Test Flights	The full scale flight test took place on February 27, 2016. The full scale rocket performed close to simulations in terms of the apogee achieved once the effect of the airbrakes is taken into account.

Milestone Review Flysheet

Institution	North Carolina State University	Milestone	FRR

Additional Comments

Appendix B MSDS

List of links for relevant MSDS documents

GOEX Black Powder: http://www.goexpowder.com/images/LoadCharts/SDS%20Sheets-GOEX%20Black%20Powder.pdf

Klean-Strip Acetone: http://www.kleanstrip.com/uploads/documents/GAC18_SDS-LL34.pdf

West System 105 Epoxy Resin: http://www.westsystem.com/ss/assets/MSDS/MSDS105.pdf

West System 206 Slow Hardener: http://www.westsystem.com/ss/assets/MSDS/MSDS206.pdf

Fiberglass Fabric: http://www.toolchemical.com/TOOLCHEMICAL/Tubing-Room%20Temp.pdf

Batteries: http://www1.mscdirect.com/MSDS/MSDS00024/00338228-20151101.PDF

Electronic Matches: http://www.pyropak.com/docs/sds/electric-match-(all)-sds.pdf

Cotton Floc: http://www.toolchemical.com/TOOLCHEMICAL/cotton%20flock%20msds.pdf

Baby Wipes: http://westhurleylibrary.org/CircBlog/MSDS/Pampers_Wipes.pdf

Igniter: http://www.aerotech-rocketry.com/customersite/resource_library/RegulatoryDocuments/OSHA(MSDS)/aerotech_igniter_msds_11-12-08.pdf

Liquid Nails: http://www.liquidnails.com/LNDatasheets/MSDS/LN-901_LNP-901

Glass Microspheres: http://cdn.fibreglast.com/downloads/PDCT-MSDS-00003.pdf

Turtle Wax: https://www.turtlewax.com/docs/default-source/msds-english/msds-consumer/turtle-wax-zip-wax-car-wash-concentrate

WD-40: http://wd40.com/files/pdf/msds-wd482671453.pdf

Appendix C Failure Mode Effects and Criticality Analysis

Function / Component	Failure Mode	Causal Factors	Failure Effects		Hazard	Recommendations	Verification
			Subsystem	System			
Robotic Arm Electrical System	Wires Twisted	Careless/messy wiring. Tangled wires because of poor or no planning	This could cause the robotic arm to cease functionality which means that the payload is not retrieved	The payload would not be stored in the rocket, but the rocket would still be able to launch	2	Make sure that wires are layed out cleanly in a manner that allows for easy identification and replacement	Refer to section 4.3.3. Approach to Workmanship
	Bad Servo Motor(s)	Manufacture Defect, Motor burns out due to power or programming issues			2	Make sure that servos are tested thoroughly to ensure that it is free of any manufacturer defects. Also take care to not supply too much voltage/amperage to the servos	Refer to section 4.2.6. Robot Arm Experiment
	Loss of Power	Poor connection or bad battery			2	Make sure that all batteries are fully charged and that wires are securely attached	The LiPo batteries used will be charged the day before
	Bad Programming	Careless programming of the subsystem, or no testing is done			2	Ensure that all code is tested thoroughly to minimize the risk of programmer error	Code will be locked down once the mission goals are met, to prevent any corruption.

Rocket Erector	Wires Twisted	Careless/messy wiring. Tangled wires because of poor or no planning	This could cause the erection system to fall or not get the rocket up to the proper launching angle	The rocket may not be able to launch, and it could cause damage to the entire AGSE and Rocket system	2	Make sure that wires are laid out cleanly in a manner that allows for easy identification and replacement	Refer to section 4.3.3. Approach to Workmanship
	Stepper Motor Failure	Manufacture Defect, Motor burns out due to power or programming issues			1	Make sure that the stepper motor is tested thoroughly to ensure that it is free of any manufacturer defects. Also take care to not supply too much voltage/amperage to the motor	Refer to section 4.2.6. Launch Rail Raising Experiment
	Loss of Power	Poor connection or bad battery			1	Make sure that all batteries are fully charged and that wires are securely attached	Refer to section 4.3.3. Approach to Workmanship
	Bad Programming	Careless programming of the subsystem, or no testing is done			2	Ensure that all code is tested thoroughly to minimize the risk of programmer error	Code will be locked down once the mission goals are met, to prevent any corruption.
Igniter Inserter	Wires Twisted	Careless/messy wiring. Tangled wires because of poor or no planning	This would prevent the igniter from being inserted into the rocket	The rocket may not be able to launch, because the motor will not be able to launch without a functioning	2	Make sure that wires are laid out cleanly in a manner that allows for easy identification and replacement	Refer to section 4.3.3. Approach to Workmanship

	Stepper Motor Failure	Manufacture Defect, Motor burns out due to power or programming issues		igniter	1	Make sure that the stepper motor is tested thoroughly to ensure that it is free of any manufacturer defects. Also take care to not supply too much voltage/amperage to the motor	Refer to section 4.2.6. Igniter Insertion Experiment
	Loss of Power	Power is disconnected from subsystem because of bad connections or faulty batteries			1	Make sure that all batteries are fully charged and that wires are securely attached	Refer to section 4.3.3. Approach to Workmanship
	Bad Programming	Careless programming of the subsystem, or no testing is done			2	Ensure that all code is tested thoroughly to minimize the risk of programmer error	Code will be locked down once the mission goals are met, to prevent any corruption.
Beaglebone (System Computer)	Loss of power	Poor connection or bad battery	This would halt all AGSE subsystems	The AGSE would not be able to perform its mission and the rocket would not be able to launch	2	Make sure that all batteries are fully charged and that wires are securely attached	Refer to section 4.3.3. Approach to Workmanship
	Shorting out	Incorrect amount of power is supplied to the computer			1	Ensure that the correct voltage regulators are always between the power source and the computer	Refer to section 4.3.3. Approach to Workmanship

	Program Malfunction	Careless programming of the subsystem, or no testing is done			1 or 2	Ensure that all code is tested thoroughly to minimize the risk of programmer error	Code will be locked down once the mission goals are met, to prevent any corruption.
	Bad Wiring	Inputs and outputs are connected to the incorrect ports on the computer			2	Make sure that all wiring is connected properly and follows the diagram that was computed prior to wiring	Refer to section 4.3.3. Approach to Workmanship
Crystal Oscillator	Incorrect Oscillation Rate	Oscillation output is not measured with an oscilloscope	This would cause improper functionality of the Erector and Igniter subsystems	The AGSE would may not be able to erect the rocket to the correct launching angle, and/or it may not be able to insert the igniter	2	Use an oscilloscope to make sure we are getting the desired oscillation outputs for the designated stepper motor	Before wiring the oscillator into the stepper motor it will be adjusted using an oscilloscope to the desired frequency
	Shorting out	Incorrect amount of power is supplied to the device			1	Ensure that the correct voltage regulators are always between the power source and the computer	Refer to section 4.3.3. Approach to Workmanship
Robotic Arm Structure	Gripper misses target payload	Arm gears aren't aligned on AGSE base	Payload will not be retrieved nor stored within the rocket	The payload will not be stored in the rocket, but the rocket will still be able to launch	3	Calibrate the system on a regular basis and ensure that the gears are mounted squarely	Refer to section 4.2.6. Robot Arm Experiment

	Gear Damage	Debris in gears due to incomplete inspection	Arm will not move to the correct position and payload will not be retrieved nor stored within the rocket		2	Check gears before and after each use to ensure that teeth are not blocked by debris or dull from previous use	Refer to section 4.3.3. Approach to Workmanship
		Dull gears after continued use			2		

	Support tubes break	Improper handling of equipment	The robotic arm will be rendered useless and the payload will not be retrieved nor stored within the rocket		1	Teach members proper handling procedure for robotic arm and other associated equipment	Refer to section 4.3.3. Approach to Workmanship
	Servos burn out	Improper use. (i.e. Hyper-extension, or excess voltage)			1	Check the limits for the servos before applying any loads	Refer to section 4.2.6. Robot Arm Experiment
	Faulty Equipment	Dull Gears			3	Check equipment after shipping to ensure correct dimensions and no visible damage	Refer to section 4.3.3. Approach to Workmanship
		Faulty wiring			2		
		Manufacturing Defects			2		
	Damage occurred during transit	Improper handling			3	Teach member proper handling and storage procedures for transporting the robotic arm	Refer to section 4.3.3. Approach to Workmanship
		Insufficient packing			3		
Erection System	Gearing	Gear damage	Motor will be unable to raise the rocket	Rocket will not be able to launch if not erected to 5 degrees from vertical	1	Fabricate both gears with the same thickness and same teeth depth	Refer to section 4.2.6. Robot Arm Experiment
		Gear slipping			1		
		Debris in gears due to incomplete inspection			1	Ensure that gear teeth are clear before operation	Refer to section 5.1.6. Troubleshooting
	Ratchet	Ratchet jams due to improper alignment	Erection system will stop moving		1	Ensure proper alignment of erection system on AGSE base	Refer to section 4.3.3. Approach to Workmanship
		Ratchet attachment fails	Rocket and rail will fall with no support		1	Check for loose or faulty hardware before each run	Refer to section 5.1.6. Troubleshooting

		Incorrect direction of ratcheting	Erection system does not move		1	Check the direction of ratcheting before each run	Refer to section 5.1.6. Troubleshooting
	Motor	Over torqued	Motor will be unable to raise the rocket and permanent damage may occur		1	Ensure that motor selection includes a factor of safety for applied torque greater than 1.0	Refer to section 4.2.6. Rail Raising Experiment
Leg Failure	Legs fall or break off	Screws come loose	Legs fall off of the AGSE	The AGSE topples and can't launch the rocket	2	Check that screws are tight before use	Refer to section 5.1.6. Troubleshooting
		Manufacturing defect	Structural instability in the legs		2	Check the parts before assembling	Refer to section 4.3.3. Approach to Workmanship
		Damage occurred during transit due to improper packaging or handling			2	Check equipment after shipping to ensure no visible damage	Refer to section 4.3.3. Approach to Workmanship
Blast Plate	Rocket emissions are reflected back at the rocket	Plate is angled incorrectly	Reflected emissions could ignite the motor unevenly before it leaves the launch rail	Structural damage can occur which may result in a catastrophic failure	1	Check the angle of the plate before use	Refer to section 5.1.6. Troubleshooting
Igniter Insertion System	Dowel rod fails	Dowel breaks	Motor fails to ignite	System requires human intervention to launch	2	Test dowels prior to implementation	Refer to section 5.1.6. Troubleshooting
		Dowel improper size			2	Ensure dimensions are correct on	Refer to section 4.3.3. Approach to

		Dowel scrapes propellant			2	equipment and test igniter action before launch	Workmanship
	No ignition	Igniter is not fully inserted into motor			2	Make sure igniter is secure on the rail	Refer to section 5.1.6. Troubleshooting
		Bad igniter			3	Ensure that igniters have been stored properly and are visually undamaged	Refer to section 4.3.3. Approach to Workmanship
		Electrical short in wiring			2	Ensure that no damage to the wiring has occurred via visual inspection	Refer to section 5.1.6. Troubleshooting
Batteries	Insufficient Power	System loses power during operation because of uncharged or insufficiently charged batteries	Loss of system power will halt all launch operations	Loss of system power supply will halt all launch operations	2	Check charge of battery at least 12 hours prior to operation	Refer to section 4.3.3. Approach to Workmanship
	Leaking	Battery will be rendered useless			1	Teach members safe handling and storage techniques for the batteries	Refer to section 4.3.3. Approach to Workmanship
		Permanent damage to environment or equipment			1		
	Damage occurred during transit	Insufficient packing	Battery will be rendered useless		3	Use a padded envelope to store batteries during transit	Refer to section 4.3.3. Approach to Workmanship
AGSE Stability	Instability during rocket erection or	Imbalanced AGSE	AGSE topples before or during erection	Launch platform instability could result in damage to	2	Using hand levels to orient the AGSE with no tilt	Refer to section 4.3.3. Approach to Workmanship

	launch	Strong winds		the rocket or AGSE during rocket erection and launch	3	Monitoring weather conditions prior to launch to ensure that the wind is within limits	—
		Set up on an inclined surface			4	Cleated legs for extra grip on surface	Refer to section 5.1.6. Troubleshooting
Black Powder Charges	Failure to Ignite	E-Match doesn't light	First ejection charge does not ignite	Rocket fails to separate and deploy parachute(s)	4	Conduct ground tests to ensure that enough black powder will be used for proper separation. Thoroughly check redundant systems prior to launch	Refer to section 3.1.3. Test Data and Analysis
		Altimeter Malfunction			4		
		Improper Programming			4		
	Redundant black powder fails to ignite	E-Match doesn't light	Failure of both ejection charges		1		
		Altimeter Malfunction			1		
		Improper Programming			1		
	Violent ejection causes accidental separation	Charge is too big	Causes violent separation and/or damage to surrounding area	Could cause damage to bulkheads or shock-cord, resulting in a possible failure of parachute deployment	1	Verify that charges are sealed properly and the correct amount of black powder using pre-flight checklists	Refer to section 3.1.3. Test Data and Analysis
Avionics (altimeters)	No power to avionics or charges	Uncharged or insufficiently charged batteries	Loss of real-time altitude data	Failure of parachute deployment	1	Begin charging batteries at least 12 hours prior to launch, and ensure all batteries have the correct voltage before flight	Step 32 of section 3.6.1.
	Faulty Altimeter	Manufacturer defect	No ejection or premature/late ejection		1		Refer to section 3.1.3. Test Data and Analysis

BigRedBee (GPS)	Ground System Failure	Loss of power to ground receiver or the laptop	In ability receive data from the GPS	Inability to track and recover the rocket (in a reasonable amount of time)	3	Make sure that the receiver and laptop are fully charged at least 6 hours prior to flight	Refer to section 3.1.4. Approach to Workmanship
	Loss of signal	Environment or rocket materials blocking signal			3	Perform range tests to ensure reliability of the system at simulated altitudes and ground distances	Refer to section 3.1.3. Test Data and Analysis
	Radio Interference	Multiple radio devices on the same local frequency and channel			3	Make sure that all transmitting devices are on separate channels and confirm with other teams and launch officials that no frequency conflict exists	Coordinate with NASA to ensure selected frequency is free of conflicted transmissions
	Loss of power	Flight forces cause GPS to disconnect from power supply			3	Make sure all GPS units are fully charged and use simulated load tests to determine the necessary procedures to secure the units	GPS units functioned through full scale test flight
Airbrakes and Telemetry	Arduino Failure	Loss of power, damage during flight, severed data connection, bad altitude	Failed deployment of one or both airbrake flaps	Failure of airbrakes may cause the rocket to break the altitude goal	4	Take steps to ensure that all system components are properly seated to prevent any shifting	Refer to section 3.1.4. Approach to Workmanship
	Altimeter Connection Failure				4		

	Data logger Failure	readings			4	during flight. Ensure that all wires are connected properly and that batteries are fully charged prior to launch	
	GPS Failure				4		
	Radio Failure				4		
	Linear Actuator Failure				4		
Fiberglass Airframe	Cracks or Breaks	Manufacturing Defect	Structural integrity of fiberglass sections at risk	Possible premature separation of rocket segments or rapid unscheduled disassembly during flight	1	Visual inspection after shipping before any structural implementation	Refer to section 3.1.4. Approach to Workmanship
		Experienced loads beyond design specifications			1	Implement a safety factor greater than 1.0 to ensure that flight conditions do not exceed design specifications	Refer to section 3.1.4. Approach to Workmanship
		Damaged during handling			1	Team members will be taught proper handling procedures for body tubing and the assembled rockets	Refer to section 3.1.4. Approach to Workmanship
		Improper maintenance			1	Thorough pre- and post-launch inspections of body tubing	Refer to section 5.1.7. Post-flight inspection
Bulkheads	Separation of bulkhead from airframe during flight	Manufacturing Defect	Structural integrity of rocket segments at risk	Possible premature separation of rocket segments, rapid disassembly of	1	Visual inspection after completing construction before any implementation	Refer to section 3.1.4. Approach to Workmanship

		Loads beyond design specifications		rocket, or recovery system failure during descent	1	Implement a safety factor to ensure that flight conditions do not exceed design specifications	Refer to section 3.1.4. Approach to Workmanship
		Damaged during handling due to improper handling techniques			1	Team members will be taught proper handling and installation procedures for bulkheads	Refer to section 3.1.4. Approach to Workmanship
		Improper maintenance			1	Thorough pre- and post-launch inspections of bulkheads	Refer to sections 3.1.4. and 5.1.7.
	Parachute and bulkhead separation during flight	Loads beyond design specifications	Without an attached parachute, a rocket segment could be free to free fall	Loss of recovery system will result in mission failure and can cause harm to ground crew	1	Implement a safety factor to ensure that flight conditions do not exceed design specifications	Refer to section 3.1.4. Approach to Workmanship
		Improper maintenance			1	Thorough pre- and post-launch inspections of bulkheads	Refer to sections 3.1.4. and 5.1.7.
	Non-compromising cracks	Loads beyond design specifications	Present potential for further damage to bulkhead	If left unnoticed, a small crack can expand during flight which may result in bulkhead failure	3	Implement a safety factor to ensure that flight conditions do not exceed design specifications	Refer to section 3.1.4. Approach to Workmanship
		Damaged during handling due to improper handling techniques			3	Adhere to proper handling procedure	Refer to section 3.1.4. Approach to Workmanship

		Improper maintenance			3	Thorough pre- and post-launch inspections of bulkheads	Refer to sections 3.1.4. and 5.1.7.
Fins	Surface damage	Loads beyond design specifications	Damage to fin will necessitate its replacement before any future launches	Fin failure during flight will decrease stability of rocket and will likely cause a catastrophic failure	1	Implement a safety factor to ensure that flight conditions do not exceed design specifications	Refer to section 3.1.4. Approach to Workmanship
		Damaged during handling due to improper handling techniques			1	Team members will be taught proper handling procedures for fins and fin section	Refer to section 3.1.4. Approach to Workmanship
		Improper maintenance			1	Pre- and post-launch thorough inspections of the fins	Refer to sections 3.1.4. and 5.1.7.
		Ground impact			2	Implement a recovery system design that ensures a low speed surface impact	Refer to sections 3.1.1.1., 3.1.3., and 3.3.5.
	Fin flutter	Loads beyond design specifications	Loss of fin subsystem effectiveness	Decreased flight stability, and possible damage to other components	4	Maintain operations within design specifications	Refer to section 3.1.4. Approach to Workmanship
		Damaged during handling due to improper handling techniques			4	Adhere to proper handling procedure	Refer to section 3.1.4. Approach to Workmanship
		Improper maintenance			4	Pre- and post-launch thorough inspections of the fins	Refer to section 3.1.4. Approach to Workmanship
Shear Pins	Pins break before charge detonation	Manufacturing Defect	Loose assembly of compartment	Separation of vehicle compartments	2	Visual inspection after shipping before any implementation	Step 54 of section 3.6.1

		Loads beyond design specifications			2	Maintain vehicle within design specifications	Refer to section 3.1.4. Approach to Workmanship
		Improper maintenance			2	Use of new pins after each launch	Step 54 of section 3.6.1
	Pins don't break at charge detonation	Manufacturing Defect	Failure to separate	Loss of safe and effective recovery system	1	Pre-launch visual inspection of shear pins	Step 54 of section 3.6.1
		Poor Design			1	Proper calculation of the force exerted on the pins during detonation	Refer to section 3.1.3. Test Data and Analysis
Avionics Sled	Detaches from secured position	Loads beyond design specifications	Damage to/loose wiring of avionics components	Loss of recovery system initiation	1	Use simulations to test max load before failure	Refer to section 3.1.4. Approach to Workmanship
		Damaged during handling due to improper handling techniques			1	Team members will be taught proper handling and installation procedures for the avionics sled	Refer to section 3.1.4. Approach to Workmanship
		Improper maintenance			1	Pre- and post-launch thorough inspections of the avionics sled	Refer to sections 3.1.4. and 5.1.7.
Nosecone	Non-compromising cracks	Loads beyond design specifications	Potential for future damage	If left unattended this could lead to catastrophic failure of the entire system	3	Use simulations to test max load before failure	Refer to section 3.1.4. Approach to Workmanship
		Damaged during handling due to improper handling techniques			3	Team members will be taught proper handling and installation procedures for nosecone	Refer to section 3.1.4. Approach to Workmanship

		Improper maintenance			3	Pre- and post-launch thorough inspections of the nosecone	Refer to sections 3.1.4. and 5.1.7.
	Damage from impact	Loads beyond design specifications	Loss of future nosecone use	If left unattended this could lead to catastrophic failure of the entire system	2	Visual inspection of nosecone after shipping before any implementation	Refer to sections 3.1.4. and 5.1.7.
		Damaged during handling due to improper handling techniques			2	Team members will be taught proper handling and installation procedures for the nosecone	
		Improper maintenance			2	Pre- and post-launch thorough inspections of nosecone	
	Premature separation from other structural members	Damaged during handling due to improper handling techniques	Potential for structural damage	Loss of controlled and stabilized flight	2	Team members will be taught proper handling and installation procedures for the nosecone	Refer to sections 3.1.4. and 5.1.7.
		Improper maintenance			2	Pre- and post-launch thorough inspections of the nosecone	
Airbrakes	Asymmetric Engagement	Rod fails	One airbrake engages, the other remains stowed	Unstable flight that could lead to catastrophic failure	1	Test the rods to find max load capacity	Refer to sections 3.1.3. and 3.1.4.
		Flap breaks			1	Implement a safety factor greater than 1.0 to ensure that flight conditions do not exceed design specifications	Refer to section 3.1.4. Approach to Workmanship

	Non-compromising cracks	Loads beyond design specifications	Potential for future damage	If left unattended could lead to catastrophic subsystem and system failure	3	Implement a safety factor greater than 1.0 to ensure that flight conditions do not exceed design specifications	Refer to section 3.3.3.1. Drag Assessment
		Damaged during handling due to improper handling techniques			3	Team members will be taught proper handling and installation procedures for airbrakes	Refer to section 3.1.4. Approach to Workmanship
		Improper maintenance			3	Pre- and post-launch thorough inspections of airbrakes	Refer to sections 3.1.4. and 5.1.7.
	Damage from impact	Loads beyond design specifications	Loss of future use of airbrakes system	Permanent damage of airbrakes will render them useless	2	After each launch, airbrake systems will be thoroughly inspected for any minor defects	Refer to section 5.1.7. Post-flight inspection
		Improper maintenance			2	Pre- and post-launch thorough inspections of airbrakes	Refer to sections 3.1.4. and 5.1.7.
	No Engagement	Rod fails because maximum load is exceeded	Both airbrakes fail to engage	The rocket will overshoot its target altitude	3	Run tests to acquire the maximum load that the rods can support and make sure that the loads on the rods stay well within the limits using a safety factor greater than 1.0	Refer to section 3.1.4. Approach to Workmanship
		Rod bends because of improper testing			3		

		Flap breaks because maximum load is exceeded			3	Use simulations to test max load before failure and implement a safety factor greater than 1.0	Refer to section 3.3.3.1. Drag Assessment
		Debris in the hinges due to incomplete inspection			3	Pre- and post-launch thorough inspections of airbrakes	Refer to sections 3.1.4. and 5.1.7.
		Linear actuator fails to activate			3	Pre- and post-launch thorough inspections of linear actuators, and proper installation of linear actuators	Refer to sections 3.1.4. and 5.1.7.
	Failure for the airbrakes to stow on descent	Linear actuator fails to activate	Damage to airbrakes subsystem on landing	Permanent damage to airbrakes will render them useless	2	Pre- and post-launch thorough inspections of linear actuators, and proper installation of linear actuators	Refer to sections 3.1.4. and 5.1.7.
		Debris in the hinges due to incomplete inspection			2	Pre- and post-launch thorough inspections of airbrakes	Refer to sections 3.1.4. and 5.1.7.

Appendix D Vehicle Verification Matrix

Vehicle Requirements	
The vehicle shall deliver the payload to an apogee altitude of 5,280 feet above ground level (AGL).	Section 3.3.6. Altitude of Launch Vehicle and Drift
The vehicle shall carry one commercially available, barometric altimeter for recording the official altitude used in the competition scoring. The altitude score will account for 10% of the team's overall competition score. Teams will receive the maximum number of altitude points (5,280) if the official scoring altimeter reads a value of exactly 5,280 feet AGL. The team will lose two points for every foot above the required altitude, and one point for every foot below the required altitude. The altitude score will be equivalent to the percentage of altitude points remaining after any deductions.	Section 3.2.1.2. Electrical Elements
The launch vehicle shall be designed to be recoverable and reusable. Reusable is defined as being able to launch again on the same day without repairs or modifications.	Section 3.1.6. Full Scale Launch Test Results
The launch vehicle shall have a maximum of four (4) independent sections. An independent section is defined as a section that is either tethered to the main vehicle or is recovered separately from the main vehicle using its own parachute.	Section 3.1.1.1. Structural Elements
The launch vehicle shall be limited to a single stage.	Section 1.2.2. Motor Choice
The launch vehicle shall be capable of being prepared for flight at the launch site within 2 hours, from the time the Federal Aviation Administration flight waiver opens.	The full scale test flight on February 27, 2016 was carried out within this time.
The launch vehicle shall be capable of remaining in launch-ready configuration at the pad for a minimum of 1 hour without losing the functionality of any critical on-board component.	Section 5.1. Checklist
The launch vehicle shall be capable of being launched by a standard 12 volt direct current firing system. The firing system will be provided by the NASA-designated Range Services Provider.	Section 3.1.6. Full Scale Launch Test Results
The launch vehicle shall use a commercially available solid motor propulsion system using ammonium perchlorate composite propellant (APCP) which is approved and certified by the National Association of Rocketry (NAR), Tripoli Rocketry Association (TRA), and/or the Canadian Association of Rocketry (CAR).	Section 1.2.2. Motor Choice

The total impulse provided by a launch vehicle shall not exceed 5,120 Newton-seconds (L-class).	Section 1.2.2. Motor Choice
All teams shall successfully launch and recover a subscale model of their full-scale rocket prior to CDR. The subscale model should resemble and perform as similarly as possible to the full-scale model, however, the full-scale shall not be used as the subscale model.	*Not in this document. Subscale flight can be viewed in CDR section 3.2.
All teams shall successfully launch and recover their full-scale rocket prior to FRR in its final flight configuration. The rocket flown at FRR must be the same rocket to be flown on launch day. The purpose of the full-scale demonstration flight is to demonstrate the launch vehicle's stability, structural integrity, recovery systems, and the team's ability to prepare the launch vehicle for flight. A successful flight is defined as a launch in which all hardware is functioning properly	Section 3.1.6. Full Scale Launch Test Results
Each team will have a maximum budget of $7,500 they may spend on the rocket and its payload(s).	Section 6.1. Budget Plan
Recovery System Requirements	
The launch vehicle shall stage the deployment of its recovery devices, where a drogue parachute is deployed at apogee and a main parachute is deployed at a much lower altitude.	Sections 3.2.1.4. and 3.2.2.
Teams 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.	Section 3.1.3. Test Data and Analysis
At landing, each independent section of the launch vehicle shall have a maximum kinetic energy of 75 ft-lbf.	Section 3.3.5. Management of Kinetic Energy
The recovery system electrical circuits shall be completely independent of any payload electrical circuits.	Section 3.2.1.2. Electrical Elements
The recovery system shall contain redundant, commercially available altimeters. The term "altimeters" includes both simple altimeters and more sophisticated flight computers. One of these altimeters may be chosen as the competition altimeter.	Section 3.2.1.3. Redundancy Features
Motor ejection is not a permissible form of primary or secondary deployment. An electronic form of deployment must be used for deployment purposes.	Section 3.2.1.2. Electrical Elements
A dedicated arming switch shall arm each altimeter, which is accessible from the exterior of the rocket airframe when the rocket is in the launch configuration on the launch pad.	Section 3.2.1.2. Electrical Elements

Each altimeter shall have a dedicated power supply.	Section 3.2.1.2. Electrical Elements
Each arming switch shall be capable of being locked in the ON position for launch.	Section 3.2.1.2. Electrical Elements
Removable shear pins shall be used for both the main parachute compartment and the drogue parachute compartment.	Section 3.2.1.1. Structural Elements
An electronic tracking device shall be installed in the launch vehicle and shall transmit the position of the tethered vehicle or any independent section to a ground receiver.	Section 3.2.1.6. Rocket Locating Transmitters
The recovery system electronics shall not be adversely affected by any other on-board electronic devices during flight (from launch until landing).	Section 3.2.1.7. Sensitivity of Recovery System to Onboard Electromagnetic Fields
Competition and Centennial Challenge Requirements	
The payload shall be designed to be recoverable and reusable. Reusable is defined as being able to be launched again on the same day without repairs or modifications.	Section 4.2.2. Mission Success Criteria
See AGSE Verification Matrix for further detail.	Appendix E
Safety Requirements	
Each team shall use a launch and safety checklist. The final checklists shall be included in the FRR report and used during the Launch Readiness Review (LRR) and launch day operations.	Section 5.1. Checklist
For all academic institution teams, a student safety officer shall be identified.	Section 5.2.8. Identify Individual Responsible for Maintaining Safety, Quality, and Procedures Checklists

Each team shall identify a "mentor." A mentor is defined as an adult who is included as a team member, who will be supporting the team (or multiple teams) throughout the project year, and may or may not be affiliated with the school, institution, or organization. The mentor shall be certified by the National Association of Rocketry (NAR) or Tripoli Rocketry Association (TRA) for the motor impulse of the launch vehicle, and the rocketeer shall have flown and successfully recovered (using electronic, staged recovery) a minimum of 2 flights in this or a higher impulse class, prior to PDR. The mentor is designated as the individual owner of the rocket for liability purposes and must travel with the team to the launch at the competition launch site. One travel stipend will be provided per mentor regardless of the number of teams he or she supports. The stipend will only be provided if the team passes FRR and the team and mentor attend launch week in April.	Section 1.1.2. Name of Mentor, TRA Number, and Certification
During test flights, teams shall 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 University Student Launch Initiative competition launch does not give explicit or implicit authority for teams to fly those certain 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.	Team mentor Alan Whitmore is the Prefect of Tripoli East North Carolina and is always informed of what the team is flying well in advance.
Teams shall abide by all rules and regulations set forth by the FAA.	The team and its mentors always follow all rules and regulations set forth by the FAA.

Appendix E AGSE Verification Matrix

AGSE		
The MAV Project will provide each team with the opportunity to develop a unique method to capture, contain, and launch a payload with limited human intervention. In addition, teams will develop a launch system that erects a rocket from a horizontal to vertical position, and has its igniter autonomously installed. The AGSE will be demonstrated at LRR and will follow this general procedure. Requirements 3.3.2.1.1 – 3.3.2.1.4 shall be conducted autonomously from start to finish within a 10 minute time limit. The only allowed human interaction is the activation of the master switch.	Teams will position their launch vehicle horizontally on the AGSE.	Section 5.1.8 Step 3
	A master switch will be activated to power on all autonomous procedures and subroutines.	Section 5.1.8 Step 9
	All AGSEs will be equipped with a pause switch in the event that a judge needs the AGSE to be temporarily halted for any reason. The pause switch halts all AGSE procedures and subroutines. Once the pause switch is deactivated the AGSE resumes operation.	Section 5.1.8
	Once the judge signals "START", the AGSE will begin its autonomous functions in the following order: 1) capture and containment of the payload; 2) erection of the launch platform from horizontal to 5.0 degrees off vertical (85.0 degrees), 3) insertion of the motor igniter. The judge may re-enable the pause switch at any time at his/her discretion. If the pause switch is re-enabled all systems and actions shall cease immediately. The judge will only do this if there is a question about safe operation of the AGSE. The judge and team leader will discuss and decide if the team will be allowed to continue their attempt. No modifications to the hardware or software will be allowed prior to a rerun.	Section 5.1.8 Step 13.1

The Autonomous Ground Support Equipment (AGSE)	For the purpose of this challenge, the ASGE is defined as all mechanical and electrical components not part of the launch vehicle, and is provided by the teams. This includes, but is not limited to, the payload containment and igniter installation devices, computers, electric motors, batteries, etc.	Section 4.3.
	All AGSE systems shall be fully autonomous. The only human interaction will be if the judge pauses the AGSE.	Section 5.1.8.
	The AGSE shall be limited to a weight of 150 pounds or less and volume of 12 feet in height x 12 feet in length x 10 feet in width.	Section 1.3.2.
Prohibited Technology for AGSE	As one of the goals of this competition is to develop equipment, processes, and technologies that could be implemented in a Martian environment, the AGSE and any related technology cannot employ processes that would not work in such environments. Therefore, prohibited technologies include:	Section 4.3.
	Sensors that rely on Earth's magnetic field	
	Ultrasonic or other sound-based sensors	
	Earth-based or Earth orbit-based radio aids (e.g. GPS, VOR, cell phone).	
	Open circuit pneumatics	
	Air breathing systems	

	Each launch vehicle must have the space to contain a cylindrical payload approximately 3/4 inch inner diameter and 4.75 inches in length. The payload will be made of ¾ x 3 inch Schedule 40 PVC tubing filled primarily with sand and may include BBs, weighing approximately 4 ounces and capped with domed PVC end caps. Each launch vehicle must be able to seal the payload containment area autonomously prior to launch.	Section 4.3.
Payload	A diagram of the payload and a sample payload will be provided to each team at time of acceptance into the competition. In addition, Teams may construct practice payloads according to the above specifications; however, each team will be required to use a regulation payload provided to them on launch day.	Section 4.3.
	The payload will not contain any hooks or other means to grab it.	
	The payload shall be placed a minimum of 12 inches away from the AGSE and outer mold line of the launch vehicle in the launch area for insertion, when placed in the horizontal position on the AGSE and will be at the discretion of the team as long as it meets the minimum placement requirements.	
	Gravity-assist shall not be used to place the payload within the rocket. If this method is used no points shall be given for payload insertion.	

	Each team will be given 10 minutes to autonomously capture, place, and seal the payload within their rocket, and erect the rocket to a vertical launch position five degrees off vertical. Insertion of igniter and activation for launch are also included in this time. Going over time will result in the team's disqualification from the MAV Project competition.	Section 4.2.2.
Safety and AGSE Control	A master switch to power all parts of the AGSE. The switch must be easily accessible and hardwired to the AGSE.	Section 5.1.8.
	A pause switch to temporarily terminate all actions performed by AGSE. The switch must be easily accessible and hardwired to the AGSE.	
	A safety light that indicates that the AGSE power is turned on. The light must be amber/orange in color. It will flash at a frequency of 1 Hz when the AGSE is powered on, and will be solid in color when the AGSE is paused while power is still supplied.	Section 4.3.
	An all systems go light to verify all systems have passed safety verifications and the rocket system is ready to launch.	

Appendix F MATLAB Code for Airbrakes

```
clear all
clc
format short g


%% airbrake theta definition
t_index=0;
t_theta=0;
theta=.001;
normal_coefficient=theta*(1.7/45);
DragCoefficient_brakes=normal_coefficient*sind(theta);
DragCoefficient_rocket=0.5;
Ab=0.11111111;%ft^2
Ar=0.165951;
rho=0;
g=32.1847;%ft/sec^2
V0=650;%ft/sec
Vog=V0;%original
Y0=1500;%ft
weight=30;%lbs
mass=weight/32.187;%lbs into slugs
Drag_Force=0;% force of rocket drag in lbs
aD=Drag_Force/mass;%ft/sec^2
a=-(aD+g);
h=Y0/3.2808;%alt in meters
T0=288.15;%in deg_K
P0=101325;%in N/m^2
R=287.04;%M^2/(K*sec^2)
Fbrakes=0;
timestep=.01;%sec
apogee=0;
trip=0;
Yap=0;%projected apogee based on current acceleration, and og velo
Table=zeros(100);
variable1=1;
variable2=1;
while V0 < 750
```

```
D_alt=1700; %deployment altitude of airbrakes

while apogee < 5200
    theta=0.001;
    V=V0;
    Y=Y0;
    t=0;
    s=1;
    Mat=zeros(8);
    k=0;
    while t<20
        h=Y/3.2808;%alt in meters
        P=P0*(1-0.0065*(h/T0))^5.2561;%pascals
        T=T0-6.5*(h/1000);%deg_K
        rho=P/(R*T);%N/m^3
        rho=rho*0.0019403203319541;%slugs/ft^3

        if Y<D_alt
            Drag_Force=(((rho*V^2)/2)*(DragCoefficient_rocket*Ar));
        else
            %
            theta=new_theta(theta,timestep);
            %
            Ab=(2/12)*2*(4/12)*sind(theta);
            normal_coefficient=theta*(1.7/45);
            DragCoefficient_brakes=normal_coefficient*sind(theta);
            Fbrakes=(((rho*V^2)/2)*(DragCoefficient_brakes*Ab));%pounds
            Drag_Force=(((rho*V^2)/2)*(DragCoefficient_rocket*Ar))+Fbrakes;%pounds
            trip=1;
        end

        aD=Drag_Force/mass;%ft/sec^2
        a=-(aD+g);



        k=0.5*rho*(Ab+Ar)*(DragCoefficient_rocket+DragCoefficient_brakes);
        %Yap=(-mass/k)*log(cosd(atand(sqrt(k/(mass*g))*V)))+Y;
        %
```

```
            V=V+a*timestep;
            Y=Y+V*timestep+(1/2)*a*(timestep^2);
            Mat(s+1,1)=t;
            Mat(s+1,2)=Y;
            Mat(s+1,3)=V;
            Mat(s+1,4)=Fbrakes;
            Mat(s+1,5)=Drag_Force;
            Mat(s+1,6)=a;
            Mat(s+1,7)=rho;
            Mat(s+1,8)=theta;
            %Mat(s+1,9)=Yap;
            %          Mat(s+1,10)=DragCoefficient_brakes;
            s=s+1;
            apogee=Mat(end,2);
            if Mat(s,2)<Mat(s-1,2)
                t=21;
            else
                t=t+timestep;
            end
        end
        D_alt=D_alt+5;
    end
    Table(1,variable1)=V0;
    deploy=(D_alt-5)

    Table(2,variable2)=deploy;
    V0=V0+1;
    apogee=0;
    variable1=variable1+1;
    variable2=variable2+1;

end

Table=Table(1:2,:);
Mat;
```

Function Referenced in MATLAB

```
function [new_theta] = new_theta( theta,timestep )
%
%   b is the angle at which the airbrakes are currently at, q is the index
%   number of the matrix containing the time/airbrake angle data.
%timestep is what it says it is

%theta is theta input

%t is a list of all possible times (in opening)

%y is all possible flapbrake angles (in refernce to t)

%matrix is [t1,y1
%            t2,y2]

%       etc

%essentially all angles matched up with the times after opening begins at
%which they exist

%error1 and error2 are just really small values to ensure code accuracy

%q and w are empty matrices
%   where q is the location in the tabulated t1y1 matrix that the desired current theta lies

%r and k are 0

%first while loop finds the closest tabulated position of y to the current theta,
% moving up in error values of .00001 until the closest value is found.
%When this value is found, the value of a goes from 0 to 1, and r becomes 1, ending the loop.



if theta < 45.2472
    t=0:.00001:1.2;
```

```
    y=8.9079.*(t.^3)-54.192.*(t.^2)+(89.909.*t);
    t=t';
    y=y';
    matrix=[t,y];

    error1=0.00001;
    error2=0.000001;
    q=[];
    w=[];
    r=0;
    k=0;

    while r==0
        q=find(abs((y-theta))<error1);
        error1=error1+.00001;
        a=size(q);
        r=a(1,1);
    end

    time1=matrix(q,1);
    time2=time1+timestep;

    while k==0
        w=find(abs((t-time2))<error2);
        error2=error2+.00001;
        b=size(w);
        k=b(1,1);
    end
new_theta1=matrix(w,2);

else
    new_theta=theta;
end

end
```

Appendix G Arduino Code Referenced by MATLAB

```
/* North Carolina State University High-Powered Rocketry Club "Tacho Lycos"
 * Penumbra Airbrake Control System
 * 2015-16 NASA USLI MAV Competition
 *
 *
 *
 *
 *
 *
 * Wiring Guide (for Arduino Mega 2650):
 *    BMP180 Altimeter:
 *      20 --> SDA
 *      21 --> SCL
 *    Firgelli LAC Board:
 *      11 -->
 *    OpenLog DataLogger:
 *      1 --> RX
 *
 *
 *
 *
 *
 *
https://www.sparkfun.com/products/11824
Like most pressure sensors, the BMP180 measures absolute pressure.
Since absolute pressure varies with altitude, you can use the pressure
to determine your altitude.
Because pressure also varies with weather, you must first take a pressure
reading at a known baseline altitude. Then you can measure variations
from that pressure
Hardware connections:
```

```
- (GND) to GND
+ (VDD) to 3.3V
(WARNING: do not connect + to 5V or the sensor will be damaged!)
You will also need to connect the I2C pins (SCL and SDA) to your
Arduino. The pins are different on different Arduinos:
Any Arduino pins labeled:  SDA  SCL
Uno, Redboard, Pro:        A4   A5
Mega2560, Due:             20   21
Leonardo:                   2    3
Leave the IO (VDDIO) pin unconnected. This pin is for connecting
the BMP180 to systems with lower logic levels such as 1.8V
Have fun! -Your friends at SparkFun.
The SFE_BMP180 library uses floating-point equations developed by the
Weather Station Data Logger project: http://wmrx00.sourceforge.net/
Our example code uses the "beerware" license. You can do anything
you like with this code. No really, anything. If you find it useful,
buy me a beer someday.
V10 Mike Grusin, SparkFun Electronics 10/24/2013
V1.1.2 Updates for Arduino 1.6.4 5/2015
*/
```

```
// ---- BEGIN BMP180 Configuration ----
  #include <SFE_BMP180.h>
  #include <Wire.h>
  SFE_BMP180 pressure;                          // Creates an SFE_BMP180 object, here called "pressure"
  double baseline;                              // baseline pressure
// ---- END BMP180 Configuration
```

```
//--------------------------------------------------


// ---- BEGIN Global Variable Declaration ----
  unsigned long currentTime;                      // Variable for temporary storage of the current time
  unsigned long deploymentAlt;                    // Calculated altitude (ft) at which the airbrakes should be deployed
  unsigned long timeAfterMeasurement;             // Time velocity measurement was taken
  double velocity;                                // Measured velocity (ft/s)
  char airbrakesDeployed;                         // Indicates whether the airbrakes are (1) or are not (0) deployed
  char calculatedDeploymentYet;                   // Indicates whether the deployment altitude has (1) or has not (0) been
calculated yet
  const char logData = 0;                         // Log data to SD card? 1 to enable, 0 to disable
  int ledPin = 12;                                // Error indication LED pin
  int velocityBlinkerLEDPin = 13;                 // Pin which will indicate velocity measurement

  // Airbrake Parameters
    const int MINIMUMDEPLOYMENTALT = 1700;        // Altitude (ft) at which the airbrakes will not be deployed prior to
    const int MAXIMUMDEPLOYMENTALT = 2800;        // Altitude (ft)at which the airbrakes will be deployed prior to
    const int VELOCITYMEASUREMENTALT = 1490;      // Altitude (ft) at which to measure rocket velocity
    const int RETRACTIONALT = 1200;               // Altitude (ft) at which to retract the airbrakes
    const int DEPLOYEDPOSITION = 100;             // Actuator position at which airbrakes will be fully deployed
    const int RETRACTEDPOSITION = 22;             // Actuator position at which airbrakes will be fully retracted

    // Deployment Altitude Calculation Data:
      const int velocityTable[]= {650, 651, 652, 653, 654, 655, 656, 657, 658, 659, 660, 661, 662, 663, 664, 665, 666, 667, 668,
669, 670, 671, 672, 673, 674, 675, 676, 677, 678, 679, 680, 681, 682, 683, 684, 685, 686, 687, 688, 689, 690, 691, 692, 693, 694,
695, 696, 697, 698, 699, 700, 701, 702, 703, 704, 705, 706, 707, 708, 709, 710, 711};    // Velocity (ft/s)
      const int altTable[] = {2730, 2705, 2690, 2670, 2650, 2630, 2610, 2590, 2570, 2550, 2530, 2510, 2495, 2475, 2455, 2440,
```

```
2420, 2405, 2385, 2365, 2350, 2330, 2315, 2295, 2280, 2260, 2240, 2225, 2210, 2190, 2175, 2155, 2140, 2130, 2110, 2095, 2075,
2060, 2045, 2030, 2010, 2000, 1980, 1960, 1950, 1930, 1920, 1900, 1885, 1870, 1855, 1845, 1825, 1810, 1795, 1780, 1765, 1750,
1740, 1720, 1705, 1700};    // Corresponding altitude (ft) at which airbrakes should be deployed
      const int MINIMUMVELOCITYTOCHECK = 650;       // Minimum velocity for which a deployment altitude was calculated
      const int MAXIMUMVELOCITYTOCHECK = 711;       // Maximum velocity for which a deployment altitude was calculated
// ---- END Variable Declaration ----



//---------------------------------------------------



// ---- BEGIN Linear Actuator Configuration ----
  #include <Servo.h>
  Servo myservo;                                    // create servo object to control a servo
  int val;                                          // variable to read the value from the analog pin
// ---- END Linear Actuator Configuration ----



//-----------------------------------------------------------------------
```

```
void setup()
{
  Serial.begin(9600);                              // Sets the baud rate (the rate at which data is communicated through the serial port)


  Serial.println("REBOOT");


  pinMode(velocityBlinkerLEDPin, OUTPUT);          // initialize digitial velocityBlinkerLEDPin as output
  pinMode(ledPin, OUTPUT);                         // initialize digital ledPin as an output.

// ---- BEGIN BMP180 Initialization ----
  digitalWrite(ledPin, LOW);
  if (pressure.begin())
    Serial.println("BMP180 init success");
  else{                                                        // Runs if BMP180 cannot be initialized
    Serial.println("BMP180 init fail (disconnected?)\n\n");    // Reports error to serial port
    int blinkPeriod = 1000;                                    // Sets blinkPeriod to 1000 milliseconds
    while(1){                                                  // Blinks the alert LED forever
      digitalWrite(ledPin, LOW);                               // Turns off the alert LED
      delay(blinkPeriod);                                      // Waits the blink period (ms)
      digitalWrite(ledPin, HIGH);                              // Turns on the alert LED
      delay(blinkPeriod);                                      // Waits the blink period (ms)
    }
  }
  baseline = getPressure();                                    // Gets the baseline pressure (millibars)
  Serial.print("Baseline Pressure (mb): ");                    // Report data to the serial port
  Serial.println(baseline);
// ---- END BMP180 Initialization ----


// ---- BEGIN Servo Initialization ----
```

```
  myservo.attach(11);  // attaches the servo on pin 11 to the servo object
  int pos = scale(RETRACTEDPOSITION);
  const int DELAYTIME = 3000;
  myservo.write(pos);
  delay(DELAYTIME);
  pos = scale(DEPLOYEDPOSITION);
  myservo.write(pos);
  delay(DELAYTIME);
  pos = scale(RETRACTEDPOSITION);
  myservo.write(pos);
  delay(DELAYTIME);
// ---- END Servo Initialization ----


calculatedDeploymentYet = 0;                  // Initializes as 0 to indicate that deployment has not yet been calculated
airbrakesDeployed = 0;                        // Initializes as 0 to indicate that the airbrakes are not deployed


}
// ---- END Setup ----






//------------------------------------------------------------------------
```

```
// ---- BEGIN Main Loop ----
void loop()
{
  if(calculatedDeploymentYet == 0){
    // ---- BEGIN Altitude Measurements ----
    double a,P,afeet;                                    // Define all the variables for this portion of the sketch
    P = getPressure();                                   // Get a new pressure reading
    a = pressure.altitude(P,baseline);                   // Show the relative altitude difference (in meters) between the new
reading and the baseline reading
    afeet = a*3.28084;                                   // Convert that difference from meters to feet
    // ---- END Altitude Measurements ----
    if(afeet > VELOCITYMEASUREMENTALT){                  // Checks to see if the current altitude is greater than the altitude
at which deployment is to be calculated
      measureRocketMotion();                             // Runs the function to determine the velocity of the rocket (feet per
second squared)
      timeAfterMeasurement = millis();                   // timeAfterVelocityMeasurement is set equal to the time (in
milliseconds) since start of program
      calculateDeploymentAlt();                          // Uses the calculated velocity to reference a table of values to find
the proper deployment altitude
      calculatedDeploymentYet = 1;                       // 1 indicate that the altitude at which to deploy the airbrakes has
been calculated
    }
  }
  else{                                                  // Runs if the deployment altitude has been calculated
    // ---- BEGIN Altitude Measurements ----
    double currentAlt,P,currentAltfeet;                  // Declare all the variables for this portion of the sketch
    P = getPressure();                                   // Get a new pressure reading
    currentAlt = pressure.altitude(P,baseline);          // Calculates the relative altitude difference (in meters) between the
new reading and the baseline reading
    currentAltfeet = currentAlt*3.28084;                 // Convert that difference from meters to feet
    // ---- END Altitude Measurements ----
    if(currentAltfeet > deploymentAlt){                  // Checks if the current altitude is greater than the calculated
altitude at chich the airbrakes should be deployed:
```

```
      if(airbrakesDeployed == 0){                           // Checks if the airbrakes have been already been deployed. True = 1,
False = 0
        airbrakesDeployed = deployAirbrakes();              // Calls function that deploys the airbrakes
        if (logData == 1) {                                 // If data is to be logged
          unsigned long deploymentTime = millis();
          Serial.print(F("Calculated Deployment Altitude (ft): "));
          Serial.println(deploymentAlt, DEC);
          Serial.print(F("Time of Deployment (ms): "));
          Serial.println(deploymentTime, DEC);
          Serial.print(F("Measured Velocity (ft/s)"));
          Serial.println(velocity, DEC);
          Serial.println("");
        }
      }
    }
    else{                                                     // If the current altitude is not greater than the deployment
altitude
      if(currentAltfeet < RETRACTIONALT){                     // If the current altitude is less than the retraction altitude
        airbrakesDeployed = retractAirbrakes();               // Retracts the airbrakes                               // ****NOTE
TO NATHAN FROM NATHAN**** Maybe insert a second or third altitude check to double and triple check the altitude measurements, or
even incorperate a time check as well.
        if (logData == 1) {
          unsigned long retractionTime = millis();
          Serial.print(F("Retraction Time (ms): "));
          Serial.println(retractionTime, DEC);
          Serial.print(F("Pressure (hPa): "));
          Serial.println(P, DEC);
          Serial.print(F("Altitude at Retraction: (ft)"));
          Serial.println(currentAltfeet, DEC);
          Serial.println("");
        }
      blinkVelocity();                                        // Blinks an LED to give a visual indication for post-flight
analysis of the measured velocity used to calculate the deployment altitude
```

```
      }
    }
  }
}
// ---- END Main Loop ----






//-----------------------------------------------------------------------





// ---- BEGIN Altimeter Measurements Function ----
double getPressure(){
  char status;
  double T,P,p0,a;


  // You must first get a temperature measurement to perform a pressure reading.

  // Start a temperature measurement:
  // If request is successful, the number of ms to wait is returned.
  // If request is unsuccessful, 0 is returned.


  status = pressure.startTemperature();
  if (status != 0)
```

```
{
  // Wait for the measurement to complete:


  delay(status);


  // Retrieve the completed temperature measurement:
  // Note that the measurement is stored in the variable T.
  // Use '&T' to provide the address of T to the function.
  // Function returns 1 if successful, 0 if failure.


  status = pressure.getTemperature(T);
  if (status != 0)
  {
    // Start a pressure measurement:
    // The parameter is the oversampling setting, from 0 to 3 (highest res, longest wait).
    // If request is successful, the number of ms to wait is returned.
    // If request is unsuccessful, 0 is returned.


    status = pressure.startPressure(2);
    if (status != 0)
    {
      // Wait for the measurement to complete:
      delay(status);


      // Retrieve the completed pressure measurement:
      // Note that the measurement is stored in the variable P.
      // Use '&P' to provide the address of P.
      // Note also that the function requires the previous temperature measurement (T).
```

```
          // (If temperature is stable, you can do one temperature measurement for a number of pressure measurements.)
          // Function returns 1 if successful, 0 if failure.


          status = pressure.getPressure(P,T);
          if (status != 0)
          {
            return(P);
          }
          else {
            unsigned long errorTime = millis();
            Serial.println(F("error retrieving pressure measurement\n"));
            Serial.print(F("Time of Error (ms):"));
            Serial.println(errorTime,DEC);
            alertBlink();
          }
        }
        else{
          unsigned long errorTime = millis();
          Serial.println("error starting pressure measurement\n");
          Serial.print(F("Time of Error (ms):"));
          Serial.println(errorTime,DEC);
          alertBlink();
        }
      }
      else {
        unsigned long errorTime = millis();
        Serial.println("error retrieving temperature measurement\n");
        Serial.print(F("Time of Error (ms):"));
        Serial.println(errorTime,DEC);
        alertBlink();
      }
    }
```

```
  else {
    unsigned long errorTime = millis();
    Serial.println("error starting temperature measurement\n");
    Serial.print(F("Time of Error (ms):"));
    Serial.println(errorTime,DEC);
    alertBlink();
  }
}


// ---- END Altimeter Measurements Function ----




//------------------------------------------------------------------------




// ---- BEGIN Scale Position Function ----
int scale(int value) {
  return value + 40;
}
// ---- END Scale Position Function ----
```

```
//----------------------------------------------------------------------




// ---- BEGIN Function to Determine Rocket's Velocity ----
void measureRocketMotion(){
  // Altitude Measurement 1
  double P1 = getPressure();                  // Get pressure measurement
  double a1 = pressure.altitude(P1,baseline);  // Calculate altitude (meters) relative to baseline altitude
  unsigned long time1 = millis();             // Measure time of first altitude measurement
  double afeet1 = a1*3.28084;                 // Convert altitude from meters to feet


  delay(50);                                  // 50 millisecond delay to improve accuracy of velocity calculation


  // Altitude Measurement 2
  double P2 = getPressure();                  // Get pressure measurement
  double a2 = pressure.altitude(P2,baseline);  // Calculate altitude (meters) relative to baseline altitude
  unsigned long time2 = millis();             // Measure time of second altitude measurement
  double afeet2 = a2*3.28084;                 // Convert altitude from meters to feet

  unsigned int interval = time2 - time1;      // Calculate time (milliseconds) elapsed between first and second altitude
measurements
  double deltaA = afeet2 - afeet1;            // Calculate the difference between the two altitude measurements
  velocity = deltaA/(interval/1000);          // Calculate the velocity (ft/sec)
```

```
  if (logData == 1) {                            // If the data is to be logged
    Serial.print(F("Measurement 1 Time: "));
    Serial.println(time1, DEC);
    Serial.print(F("Altitude Measurement 1 (ft): "));
    Serial.println(afeet1, DEC);
    Serial.print(F("Measurement 2 Time: "));
    Serial.println(time2, DEC);
    Serial.print(F("Altitude Measurement 2 (ft): "));
    Serial.println(afeet2, DEC);
    Serial.print(F("Calculated Velocity (ft/s): "));
    Serial.println(velocity, DEC);
    Serial.println("");
  }
}
// ---- END Function to Determine Rocket's Velocity ----




//-------------------------------------------------------------------------




// ---- BEGIN Function to Determine When to Deploy the Airbrakes ----
void calculateDeploymentAlt(){
  if (velocity < 650){
    deploymentAlt = 2800;                        // Maximum altitude at which airbreaks will be deployed regardless of velocity
  }
```

```
  else if (velocity > 711){
    deploymentAlt = 1700;                   // Minimum altitude at which airbreaks will be deployed regardless of velocity
  }
  else {
    double tempVal = (velocity - 650);
    int index = (int) tempVal;              // Casts it as an int (rounds to nearest integer)
    if (index > 61){                        // If for some reason the function would be indexing outside of the array
dimensions
      deploymentAlt = 1700;                 // Sets the deployment altitude to the absolute minimum
    }
    else if (index < 0) {                   // If for some reason the function tries to index outside of the array dimensions
      deploymentAlt = 2800;                 // Sets the deployment altitude to the absolute maximum
    }
    else{                                   // If the index is within the array dimensions
      deploymentAlt = altTable[index];      // Finds the deployment altitude that corresponds to the measured velocity
    }
  }
  if (deploymentAlt < 1700)                 // Failsafe to ensure airbrakes will not deploy below minimum altitude
    deploymentAlt = 1700;                   // Altitude below which airbrakes should not be deployed
  if (deploymentAlt > 2800)                 // Failsafe to ensure airbrakes will deploy below maximum altitude
    deploymentAlt = 2800;                   // Altitude by which airbrakes must be deployed
}
// ---- END Function to Determine When to Deploy the Airbrakes ----




//------------------------------------------------------------------------
```

```
// ---- BEGIN Function to Deploy Airbrakes ----
char deployAirbrakes(){
  int pos = scale(DEPLOYEDPOSITION);
  myservo.write(pos);                             // Sets the servo position according to the scaled value
  return 1;
}
// ---- End Function to Deploy Airbrakes ----




//------------------------------------------------------------------------




// ---- BEGIN Function to Retract Airbrakes ----
char retractAirbrakes(){
  int pos = scale(RETRACTEDPOSITION);
  myservo.write(pos);                             // sets the servo position according to the scaled value
  return 0;                                       // 0 indicates airbrakes are now in the retracted position
}
// ---- END Function to Retract Airbrakes ----
```

```
//--------------------------------------------------------------------------

// ---- BEGIN Function to Blink Alert LED ----
void alertBlink(){
    const int BLINKPERIOD = 250;                  // Set period (ms) of the phase of each blink
    //for(int blinks = 0; blinks>100; blinks++){
    digitalWrite(ledPin, LOW);
    delay(BLINKPERIOD);
    digitalWrite(ledPin, HIGH);
    delay(BLINKPERIOD);
    digitalWrite(ledPin, LOW);
    //}
}
// ---- END Function to Blink Alert LED ----

//--------------------------------------------------------------------------
```

```
// ---- BEGIN Function to Blink Velocity LED ----
void blinkVelocity(){
  int v = (int) velocity;                          // Rounds the measured velocity to the nearest integer
  int dig1;                                        // Hundreds place
  int dig2;                                        // Tens place
  int dig3;                                        // Ones place


  dig3 = v % 10;                                   // Finds the digit in the ones place by taking the remainder of v divided by 10
  v = floor(v/10);                                 // Sets v to the value of v divided by 10, rounded down to the nearest int
  dig2 = v % 10;                                   // Finds the digit in the tens place by taking the remainder of v divided by 10
  v = floor(v/10);                                 // Sets v to the value of v divided by 10, rounded down to the nearest int
  dig1 = v;                                        // Finds the digit in the hundreds place by taking the remainder of v divided by
10
  if (dig1 == 0){
    dig1 = 10;                                     // So that LED will blink 10 times in place of a zero digit
  }
  if (dig2 == 0){
    dig2 = 10;                                     // So that LED will blink 10 times in place of a zero digit
  }
  if (dig3 == 0){
    dig3 = 10;                                     // So that LED will blink 10 times in place of a zero digit
  }

  const int onDuration = 500;                      // Time (ms) the led will be on during each blink
  const int offDuration = 500;                     // Time (ms) the led will be off during each blink
  const int betweenDuration = 2000;                // Time (ms) between each digit is indicated

  while (1){                                       // Runs the following loop indefinitely
    for (int i = 0; i <= dig1; i++){               // Loops for appropriate number of times to indicate value of the hundreds place
      digitalWrite(velocityBlinkerLEDPin, HIGH);   // Illuminate the LED
```

```
      delay(onDuration);
      digitalWrite(velocityBlinkerLEDPin, LOW);   // Turn the LED off
      delay(offDuration);
    }
    delay(betweenDuration);


    for  (int i = 0; i <= dig2; i++){            // Loops for appropriate number of times to indicate value of the tens place
      digitalWrite(velocityBlinkerLEDPin, HIGH);  // Illuminate the LED
      delay(onDuration);
      digitalWrite(velocityBlinkerLEDPin, LOW);   // Turn the LED off
      delay(offDuration);
    }
    delay(betweenDuration);


    for (int i = 0; i <= dig3; i++){             // Loops for appropriate number of times to indicate value of the ones place
      digitalWrite(velocityBlinkerLEDPin, HIGH);  // Illuminate the LED
      delay(onDuration);
      digitalWrite(velocityBlinkerLEDPin, LOW);   // Turn the LED off
      delay(offDuration);
    }
    delay(1000);

    digitalWrite(velocityBlinkerLEDPin, HIGH);    // Illuminate the LED
    delay(3000);                                  // Wait for 3 seconds before turning it off to signify end of velocity
indication
    digitalWrite(velocityBlinkerLEDPin, LOW);     // Turn the LED off
    delay(1000);
  }
}
```