Wisconsin Regional Rocket Competition

University of Minnesota Senior Design Team
Team Firepower

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1. Executive Summary

This report describes the details of The University of Minnesota High Powered Rocket Senior Design Team design for the Wisconsin Regional Rocket Competition. The rocket created for the competition has a 4 in. diameter body, is 46 in. long, and weighs 7.5 lbs. The rocket is comprised of three pieces: a forward body, mid body, and aft body. The forward body consists of the nose cone which holds the primary parachute. The mid body contains an avionics bay which contains instruments for recording flight data, including acceleration and velocity vs. altitude and for deploying both the main and drogue parachutes. The aft body of the rocket contains the drogue parachute, the drogue parachute deployment system, the J357 motor, and three fins. The wetted surfaces of the rocket are carbon fiber except for the polypropylene nose cone.

To meet the target altitude of 3000 ft., the rocket will deploy a Kevlar drogue parachute from the aft end of the rocket on ascent near apogee. This fulfills the dual deploy requirement of the competition and provides an air brake to help slow the rocket down to zero vertical velocity at 3000 ft. The drogue parachute will be deployed by an Arduino microprocessor that will dynamically calculate the flight profile of the rocket and will deploy the drogue parachute at the proper altitude. There will also be an Inertial Measurement Unit, a Raven3 altimeter, a Stratologger altimeter, and a competition altimeter onboard. These four modules will all be powered by their own discrete power source to ensure each module will be powered even if another module fails. The primary ejection charge to deploy the drogue parachute on ascent is

controlled by the Arduino. The Raven altimeter will deploy a secondary ejection charge for the drogue parachute at apogee, and the motor backup will be left in place as a third failsafe for the drogue parachute. The primary parachute will be deployed on descent by the Raven Altimeter at 1500 ft., and if necessary a backup deployment charge controlled by the Stratologger altimeter at 700 ft.

To survive the parachute deployment the aft end of the rocket has multiple aluminum pieces. The Finite Element Analysis program ANSYS was used to ensure the rocket would survive the drogue deployment. The flight and stability profile of the rocket was found by using the program RockSim. A MatLab numerical simulator was written, named PebbleSim, to model a parachute deployment on ascent and matched well with the RockSim program. PebbleSim is used to create a table that will be read by the Arduino during flight to deploy the parachute at the correct time to meet the 3000 ft. altitude requirement.

2. Design Features of Rocket

2.1 Design Overview

The rocket has a 4 in. diameter and is 46 inches long. The rocket weighs 7.5 lbs. and will be propelled by a Cesaroni J357 rocket motor. The rocket design incorporates a dual-deployment parachute system. This means two parachutes will be deployed to recover the rocket safely; a smaller drogue parachute will be deployed near apogee, and a larger primary parachute will be deployed during descent. To fulfill the dynamic measurement requirements, an avionics bay onboard the rocket contains two altimeters, an Inertial Measurement Unit (IMU), and an Arduino microprocessor. To achieve the target altitude the drogue parachute will be deployed out of the aft end of the rocket on ascent near apogee, acting as an airbrake. The main parachute is located in the nose cone and will be deployed during descent.

2.2 Additional Objectives of Design

Our design objectives went beyond the requirements of the competition. These objectives are: to achieve zero velocity within fifty feet of the target altitude of 3000 ft.; to design an accurate simulation model; to incorporate a recovery system that is redundant to ensure parachute deployment; and to be able to recover the rocket in a re-flyable condition with the drogue parachute alone.

2.3 Rocket Body

The rocket body consists of a nose cone, a mid body, an aft body, and three fins. The nose cone houses the primary parachute, the mid body contains the avionics bay, and the aft body houses the drogue parachute and the ejection system. The mid body, aft body, and fins are constructed from carbon fiber because of its high strength and low weight.

2.4 Forward Body

The nose cone is standard polypropylene plastic which is inexpensive and structurally sufficient for the loads the nose cone will experience. The nose cone was modified by removing the enclosed aft end of the nose cone which gave access to the space inside for the primary parachute. The main parachute is made from a standard nylon material with a diameter of 48 in. This size was chosen to result in a safe descent rate for recovery. A pine bulkhead is installed mid-way up the nose cone and the parachute shock cord is directly attached to it.

There are two deployment charges configured to deploy the main parachute. The first will be triggered by the onboard Raven altimeter when the rocket descends to an altitude of 1500 ft. after apogee. A second charge will be ignited by the Stratologger altimeter when the rocket descends to 700 ft., acting as a backup to the first charge.

2.5 Mid Body

The wetted surface of the mid-body is a carbon fiber tube. The mid-body houses the avionics bay and its instrumentation, which is described below.

2.5.1 Avionics Bay

The onboard avionics system is used to measure altitude, acceleration, and velocity as well as to activate the Pyrodex charges used to deploy the parachute. The competition requirement for a dual-deploy parachute recovery system led to the use of redundant ejection systems. The main parachute is deployed by two discrete onboard altimeters, a Raven3 and a Stratologger. The Raven3 is the primary altimeter and is widely used in rocketry because of its reliability. The Stratologger is the secondary altimeter and was chosen because of its low cost. The Raven is the primary instrument used to deploy the main chute at 1500 ft. while the Stratologger is a backup for the main and is set to go off at 700 ft. Using multiple altimeters which are each powered by an independent 9V battery; introducing redundancy against an altimeter or motor eject failure. The four independently powered sub-systems are: the Raven altimeter, the Stratologger altimeter, the IMU/microprocessor, and the competition Raven altimeter. Each sub-system has a separate power switch and the ability to give an audible indication when it has become operational on the launch pad. These can be seen in Figure 1.

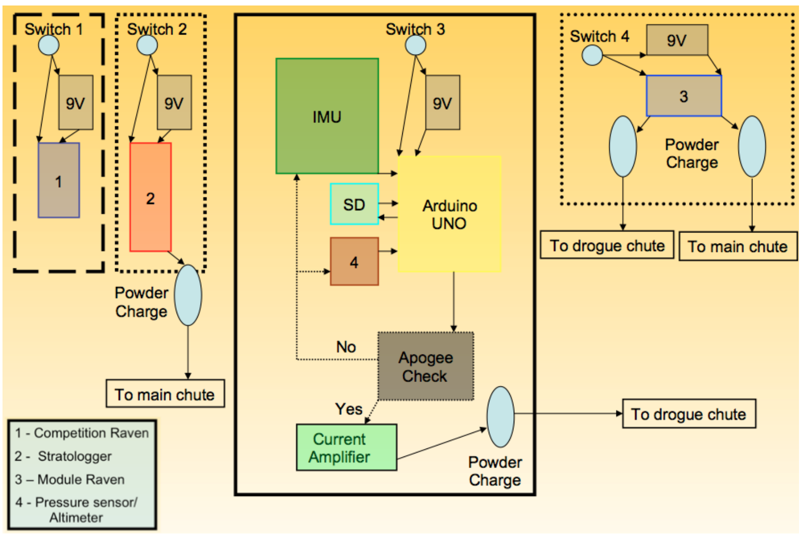

Figure 1 The four independently powered modules comprising the Avionics System and the ejection charge each instrument controls.

The drogue parachute will be deployed using a digital signal sent from the Arduino microprocessor. In order to make the Arduino's digital output signal strong enough to ignite an e-match the signal controls a transistor-switch. When switched this transistor allows current from a 9V battery to flow to the e-match. In the event that the Arduino's digital output signal or transistor-switch fails, the Raven altimeter is programmed to deploy the drogue parachute at apogee.

Each deployment charge is configured to be triggered by a separate unit that has its own power source; the first of the fabricated charges will be ignited by the Arduino microcontroller unit's altitude lookup system. This deployment will be performed in order to slow the rocket to achieve the target altitude as closely as possible. A redundant charge will be fired by the Raven altimeter upon apogee and the motor backup charge will be kept intact to be ignited as another drogue failsafe measure. In the event that the first charge performs its function, the secondary and tertiary charges will vent harmlessly out of the rocket as the parachute chamber will be open to the atmosphere. The redundant nature of the deployment scheme is designed to prevent any single circuit failure from disrupting the safe recovery of the rocket. Figure 2 shows a summary of the profile of deployment charge detonations that will be triggered by the various electronics on board.

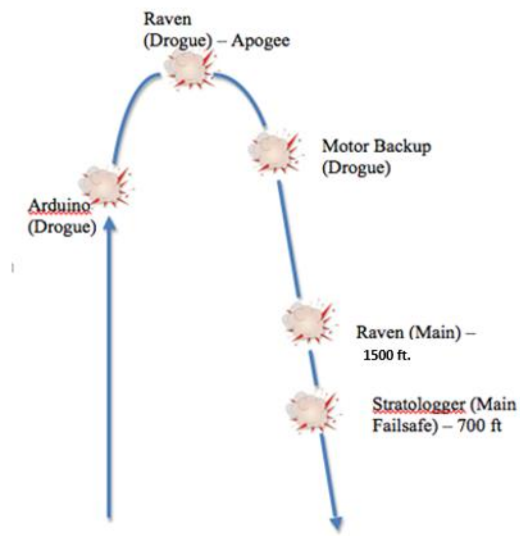

Figure 2 This shows an overview of the ejection charges that will be ignited during flight.

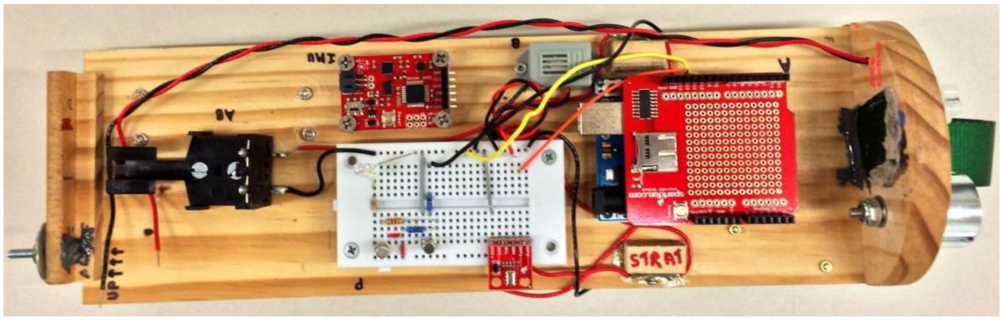

Figure 3 The front face of the avionics bay is shown which features the bulk of the circuitry, most prominently the Arduino and SD shield on the right.

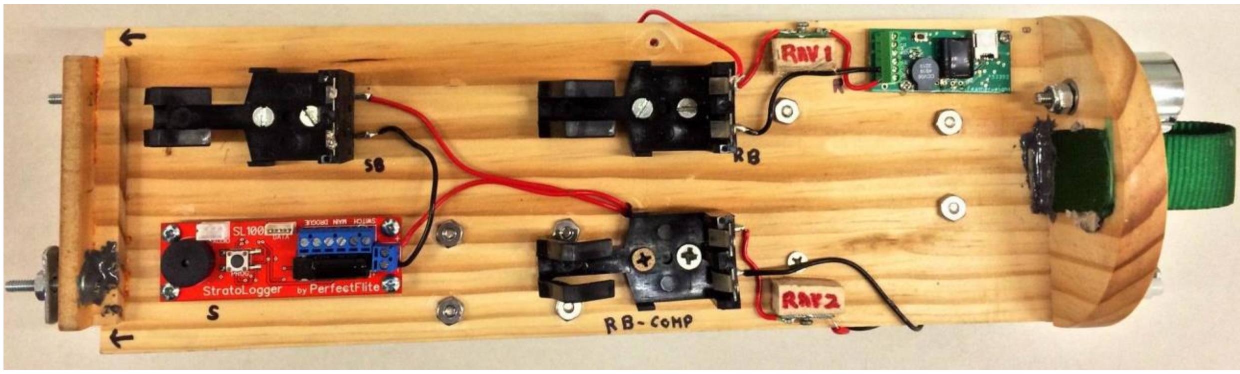

Figure 4 The back face of the avionics bay is displayed here, showing the Stratologger sensor on the left as well as a pair of rocketry-grade 9-volt battery holders. The contacts on the battery holders are oriented downward so acceleration at takeoff acts to maintain contact between the battery and the holder.

2.5.2 Individual Components

As per competition requirements, acceleration and velocity will be reported as functions of altitude by more than one method. To accomplish this a microprocessor (Arduino UNO), altimeters, pressure sensor, SD shield, and an Inertial Measurement Unit (IMU) are used to measure and record data. The Arduino Uno is capable of processing and storing altitude data from our pressure sensor as well as logging data from the IMU. By measuring altitude over time we measure and log vertical velocity with the Arduino and pressure sensor. Another method to measure these parameters is to directly use the IMU. The IMU has its own processor which is used to record acceleration, to place a filter over its gyro, accelerometer, and magnetometer readings in order to provide accurate orientation data, and to interface with the Arduino via a serial connection.

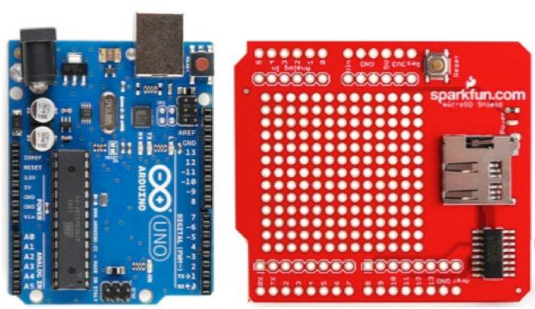

Figure 5 Here are shown the Arduino UNO microprocessor unit (left) and its accompanying SD shield (right). The Arduino is responsible for altitude calculations, drogue brake deployment decisions, and recording measurements from the inertial measurement unit.

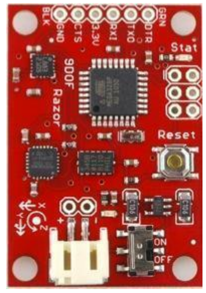

Figure 6 The Razor inertial measurement unit (IMU) is used to measure inertial acceleration and rocket orientation.

Figure 7 The pressure sensor gathers atmospheric data which is used to determine altitude and vertical velocity.

A further method of measuring data is the onboard Raven altimeter, shown in Figure 8. Acceleration, velocity, altitude and other flight data is recorded during the flight and is available upon recovery.

Figure 8 The Raven3 Altimeter used in drogue and main deployment as well as data recording.

Figure 9 The Stratologger Altimeter used in secondary main deployment as well as data recording.

The Arduino microprocessor is the main method used to deploy the drogue parachute on ascent to act as a brake. On ascent the Arduino processes data from the on-board sensors and reads from and writes to a micro SD card. Preloaded on the SD card is a table with values corresponding to altitudes, vertical velocity, and pitch angles. The Arduino continuously checks this table during ascent until a deployment criteria is met. This process allows the Arduino to dynamically determine when to deploy the drogue parachute on ascent to achieve the target altitude. To prevent the Arduino from becoming computationally overwhelmed during the flight, the IMU will also perform computations, including acceleration/velocity and attitude angles.

2.5.3 Retrieval

Because the projected altitude of the rocket is only 3000 ft. visual contact will be maintained throughout the flight and a more intensive retrieval system, such as GPS, is not necessary. Immediately prior to launch the RockSim program will be used to predict a general landing area based on the weight and engine of the rocket, as well as wind and other real-time atmospheric data. This prediction will significantly reduce landing area uncertainty. Additionally, an audible siren is mounted to the inside of the body tube with the trigger attached to the nose cone as shown in Figure 10. When the nose cone separates upon deployment of the main parachute, the trigger will be removed and the siren will engage. This will help audibly track the rocket as it descends and precisely locate its position once it is on the ground, in the event that it is not immediately visible.

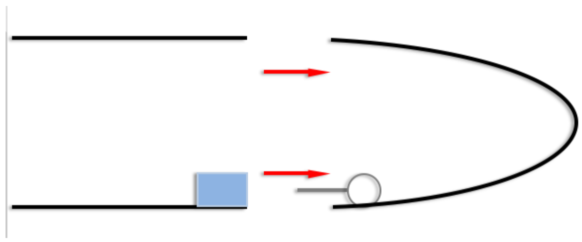

Figure 10 This schematic shows the siren mounted to engage when the nose cone detaches.

2.6 Aft Body

The wetted surface of the aft end of the rocket is the aft carbon fiber body tube and the three carbon fiber fins. The aft body contains the drogue parachute deployment system and the motor. This system is designed to eject the drogue parachute out the aft end of the rocket so the fully deployed parachute will be trailing directly behind the rocket. This system is used because the method of deployment is reliable enough to guarantee the drogue parachute deployment contributing to a safe recovery. To attach the parachute, shock cord was wrapped around the four 6061-T6 aluminum, threaded through the piston and tied to the drogue parachute. The parachute is loaded into the aft end of the rocket and is wrapped around the motor casing. A piston is placed above the loaded parachute to provide protection and to push the parachute out of the parachute tube. Above this piston mounted on the avionics bay bottom bulkhead are the ejection charge holders which when ignited will provide a big enough pressure difference to push out the piston along with the parachute. The exact time of the drogue parachute deployment is determined by PebbleSim. To prevent the parachute from being deployed to early on ascent due to liftoff, a 3D printed plastic bulkhead, with a metal outer ring was attached by shear pins underneath the parachute. These shear pins will then break by the force exerted on them from the ejection charges. The parachute deployment system can be seen in Figure (11).

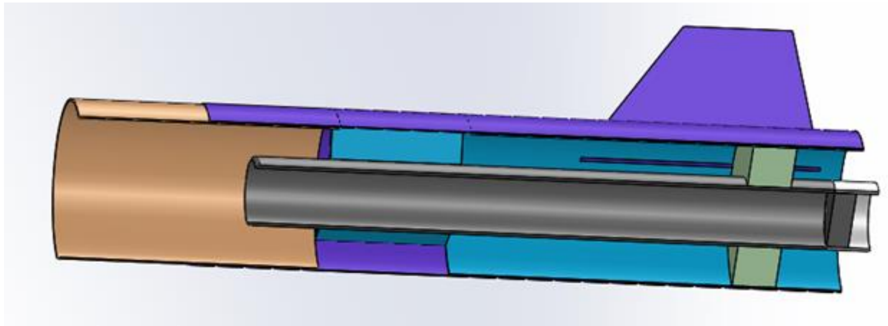

Figure 11 Cutaway model developed in SolidWorks of deployment system in the aft end of the rocket.

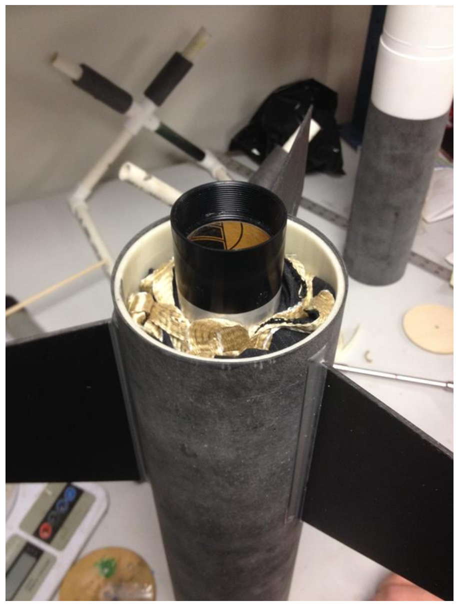

Figure 12 Image of completed parachute deployments system with drogue parachute loaded.

2.6.1 Drogue Parachute Deployment System

Using a drogue parachute as a brake offers several advantages: first, this method is reactive and allows compensation for motor variability as well as unexpected wind effects and has the advantage over methods such as altering the weight, static margin, or drag on the ground. Furthermore, parachute deployment systems are very well understood and mechanically simpler than other reactive methods such as mechanically actuated air brakes. Another advantage of the large area of the parachute is that a significant amount of control can be exerted over the rocket later in the flight. Therefore, less of the flight profile needs to be predicted, and the 'decision point' for deployment can be moved to later in the flight when the rocket is moving slower and there is more time to measure and process its state. Finally the drogue parachute doubles as a means of recovery.

Using a parachute to decelerate a rocket down results in large forces on the parachute upon deployment. Furthermore the proximity of the drogue to the motor leads to thermal concerns. It was determined that, in order to serve both purposes effectively and safely, the drogue parachute material should be Kevlar and the diameter should be 36 in. with a 5 in. spill hole. This diameter was chosen to give enough control authority to slow the rocket without exceeding the strength limit of the Kevlar. Thermal effects on the drogue parachute were also analyzed. Kevlar has higher thermal limits than nylon and degrades far more gracefully when these limits are exceeded. The motor case temperature for the J357 motor should not exceed 150F. At this temperature Kevlar retains over 95% of its strength. Another modification made to the rocket to prevent drogue from overheating was to allow a space between the motor tube and the aluminum housing which is in contact with the parachute. This gap provides insulation to prevent the drogue from experiencing heat from the motor. The motor chosen reduces the thermal effects on the drogue. The relatively short burn time of the motor means the motor will be extinguished long before the parachute is deployed behind the rocket.

Two other deployment system components of the aft end are the motor tube and motor retainer. While the motor in most amateur high power rockets is anchored to the body tube by bulkheads at either end, our design requires a way to allow the parachute to be mounted around the motor. This necessitates the use of an aluminum motor mount tube instead of the traditional phenolic because of the strength needed to hold the motor in place during ascent. The motor retainer also needs to allow the parachute to slide along the length of the motor tube for deployment. A commercial motor retainer that would allow the parachute to slide on its intended path was found – this retainer has the threads on the inside, compared to other high power rocketry motor retainers featuring threads on the outside of the tube. These two pieces shown in Figure 13 allowed for a smooth surface for the parachute to slide along while holding the motor securely in place.

Figure 13 38mm motor tube. The aluminum sleeve surrounding the motor tube was custom manufactured by J.R. Williams Co., Inc.

On most amateur high power rockets the fins are slotted into the body tube and are anchored against the motor mount tube. This standard design would have interfered with the parachute deployment. One solution would be to have the fins anchored onto the outside of the lower body tube, but it was believed that this did not provide sufficient strength to survive a non-ideal landing. This led to the internal-slotting parachute tube design shown below.

Figure 14 Inner sleeve of the aft body, showing slots for anchoring the fins.

With this design, the fins could partially protrude inside the rocket, thus adding structural support while allowing the parachute to slide out of the rocket. The material for this piece was chosen to be 3D printed ABS plastic for several reasons. The first reason was the cost of fabricating the component from aluminum. The second reason for the material choice was that ABS 3D printed plastic would retain a significant value of structural strength while limiting the weight penalty.

3. Analysis of Anticipated Performance

3.1 Stability

To understand the stability of a rocket the locations of the center of gravity and the center of pressure must be known. As the rocket flies through the air, the velocity of the air flowing over the rocket surface varies. This variation in velocity also creates a variation in pressure along the body. The aerodynamic forces acting on the body of the rocket can then be determined by integrating this pressure over the surface area. These aerodynamic forces can be resulted into a force acting on a single point called the center of pressure. The center of gravity of the rocket is located at the point of action of the total weight of the rocket. This is the point about which any rotation occurs. As the rocket ascends with the motor burning, the rocket is shedding mass and therefore changing its center of gravity. The more mass the rocket engine burns, the farther forward the center of gravity will move. Thus it is necessary to find the center of gravity before and after motor burnout. A good measure of how stable the rocket will be during flight can be found by analyzing the location of the center of gravity with respect to the center of pressure.

For a rocket to be stable the center of gravity must be located forward of the center of pressure. The static margin, measured in calibers, is the distance between the center of gravity and center of pressure divided by the diameter of the body tube. If the body tube diameter varies it is safest to take the largest diameter present in the body tube. Generally, it is desired to have a static margin between 1 and 2 calibers. Anything higher than 2 will cause the rocket to be highly stable and turn too far into the wind, or windcock. This can cause early deployment of parachutes and may not allow the rocket to reach the desired altitude. Anything lower than 1 will cause the rocket to be unstable during flight.

The center of pressure is located at 36.5 inches from the rocket nose. The center of gravity with a fully loaded rocket motor is located 31.2 inches from the front end of the rocket giving the rocket a stability margin of 1.28 calibers. After motor-burnout the center of gravity is located at 30.3 inches from the nose giving the rocket a stability margin of 1.49 calibers. Furthermore our speed of the launch rail is predicted to be 67.4 ft/s which is sufficient for stable flight. Thus the rocket will be stable from motor ignition through glide.

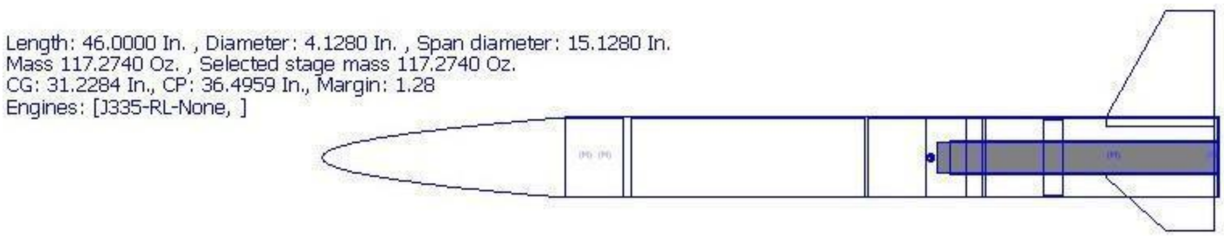

Figure 15 Schematic of rocket with engine loaded before burnout obtained from RockSim.

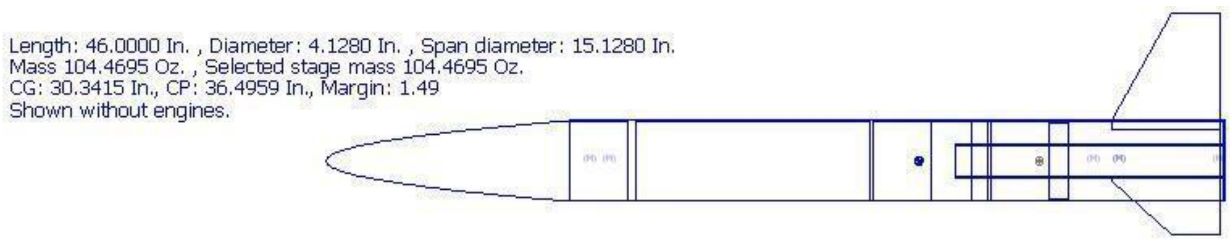

Figure 16 Schematic of rocket with engine loaded after burnout obtained by adding a mass object equal to the weight of the burnt out motor to the RockSim model.

3.2 Flight Analysis

Using RockSim we were able to simulate the flight if the drogue parachute does not deploy as well as to update our own simulator, PebbleSim, to simulate flight with drogue deployment. The values below are from RockSim while the motor is burning and thereafter obtained via PebbleSim. Without drogue deployment RockSim predicts an apogee of 3608 ft., maximum acceleration of 383 ft/s^2, and a launch guide velocity of 67.4 ft/s. These values were taken from a RockSim simulation with no wind and a J335-RL motor, comparable to the J357 motor we will be using in the competition.

We have calculated a descent rate of 31.2 ft/s under drogue only and 26.9 ft/s under main only. Because we will expect both parachutes to deploy our actual descent rate will be much less than these values.

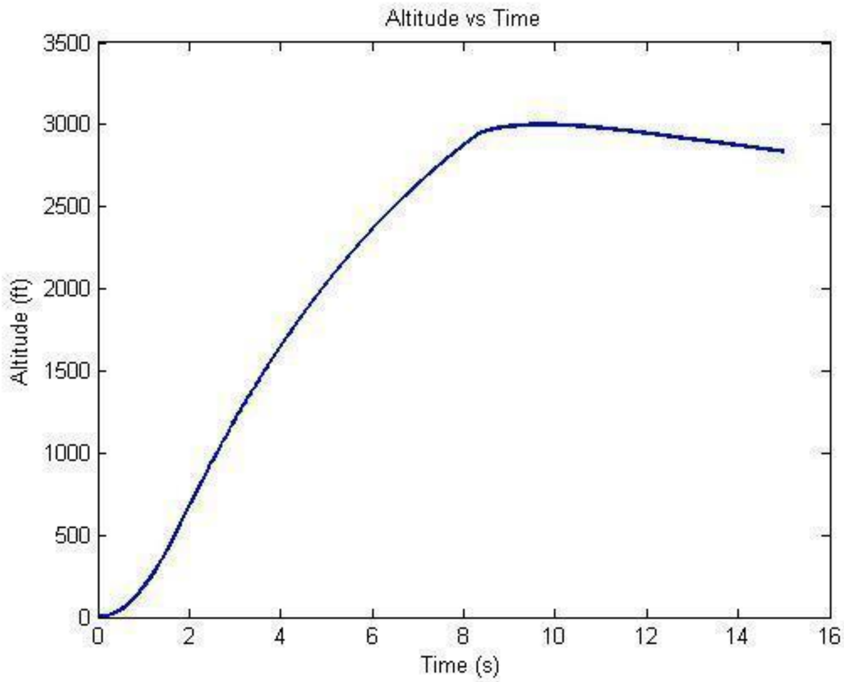

Figure 17 The expected altitude over time for a launch with 5 miles per hour wind speed and the beginning of a drogue only descent. During motor burn RockSim was used to compute values. Thereafter the state of the rocket was entered into PebbleSim which completed the simulation.

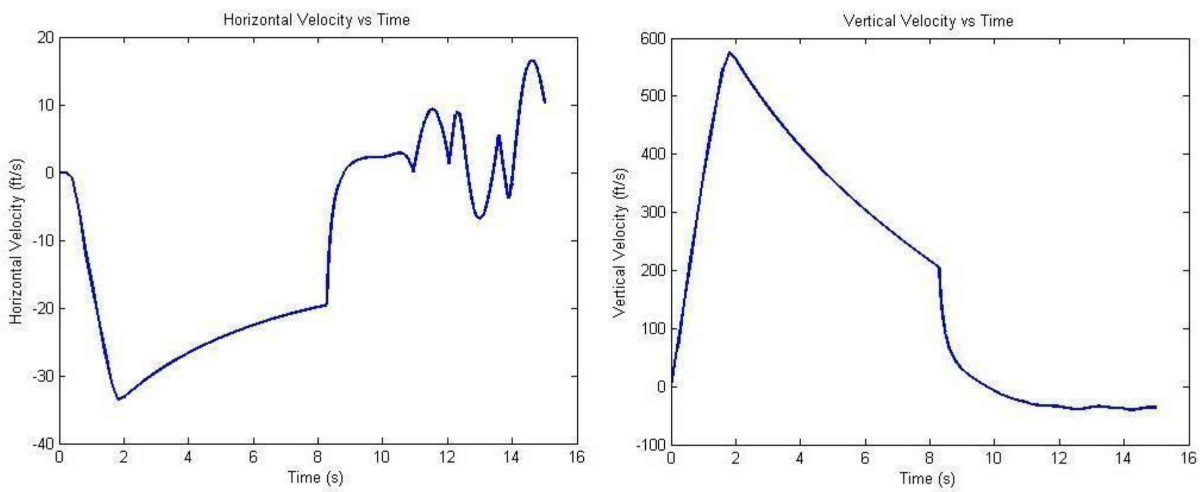

Figure 18 The expected velocities as a function of time. The values are for the same flight and computed in the same way as in Figure 17. During the first 1.9 seconds the motor is burning and we observe rapid acceleration. After burnout the rocket decelerates and the drogue deployment quickly brings the vertical motion to a halt. During descent the vertical velocity oscillates around 37 ft/s.

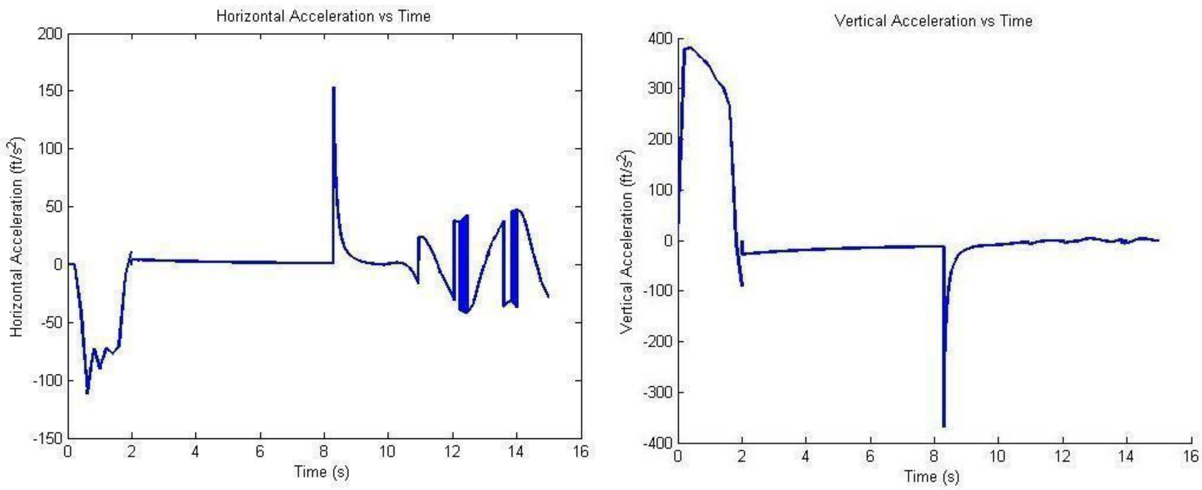

Figure 19 The expected vertical accelerations as a function of time. The values are for the same flight and computed in the same way as in Figure 17. We observe spikes in acceleration during motor burn and when the drogue parachute brakes the rocket to stop at 3000 feet. There are also oscillations during descent as the rocket rocks back and forth.

3.3 Structural Analysis

The survivability of the rocket upon drogue deployment is vital to the success of the overall design. To confirm the structural integrity of the rocket during the drogue event of the flight the Finite Element Analysis program ANSYS was used for stress analysis. In order to satisfy the design objectives, the structure of the rocket needs to be able to survive an ultimate load test case. The conditions of this ultimate load case include zero wind and a plus-ten-percent rocket motor. Using these maximum conditions, PebbleSim calculated an ultimate load of 1070 N which we increased by 10% to 1200 N. This ultimate load can be applied in a number of different load distributions to the interior spars, where the drogue is attached. The ANSYS analysis discussed below focuses on the two extreme load cases: (1) a symmetric drogue release with 300 N applied to each of the four interior spars, and (2) an asymmetric drogue release with 1200 N applied to only one spar.

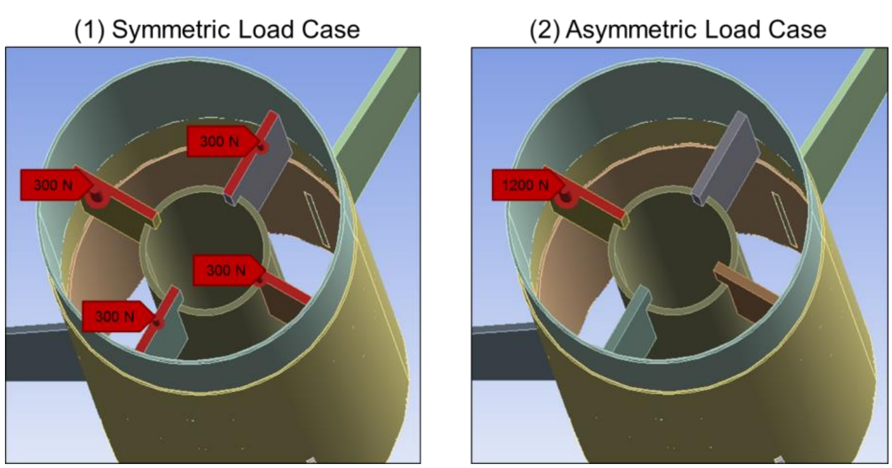

Figure 20 ANSYS load conditions for symmetric and asymmetric ultimate load subcases.

The simulations conducted on each of the above load cases achieved distinct values for maximum shear and principal stresses and values for total model deformation. These values are shown below in Table 1.

	Symmetric Load	Asymmetric Load
Maximum Shear Stress (psi)	1210.4	2995.3
Maximum Principal Stress (psi)	1931.7	4389.7
Total Deformation (in.)	0.0005	0.0029

Table 1 Maximum stresses and deformations achieved during ultimate load case simulations.

The values achieved for total deformation are negligible in comparison to the size of the parts and rocket assembly. The stresses, however, are examined more closely. The shear stress exerted on each of the spars is the stress most relevant to the drogue deployment event. This is because in an ideal case, the drogue cords will exert a load of pure tension on the spars. Shown below in Figure 21, the maximum shear stress in both the symmetric and asymmetric load cases occurs on the outer corner of the top surface of the spars.

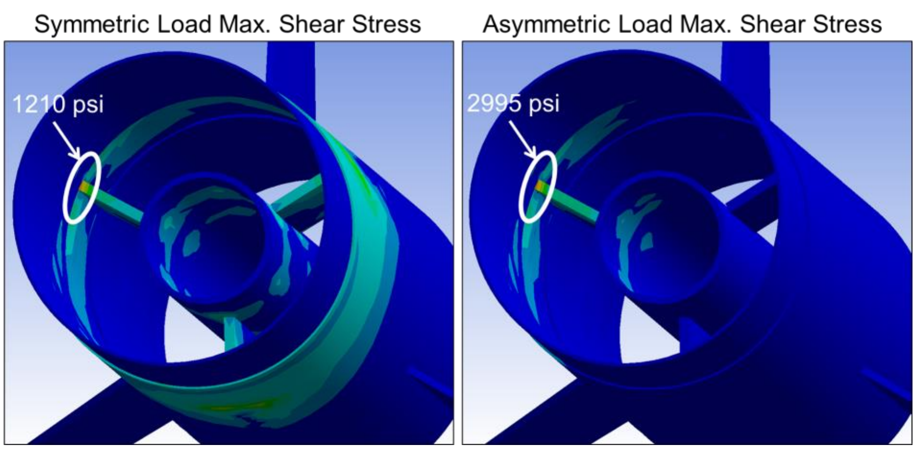

Figure 21 Maximum shear stresses achieved during the ultimate load cases.

The four spars and the epoxy that connects them from the motor tube to the body tube undergo shear stress from the tensile load of the drogue cords and compressive stress from any resultant bending. The highest stresses exerted on each of these materials was compared to the respective material strengths, and a safety factor was calculated by dividing the material strength by the design load. Table 2 below tabulates these resultant safety factors.

	Material Strength (psi)		Maximum Stress Measured in Analysis (psi)		Safety Factors	
	Al 6061-T6	**Epoxy**	**Al 6061-T6**	**Epoxy**	**Al 6061-T6**	**Epoxy**
Compressive	25,000	11,500	4390	1492	**5.7**	**7.7**
Shear	30,000	7,300	4390	1997	**6.8**	**3.7**

Table 2 Safety factors of aluminum spars and epoxied areas. Stress values measured in ultimate load case.

Typical safety factors in the aerospace industry range from 1.25 (landing gear on aircraft) to 2.0 (fuselage pressure). One of the main design objectives of this rocket, however, is structural integrity. As a result, the higher-than-average safety factors – particularly for the aluminum – obtained from the ultimate load case serve to accomplish this goal. Furthermore, the high safety factors validate the structural design of the rocket and verifies its survivability during drogue deployment

3.4 Software Simulation

There were no existing equations or simulation software available to predict apogee with the drogue parachute deployed. Therefore, a 2D MATLAB numerical simulator was developed and named PebbleSim, as a smaller version of RockSim. PebbleSim allowed the drogue parachute force to be added on top of the other forces due to wind or drag. Figure 22 shows the scope of the dynamics included in PebbleSim. The parachute is modeled as an axial drag force until upcoming flight testing confirms or refutes this assumption. The dynamic equations were taken from [1] and [2] and were integrated into one simulator. See Appendix 1 for the force and moment equations used.

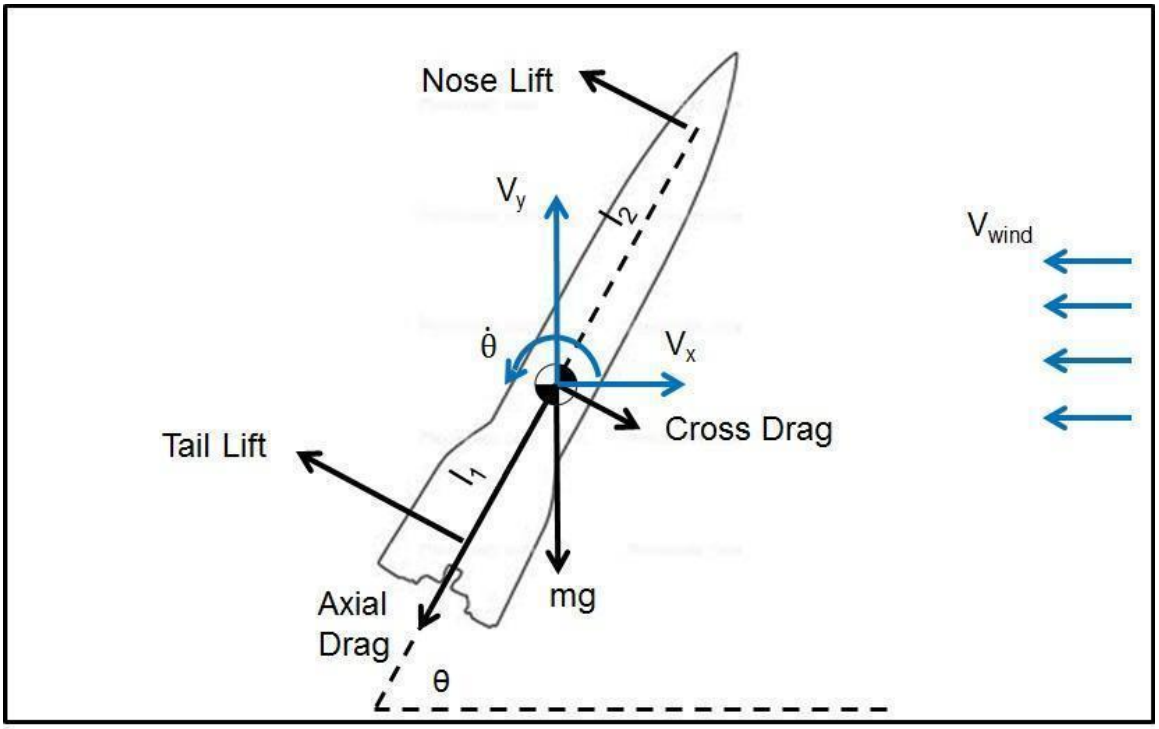

Figure 22 Schematic showing the variables accounted for in our MATLAB simulator, PebbleSim. The damping moment and the parachute drag force are both accounted for but not pictured for clarity.

Given an altitude, vertical velocity, and pitch angle, PebbleSim answers the question "What will the apogee and maximum force on the drogue parachute be if the command to deploy is sent when the rocket is at this state?" A MATLAB script is used to run simulations over the range of altitudes, vertical velocities, and pitch angles expected around the time of drogue deployment. Based on the returned apogee and maximum parachute force, the MATLAB code then decides whether to send the command to deploy the parachute at the current state. This decision is recorded in a text file on an SD card. From here, the SD card is loaded into the SD shield and read into the Arduino internal memory on the Launchpad. During flight, the Arduino looks up the decision corresponding to the rocket's current altitude, velocity, and pitch angle. If the decision is a yes, the Arduino sets a digital pin high. This pin is connected through a current amplification circuit to an E-match and charge near the drogue chute. Thus when the pin goes high, current is passed through the E-match and the drogue chute is deployed.

The PebbleSim simulator was verified using RockSim and flight data from a ¼-scale Patriot kit rocket. A RockSim model of the Patriot Kit was created and verified post-flight using data from a Raven altimeter. The RockSim simulations were then compared to PebbleSim (without drogue parachute deployment) making sure to use the same mass, rocket drag coefficient and area, center of gravity and pressure locations, and moment of inertia in both programs. The rocket's lift coefficient was computed using equations in [2]. Several RockSim simulations were run with different constant cross-wind speeds and with the input of a rocket's velocity. The rocket's state was taken from in RockSim just after motor burnout and PebbleSim was subsequently run with these inputs. The results are shown in Table 3, which displays very accurate results.

Wind Speed (mph)	RockSim Apogee (ft.)	PebbleSim Apogee (ft.)	Target Drogue Deployment Altitude (ft.)
0	3260	3257	2943
5	3249	3247	2945
10	3216	3214	2950
15	3161	3153	2961
20	3084	3071	2976

Table 3 This is a comparison between PebbleSim Apogee and RockSim simulations for a practice Patriot kit rocket. The values were obtained by taking the RockSim state just after burnout and inputting these values into PebbleSim. Exceptional agreement is shown with one possible source of error being the air density. The RockSim air density model was never obtained and thus PebbleSim has a slightly higher density and consequently slightly greater drag at higher altitudes. Additionally through trial and error the required drogue deployment altitude was obtained, showing our intent to have control late into the flight while also minimizing how accurate our models needed to be.

Unfortunately the dynamic effects of deploying the parachute have not been determined as such techniques are non-traditional and undocumented. This behavior was set to be studied with a prototype launch in February, but the flight failed due to catastrophic motor failure on takeoff. Based on ejection tests, a smooth parachute deployment that is symmetric about the rocket's axis is planned, so no violent pitching after drogue deployment is expected.

We repeated the PebbleSim and RockSim simulation for our competition rocket. The results are shown in Table 4 and will be validated during a test flight.

Wind Speed (mph)	RockSim Apogee (ft.)	PebbleSim Apogee (ft.)	Target Drogue Deployment Altitude (ft.)	Max Parachute Force (N)
0	3550.1	3539.9	2934	1069.6
3	3546.0	3535.7	2935	1065.8
8	3520.0	3508.6	2937	1049.7
15	3441.90	3424.4	2944	996.5
20	3357.7	3334.2	2952	934.7

Table 4 A comparison between RockSim and PebbleSim predicted apogees. We observe suitably good agreement between the two. Furthermore the deployment altitude required to reach 3000 feet is shown with the maximum expected parachute force computed using drag.

4. Ground Procedures

In addition to undergoing a preflight safety inspection and working with a Range Safety Officer, we have developed our own ground procedures to ensure successful flight and safety of team members.

Prior to the day of the launch, we will have calculated the required size of ejection charge through calculations and ejection testing on the ground. Furthermore all SD deployment tables will be computed using PebbleSim for all expected wind conditions prior to the day of the launch.

On the day of the launch, the team will step through a checklist to ensure we are bringing all the required parts and tools. At the launch site we will place all materials in one location before beginning to assemble the rocket. Ejection charges will be measured to the pre-determined amount, placed in the tip of a rubber glove with an e-match, and wired to the deployment systems after verifying they are turned off. The avionics bay will then be inserted into the mid body and wired to the fore ejection charges. From here the parachutes will be packed and the nose, mid body, and aft body sections mated and attached with rivets or shear pins as appropriate. We will then submit to a preflight safety inspection.

Several members of the team will then proceed to the launch pad with an RSO. The rocket will be mounted on the launch rail and raised into the vertical position. The electronic systems will then be turned on via screw switches accessible through the static ports, beginning with the Arduino and continuing on through the altimeters. Team members will listen for audible signals that each component is powered on before turning on the next. After all electronic systems are turned on the motor igniter will be inserted and tested for continuity and the launch pad will be cleared.

The rocket will then be launched by the RSO. During flight all team members are expected to observe the rocket and count ejection charge detonations. The detonations are set such that they will be separate in time and therefore able to be counted. The team will then wait for the rocket to reach the ground before approaching the landing zone.

If all ejection charges have not been deployed, only team members wearing face and hand protection will be allowed to approach the rocket. Their first priority will be to remove all chance of detonation through cutting e-match wires, where accessible, and turning of screw switches.

When the rocket is safe it will first be visually inspected and photographed before being touched. After the rocket has been documented, the team will approach the rocket and turn off the electronics bay. We will then bring the rocket components back to our point of assembly and continue the visual inspection. The avionics bay will then be removed and all data will be saved to a computer. The data will then be analyzed for any anomalies and we will continue to the recovery check-in.

If desired and time permits we will analyze the data, make changes to the electronics or SD deployment table to achieve a better flight, and re-fly the rocket following the same procedure.

5. Construction of Rocket

Figure 23 Team members inspect epoxy on the avionics bay and ensure the motor tube is centered while the epoxy dries.

For the construction of the rocket a step by step plan was outlined to ensure proper assembly. Some pieces had to be inserted before others due to size and the order of application of the epoxy. We chose JB Weld Epoxy for its strength and its tendency to not drip after application. This ease of use led to smoother epoxy edges. Painting tape was used to make an outline for the application of the epoxy. For example for each fin we surrounded the fin with painter tape leaving enough space to allow a fillet that will provide the least amount of drag. Since we used JB Weld we could remove the tape within an hour and not have the epoxy run leaving a nice clean edge which can be seen below.

Figure 24 An example of a fin fillet epoxied with painter tape to form a clean edge.

Instead of painting and leaving a matte finish on the rocket. We choose to do a clear coat to provide a smooth finish to cut back on the drag. It also brings out the natural aesthetics of the carbon fiber. Because the carbon fiber arrived with a milled outer surface from Public Missiles, we had to sand the outer surface to provide a smooth surface to reduce drag and provide a good surface for the paint to adhere. 320 grit sandpaper, followed by 600 grit wet sandpaper was used. We used wet sandpaper because it filters out the removed material, otherwise it clogs the grains of the paper and inhibits the ability of the sandpaper to function.

Several custom parts were created using the University of Minnesota's Mechanical Engineering Department 3D-Printing services. These parts were modeled in SolidWorks, printed, and sanded to remove surface defects and correct any size errors. It should be noted that these parts were made of ABS plastic which is rated to 174 F and will therefore not be damaged by the motor temperature.

Figure 25 The 3D printed drogue piston showing build quality able to be achieved using 3D printing.

Safety was paramount while we were building and testing our rocket. During construction we made sure to always wear gloves and masks while applying epoxy and the clear coat paint. Along with the gloves and paint, safety goggles were worn during any cutting of metals, and sanding either wood, plastic, or the carbon fiber body tube. During ejection testing, proper protective gear was worn personnel were kept a safe distance from the rocket. During test launches out at North Branch, all the Tripoli rules and regulations were followed rigorously.

6. Completed Rocket

Figure 26 The aft end of the rocket shown next to a spare section of body tube we tested the clear coat on. We are still in the process of clear-coating the rocket body but expect a smooth, shiny finish which brings out the carbon fiber weave.

Figure 27 The completed rocket without clear-coating on the body tube and silver paint on the nose cone.

7. Conclusion

The University of Minnesota High Powered Rocket Senior Design Team has built a rocket to compete in the Wisconsin Regional Rocket Competition. The rocket is 46 in. long, weighs 119 oz., and has a 4 inch body tube. The fins and the body tube were constructed out of carbon fiber for its high strength and low weight and the nose cone is standard polypropylene. To succeed in the competition our avionics bay contains two altimeters, a microprocessor, pressure sensor, and an IMU. These instruments provide multiple methods to measure velocity and acceleration vs. altitude, meeting that requirement of the competition. The avionics will also ignite the ejection charges to deploy the parachutes. The drogue parachute will be deployed on accent near apogee to slow the rocket to zero velocity at the target altitude of 3000 ft., which fulfills the target altitude portion of the competition. Flight, structural, and thermal analysis were completed to ensure the integrity of the rocket for a successful flight. The University of Minnesota Senior Design Team is confident in our design and are looking forward to having a successful competitive flight during the competition.

8. Budget

Date	Design Teams	Name	Item	Total Amount
09/23/2013	Philip DiSalvo_Rocket Team	Featherweight Altimeters	Raven Altimeter	**165.00**
09/23/2013	Philip DiSalvo_Rocket Team	Off We Go Rocketry	Patriot Kit Rocket	**193.92**
11/01/2013	Philip DiSalvo_Rocket Team	UPS	Shipping	**13.27**
02/11/2014	Philip DiSalvo_Rocket Team	Sparkfun	Avionics Components	**212.15**
02/11/2014	Philip DiSalvo_Rocket Team	PerfectFlite	Stratologger Altimeter	**76.18**
02/19/2014	Philip DiSalvo_Rocket Team	Giant Leap Rocketry	Motor Retainer	**41.93**
03/14/2014	Philip DiSalvo_Rocket Team	Apogee Components	Coupler Tube	**36.09**
03/14/2014	Philip DiSalvo_Rocket Team	Sparkfun	Avionics Accessories	**18.82**
03/18/2014	Philip DiSalvo_Rocket Team	Off We Go Rocketry	Rocket Accessories	**12.47**
03/18/2014	Philip DiSalvo_Rocket Team	Public Missiles LTD	Carbon Fiber	**283.10**
03/19/2014	Philip DiSalvo_Rocket Team	Featherweight Altimeters	Switches	**30.00**
03/26/2014	Philip DiSalvo_Rocket Team	Off We Go Rocketry	Rocket Accessories	**111.90**
04/02/2014	Philip DiSalvo_Rocket Team	Off We Go Rocketry	Rocket Accessories	**119.59**
02/10/2014	Philip DiSalvo_Rocket Team		Rocket Accessories	**80.00**
04/02/2014	Philip DiSalvo_Rocket Team		Rocket Accessories	**80.00**
04/03/2014	Philip DiSalvo_Rocket Team	J.R. Williams Co., Inc.	Fabricated Aluminum	**161.66**
				$1,636.08

Appendix 1

The PebbleSim force and moment equations are shown below. For these equations pitch angle is defined from the ground up such that a rocket traveling straight up would be at a pitch of 90°. Equations 2 through 4 act in the axial direction. The drag coefficient of the rocket was estimated as 0.35 using RockSim while the parachute drag coefficient was estimated to be 0.75 as this value was widely cited. The forces in the normal direction are calculated according to Equations 5 through 8. These forces are due to the lift of the nose and fins, gravitational force, and drag due to normal motion which we modeled as a cylinder in perpendicular flow. The moment due to the lifting force and damping moment due to oscillation are shown if Equations 9 and 10, respectively. Using these equations we compute the acceleration of the rocket and which can then be used to step the simulation's velocity and position.

Symbol	Meaning
α	Angle of Attack
ρ	Air Density
V	Total Velocity of Rocket
Θ	Pitch Angle
g	Acceleration due to Gravity
l_1	Distance from rocket C_G to nose C_P
l_2	Distance from rocket C_G to fin C_P

Symbol	Meaning
F	Force on the rocket
C_D	Drag coefficient
A	Area
C_N	Normal lift coefficient
M	Moment
d_{body}	Diameter of body tube
l_{rocket}	The length of the rocket

$$\alpha = -\tan^{-1}\frac{V_{norm}}{V_{axial}} \tag{1}$$

$$F_{drag,rocket} = -\frac{1}{2}\rho V_{tot}^2 C_{D,rocket} A_{rocket} \tag{2}$$

$$F_{grav,axial} = -mg\sin\theta \tag{3}$$

$$F_{drag,parachute} = -\frac{1}{2}\rho V_{tot}^2 C_{D,parachute} A_{parachute} \tag{4}$$

$$C_{N,tot} = C_{N,nose} + C_{N,fins} \tag{5}$$

$$F_L = \frac{1}{2}\rho V^2 A_{rocket}\frac{\partial C_{N,tot}}{\partial \alpha}\alpha_{CG} \tag{6}$$

$$F_{grav,norm} = -mg\cos\theta \tag{7}$$

$$F_{drag,norm} = -\frac{1}{2}\rho V_{norm}^2 C_{D,cyl} d_{body} l_{rocket} \tag{8}$$

$$M_{lift} = -F_L(C_{P,pos} - C_{G,pos}) \tag{9}$$

$$M_{damp} = -\frac{1}{2}\rho V A_{rocket}\dot{\theta}\left(\frac{\partial C_{N,fin}}{\partial \alpha} l_1^2 + \frac{\partial C_{N,fore}}{\partial \alpha} l_2^2\right) \tag{10}$$

References

[1] Newlands, Rick, "A Dynamic Stability Analysis Rocket Simulator", Aspire Space, June 6 2011.

[2] Box, S., Bishop, C. M. and Hunt, H., "Estimating the dynamic and aerodynamic parameters of passively controlled high power rockets for flight simulation", Cambridge Rocketry, February 2009.