UMN Senior Design Rocketry Team

Flight Readiness Report

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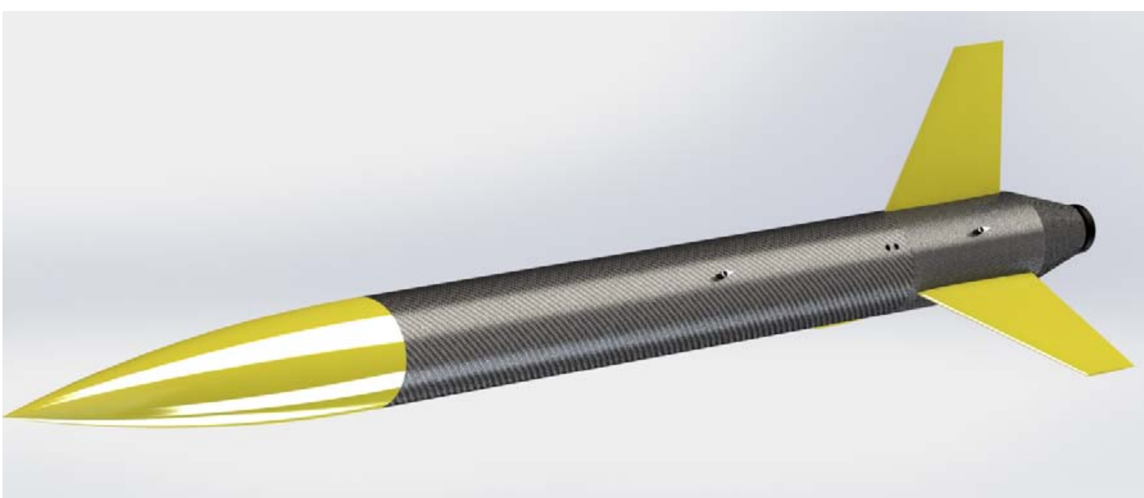

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Constraints

Given that the purpose of this competition is to design and build a rocket to get as close to 3,000 feet as possible, our design was tightly limited by the restrictions placed on us by the competition. The competition constraints are the core from which our design was derived. The 4 inch outer diameter constraint was one of the most restrictive aspects as it limited our ability to access our internal components and required us to have access considerations at the forefront of our design. The motor backup requirement was also a significant factor in how we designed our internal structure as we needed to vent the expanding gases in a way that prevented damage to our pneumatic system, the details of which are discussed later in this report. The most important and restrictive constraint on our design was the weight limitation of 7.5 pounds which required us to make very careful decisions about component selection and manufacturing methods. The motor restriction of the Cesaroni I540 simplified the entire motor selection process of our design and forced us into very reasonable sizing and weight limits to accomplish our goals. These restrictions made an air braking system a sensible approach to meeting the altitude requirements, even with maximum weight and sizing it is difficult to reliably reach 3,000 feet under all wind conditions.

Our budget allowance was fairly generous thanks to the University of Minnesota aerospace engineering department and the Minnesota Space Grant, which provided most of our funding of about $2,500. We also had several corporate sponsors who supplied materials and services that we would have otherwise not been able to afford. These sponsors include Stratasys, which provided an extensive amount of 3D printing for internal components and for use as molds for our composites work. Protolabs, which made a custom brass fitting for our pneumatics system. Ameristar, which provided the water jet cutting used to manufacture our aluminum and G-10 fiberglass components which were critical in our internal structural design. Aerospace fabrication and 3M both also provided a wide variety of components and tools which were used in constructing the rocket. Lastly, Off We Go Rocketry supplied expertise in the form of Gary Stroick, who assisted us in test launches and general advice.

Rocket Build and Aerodynamics

The nosecone that was chosen for our rocket, shown on the next page in Figure 1, is an off-the-shelf nosecone that was ordered from Public Missiles Limited that we modified slightly. The nosecone was chosen for its appropriate length (16 inches), appropriate diameter (4 inches), and for the aerodynamic ogive shape. Due to our custom made body tube being a nonstandard diameter, we needed to remove some material from just above the shoulder of the nosecone so that there would be a smooth transition from the nosecone to the body tube. To achieve this, the nosecone was placed on a lathe and material was slowly removed until the outer diameter of the lower part of the nosecone matched the outer diameter of our body tube. We also removed the lower part of the shoulder so that we could use the interior space for our parachute. A wooden bulkhead with an eyebolt was epoxied into the nosecone approximately 7 inches in with West Systems epoxy so that the parachute would not be forced farther in during the ejection and get stuck. The eyebolt allowed for the parachute to be attached to the nosecone with a piece of shock cord. The shoulder of the nosecone fits snugly into the top of the main body tube and is held in place during launch with three nylon shear pins placed an inch below the top of the main body tube. The shear pins prevent the nosecone from moving during flight, but allow for the nosecone to separate and release the parachute when the ejection charge is detonated. Ground testing of the shear pins was performed and the pins successfully sheared when the ejection charge was fired.

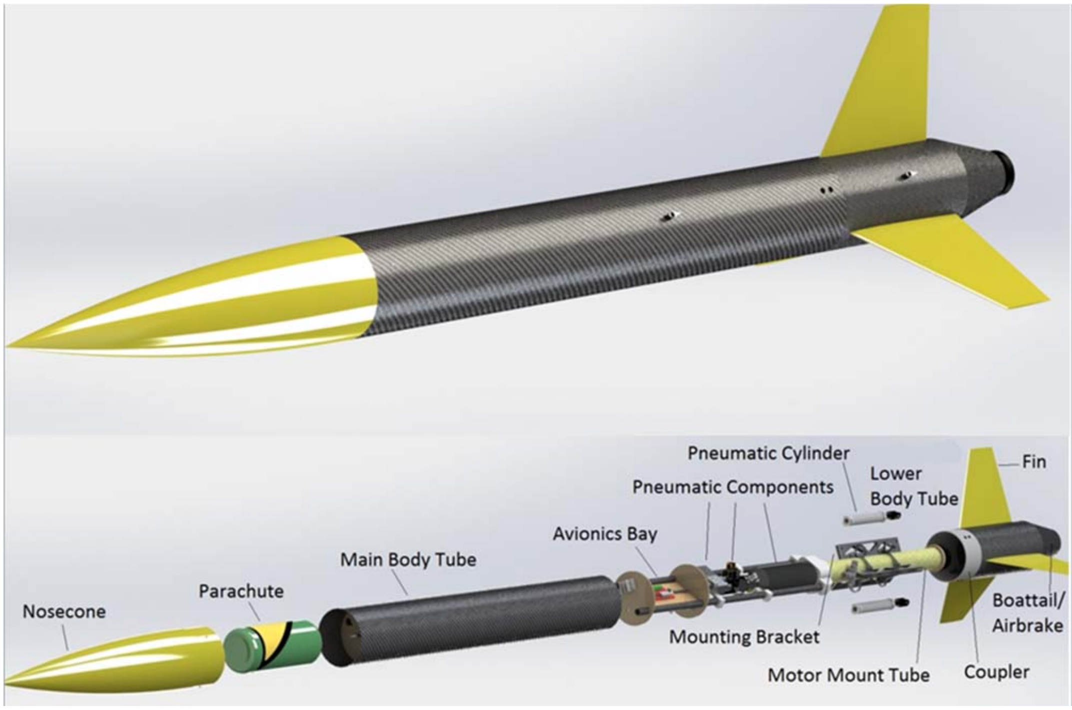

Figure 1. Fully assembled view of the rocket (top) and an exploded view of how the rocket comes apart (bottom).

The outer diameter of the body tube was chosen to be 3.95 inches which maximized the space inside the rocket, but ensured that it was within the competition requirements of less than 4 inches. The body tube of the rocket was custom made out of carbon fiber and is split into two parts, shown in Figure 1. This was done so that broken parts could easily be replaced and for ease of access to the internal components of the rocket. It can be seen from the exploded view in Figure 1 that the main body tube section, with the parachute and nosecone, slides completely off of the internal structure of the rocket. This allows for easy access to the pneumatic components, electronics, and other various internal components. The lower body tube section, also made of carbon fiber and seen in Figure 1 , is removable by removing the bolts holding it on and sliding it of the back of the motor mount tube. The lower body tube has the fins mounted to it along with the lower 1010 sized rail button which is made from black Delrin and is backed by a piece of 1/2 oak which is epoxied in place with DP-460NS to the inside of the lower body tube. This section of the body tube connects to the motor mount tube via a mounting system that will be discussed in a later section. The two body tube sections are connected together with a custom made carbon coupler, shown in Figure 1, and six evenly spaced rivets. The rivets are low profile to improve aerodynamics and are 5/32 of an inch in diameter.

A boattail roughly one diameter of the rocket in length was added to the end of our rocket to decrease drag and to serve as airbrakes. The boattail decreases from the diameter of the body tube to the diameter of the motor mount tube at a constant angle of transition. The boattail was custom made from carbon fiber and was cut in half so that each half could act as an airbrake. Figure 2, on the next page, shows what the boattail looks like when closed and also what it looks like when it is fully open and acting as an airbrake.

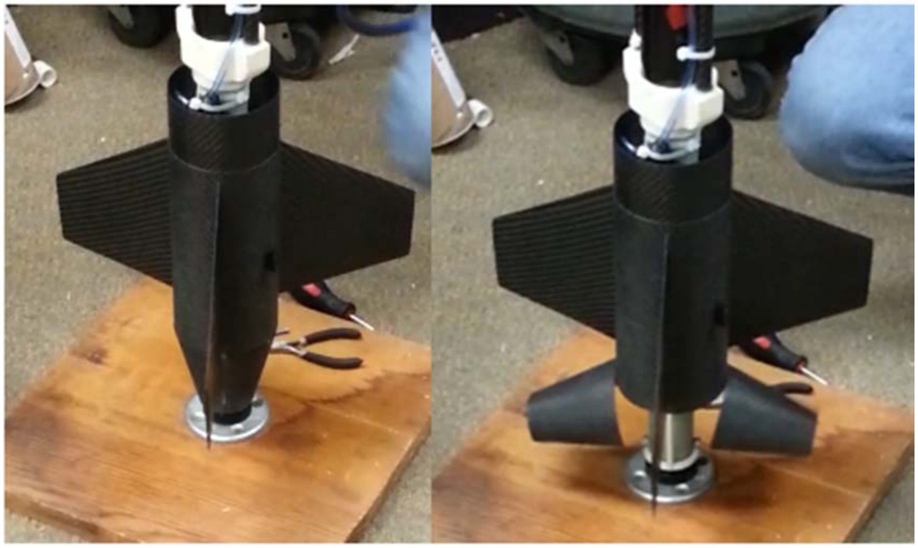

Figure 2. Closed boattail section (left) and boattail section fully open acting as an airbrake (right).

A three fin design was chosen for our rocket to minimize weight and provide adequate stability during flight. The fins are a NACA 0003 airfoil, which corresponds to a three percent chord max thickness. The chord at the root of the fin is 7 inches and the chord at the tip is 3 inches which leads to a max thickness of 0.2 inches. The semi-span of the fins is 6 inches with a sweep angle of zero degrees. The fins were 3D printed of ABS plastic and the 3D printed fins were then overlaid with one layer of 10.8 ounce carbon to add strength and durability.

The fins are mounted to the lower body tube with a mounting system that ensures that the fins are exactly 120 degrees apart from one another and also ensures that they are perfectly vertical on the lower body tube. This mounting system can be seen below in Figure 3.

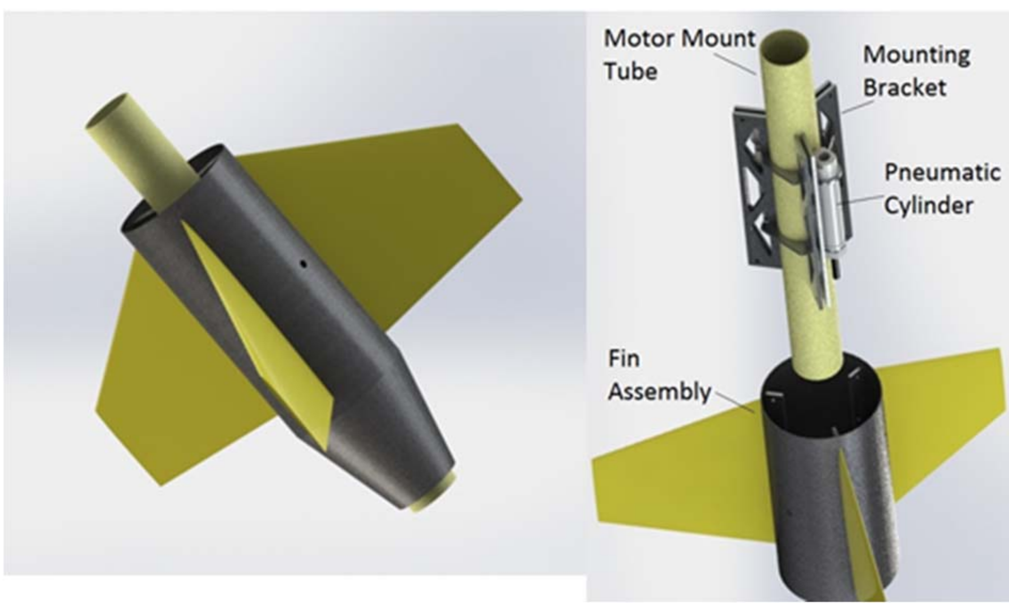

Figure 3. Fin assembly fully assembled with boattail (left) and how the fin assembly is removed from the motor mount tube (right).

The separators are made of 6061-T6 aluminum and are permanently epoxied to the motor mount tube. The separators have holes cut in them that allow for the pneumatic cylinders that actuate the airbrakes to be easily inserted and removed while being securely attached during flight. They also have slots cut in them that allow for the mounting brackets to be held in place. The mounting brackets are made from G-10 fiberglass and are also permanently epoxied to the motor mount tube. The fin inserts, which are made of 6061-T6 aluminum, are epoxied into the fin and then the fin is epoxied to the lower body tube. This mounting system allows for the fin assembly to be removed for access to the pneumatic cylinders and for replacement of the fin assembly should something break, as seen in Figure 3. The fin assembly is held in place by 6 bolts with locknuts, one at each end of each fin. DP-420NS epoxy was used for all components of the fin assembly.

The internal structure of the rocket was primarily shaped by the motor backup eject requirement for the competition. With a motor backup ejection charge, we needed to be concerned about hot gases damaging our sensitive pneumatics and electronics. The solution that we came up with for this problem was to attach a pressure redirect to the back of the motor mount tube which would direct the gas up to the parachute bay through two carbon fiber tubes. The pressure redirect is shown below in Figure 4 and was 3D printed out of ABS plastic. The pressure redirect was tested with black powder for a much larger charge then that of that of the motor eject with all of gas vents sealed except the carbon tubes and there was no visible damage to the system. The two carbon fiber rods that direct the gases from the pressure redirect to the parachute bay also act as the main supports of our internal structure. Carbon fiber was chosen as a material for these rods for the strength and low weight of the material. A tank brace and valve mount were 3D printed from ABS plastic and attached to the carbon fiber rods and can be seen in Figure 4. The tank brace also had a slight extension with a hole in it off to one side which allowed for the mounting of the upper rail button which screws into that hole. Both the tank brace and valve mount slide on to the carbon rods and were epoxied in place with DP-460NS. These ABS parts not only served as a mounting points for the air tank and the valve, but were also designed to go all the way to the inside of the body tube so that when the main body tube is slid over the internal structure, they hold the rods in place an prevent them from swaying.

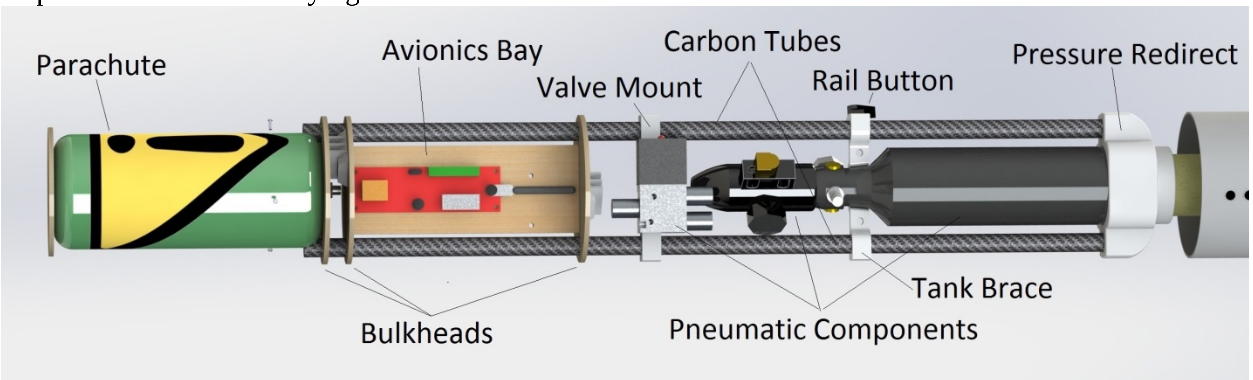

Figure 4. Internal structure of rocket.

The body tubes and airbrakes were constructed by using a dissolvable mold system. Molds were 3D printed out of dissolvable support material, and then one layer of 5.7 ounce carbon followed by one layer of 10.8 ounce carbon was laid over the mold. Once the carbon had cured for at least 12 hours under vacuum, the mold was dissolved and we were left with just the carbon part. The coupler was made in a similar fashion with a dissolvable mold, but used three layers of 10.8 ounce carbon to increase its strength. Carbon was chosen for our primary material due to its high strength to weight ratio. With the weight limit at only 7.5 pounds, we were forced to use carbon to save weight on the airframe so that we could implement our pneumatic air braking system which is rather heavy.

The rocket finish was made to be as smooth as possible by sanding, painting, and clear coating. The nosecone and body tubes were sanded smooth, primed, painted with high gloss paint and then clear coated with high gloss clear coat. The fins and boattail were sanded, and clear coated with high gloss clear coat so that the carbon texture could still be seen. After the rocket had been completed, the total length of the rocket came to 56.5 inches and the total weight of the rocket came to 7.4 pounds.

Epoxy

Epoxies used in our construction were DP-420, DP-420NS, DP-460NS, West Systems, and DP-100. The DP-420 and DP-460NS were used to glue pieces together that would be experiencing a lot of stress during flight as it is the strongest and most shock resistant. This included the external fillets for the fins and the pressure redirect component. DP-420NS or “no-sag” was used for the external fillets of the fins due to its resistance to sagging, leaving a better surface finish and final result. This was important because we wanted the external fillets to be as smooth as possible. West Systems was used on some of the internal parts such as gluing the bulkheads in place because it is strong enough to handle the forces involved and the surface finish of the epoxy does not matter. DP-100 was used for holding components in place that were not under stress so this weaker and quick setting epoxy could be used. For mixing the epoxies, the DP series had applicators made by 3M that mixed the two components in a proper ratio as you squeezed the amount you wanted out and for the West Systems we used a scale to measure out the correct ratio as stated on the container and mixed the two together in a cup. Pictures of our fin fillets are shown in Figure 5.

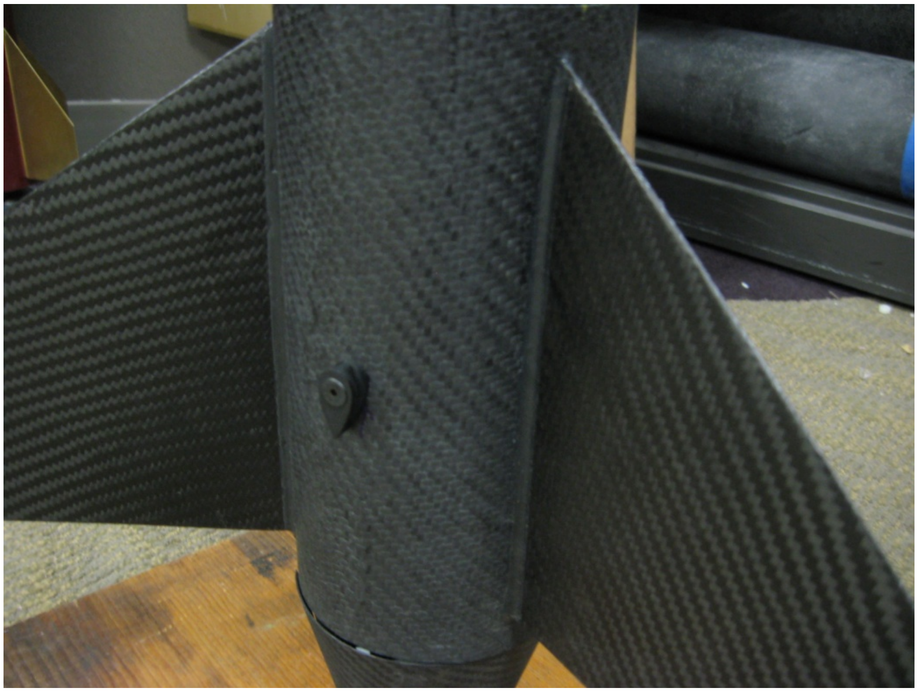

Figure 5. Close up of fin can with exterior fillets visible.

Hinge Design and Analysis

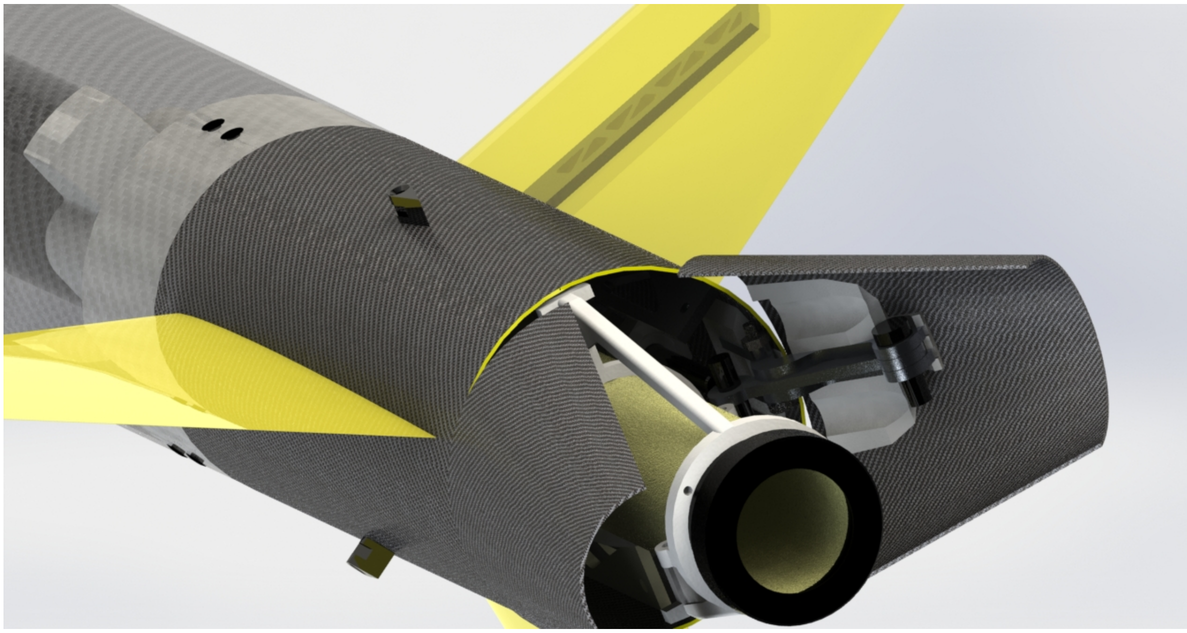

Figure 6. Airbrake and attachment system.

The air braking system used makes use of two actuating airbrakes which are halves of the boattail to ensure the maximum amount of drag differential. The airbrakes are actuated by the pneumatics system discussed in its section of this report. The airbrakes themselves are hinged by pieces attached to the carbon fiber of the airbrake pieces and the lower body tube component. These components are covered with a carbon layup for additional strength in addition to DP-420 adhesive used to attach the components initially. The 3D printed components attached to the motor mount tube serve primarily as rests to make sure no gaps are present when the airbrakes are closed and that the airbrakes have something solid to rest on when they are closed. The spring return pneumatic cylinders do not close all the way before the airbrakes hit their rests; thus, during flight the airbrakes are under constant spring force of 3 pounds each which holds the whole system tightly closed.

The hinge used for the air braking system was a custom design composed of two 3D printed components as well as well as a series of 6061-T6 aluminum components for the hinge itself. The 3D printed components serve as a means of connecting the aluminum pieces to the carbon as well as properly spacing and aligning all of the components used. The design of the hinge system ensures that the majority of the forces during actuation are born by the sturdy aluminum components. Assuming the maximum extension force of the pneumatic cylinders, there is a maximum force of just under 100 pounds on the aluminum hinge pieces that are glued directly to the airbrake itself. After analysis using ANSYS, it appears that the pieces should be able to survive forces of this magnitude. All other aluminum components were similarly analyzed and were under forces of lesser magnitude and demonstrated similar safety factors of around 2 or greater. The primary area of failure to worry about is the connection points to the carbon body tube which has been tested using a mock hinge setup and will not fail under standard operating conditions and expected wind loads. An advantage of this design is that not all of the braking force is born directly by the airbrake itself, a significant fraction of the load is due to increased separation in the lower regions of the rocket.

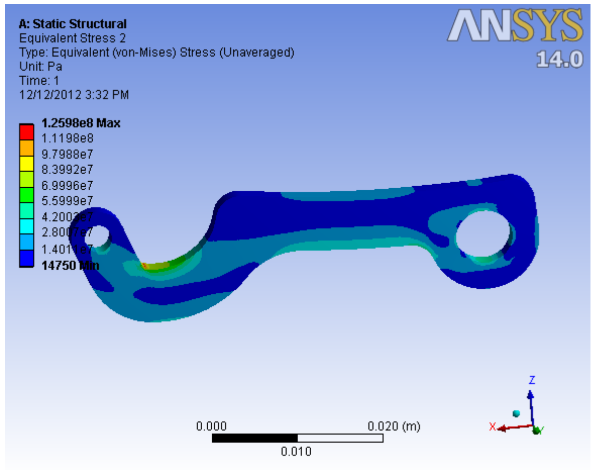

Figure 7. Internal structural analysis.

Airbrake Control System and Avionics

<u>Pneumatics</u>

The initial concern in designing the airbrake control system was in the selection of an appropriate actuation method. A study of similar airbrake designs, all of which utilized large electric linear actuators, concluded that such actuators were too large, heavy, slow, and complicated to operate and were thus eliminated from further consideration. A properly designed pneumatic system, on the other hand, would yield a significant boost to performance, especially in actuation time, for a similar actuation force. The main challenge arose in designing such a system at the lowest possible weight. From early calculations, it was found that no more than three pounds could be allotted to the entire pneumatic actuation system. After extremely careful selection of pneumatic system components, this goal was achieved.

The first component selected was also the heaviest—the air tank. Two options were available for the compressed air source: carbon dioxide (CO_2) and high-pressure air (HPA). CO_2 was quickly ruled out for several reasons. First, it is stored as a liquid, which means the tank orientation would need to be very carefully considered so the accelerations encountered during flight would not cause the CO_2 to pool at one end of the tank. Second, many of the other components (cylinders, valves, regulators, etc.) would have been more difficult to source for a CO_2 system, since most of these components are designed for use with HPA systems. Finally, since the CO_2 expands from a liquid to a gas, a large amount of enthalpy is transferred out of the gas as the system operates, which could cause other components in the system to literally freeze up. Thus, a HPA system was selected. Unfortunately, the smallest HPA tanks available, which are designed for use with paintball guns, are still quite heavy. After some searching, the smallest, lightest HPA tank on the market was found, the Guerrilla Air 13 cubic inch, 3000 psi tank, seen in Figure 8. The tank weighs just over one pound when full.

Figure 8. Compressed air tank.

The next component selected was the regulator. While the tank includes a regulator, it simply brings the pressure from 3,000 psi down to 650 psi, which is still far too high. For safety, it was also concluded that a system pressure release valve and a system pressure gauge were needed, so the entire pneumatic system could be degassed quickly and safely. Fortunately, a regulator was found that incorporated both of these aspects into the regulator body, while remaining fairly lightweight: the Empire Relay On/Off ASA, seen in Figure 9. The regulator has an output pressure gauge which can be used to accurately set the operating pressure of the pneumatic system (in the range of 50-150 psi), as well as a lever which degasses the system and disconnects the air supply from the rest of the system. Unfortunately, the regulator was designed for use with a limited range of paintball guns, so it has non-standard output fittings. This was resolved by designing a custom adapter, which was then CNC machined with a generous donation from Proto Labs. The adapter is also seen in Figure 9.

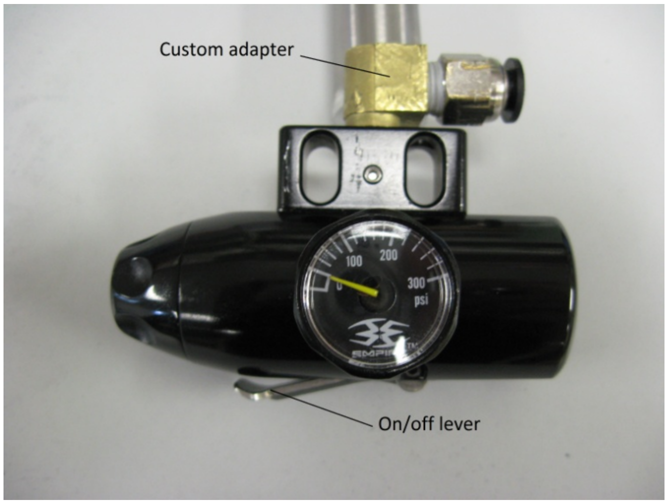

Figure 9. Regulator with custom-made adapter and on/off lever.

The next component selected was the valve. This was a simple choice, as the only requirements were that it be lightweight and have a solenoid to allow it to be controlled electronically. An Ingersoll-Rand 3-way Body Ported solenoid valve was selected, seen in Figure 10. The valve also includes a button for manual operation. The valve has a maximum operating pressure of 125 psi, which is the lowest safe pressure of any of the components in the whole system. Thus, 100 psi was selected as the operating pressure.

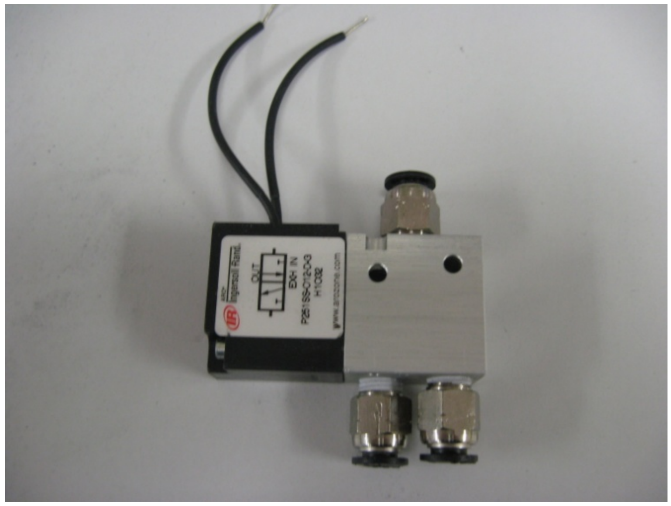

Figure 10. Solenoid valve with fittings installed.

The final components selected were the pneumatic cylinders. The sizing of these cylinders was determined by the design of the airbrake hinges. It was determined that a 1-1/2 inch stroke length would be more than sufficient. To provide the largest possible actuation force, the largest possible bore diameter was selected that still allowed the cylinders to fit inside the airframe. This bore diameter is 3/4", which allows each cylinder to generate 40 pounds of actuation force at 100 psi. To simplify the system, spring-return cylinders were selected. This was done to maximize the number of actuations possible from a single tank of air, since only half as much air is used to complete one full actuation cycle. The tradeoff is that the springs only produce 6 pounds of retraction force; however, this is sufficient to close the airbrakes. In addition, the airbrakes are designed such that aerodynamic forces will assist in the closing process. The cylinders selected were Nitra A-series 3/4" bore, 1-1/2" stroke spring return cylinders, which are the lightest of their kind. They can be seen in Figure 11.

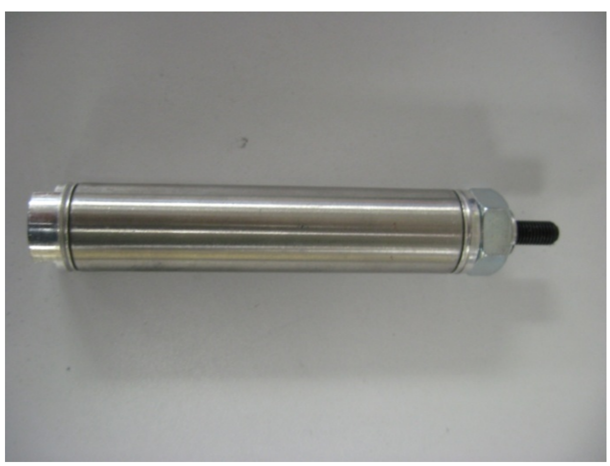

Figure 11. One of the two spring-return pneumatic cylinders.

The components of the system were connected using 1/4" flexible polyurethane air hose, rated for 180 psi, and 1/8" NPT push-in fittings. This allows the system to be quickly and easily assembled and disassembled. A functional block diagram of the entire system can be seen in Figure 12. The exhaust line for the system is routed through the airbrake rest in the bottom of the rocket, next to the motor retainer.

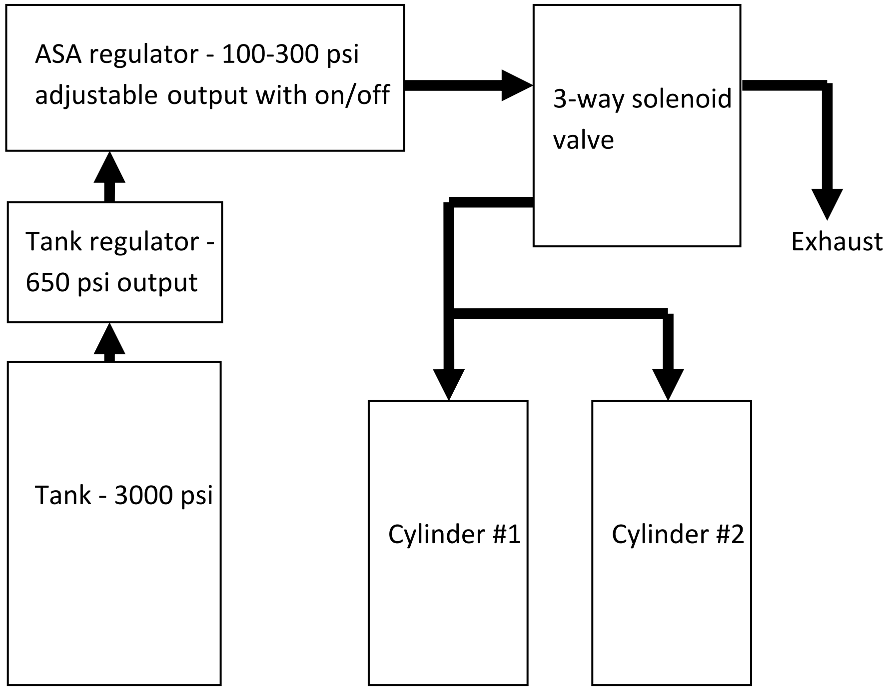

Figure 12. Functional block diagram of pneumatic system.

Electronics

There are two sets of electronics used in the rocket: an off-the-shelf altimeter to fire ejection charges and log flight data, and a microcontroller and external components devoted to controlling the airbrakes. The altimeter selected was the AIM XTRA (seen in Figure 13), for a few reasons. First, it is the only altimeter that can be easily programmed to fire ejection charges during the ascent phase of flight, which allows us to deploy the parachute early, very near 3,000 feet, as a backup altitude control method if the airbrakes fail (this will be discussed more later). Second, the AIM XTRA includes a GPS module and a radio transmitter, potentially allowing us to use it as a tracking device as well as a flight altimeter. Typically, a carbon fiber airframe is not RF transparent enough for such use, but bench tests have been fairly successful in establishing a radio link through the airframe, although a sizeable reduction in gain is incurred. The radio link was tested further during our first test launch, and while it did work, our range was limited to about 1,000 feet. On further test flights, a high gain directional receiving antenna will be used to see if the results may be improved. Finally, the AIM is an all-around exceptional altimeter. It utilizes sensor fusion of accelerometers, a barometer, and GPS to fire ejection charges at specific altitudes with great accuracy, and can function as a high-speed data logger for post-flight analysis. The AIM includes proprietary software to program ejections and readout logged data, which is installed on Seth Frick's personal laptop. He will be responsible for programming ejections and downloading data for each flight.

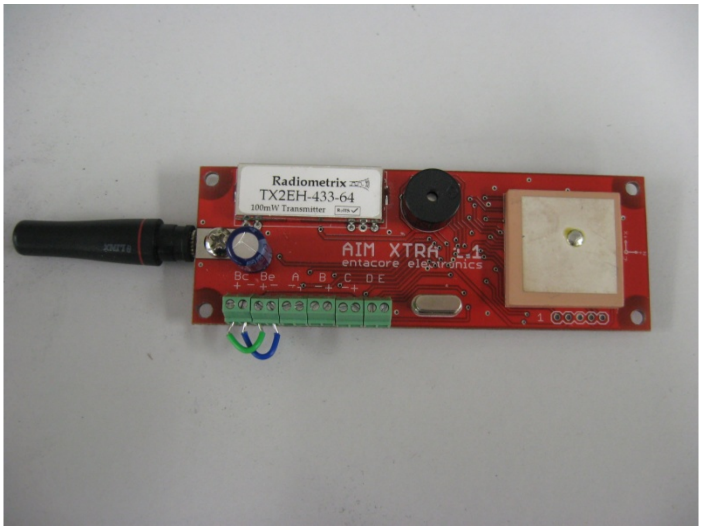

Figure 13. AIM XTRA altimeter.

The remainder of the electronics are devoted primarily to controlling the airbrakes. The microcontroller selected was an Arduino Uno, chosen for its ease-of-use and highly active open-source development community. To accurately predict the apogee and run the control model, the Arduino requires sensors to measure altitude, velocity, and acceleration at a high rate—a minimum of 100 Hz. The sensors were chosen to obtain the best possible balance of affordability, ease-of-use, speed, and accuracy. With these factors in mind, three total sensors were selected: the InvenSense MPU-6050, a 6-axis IMU (integrating a 3-axis accelerometer and a 3-axis gyroscope); the Honeywell HMC5883L 3-axis magnetometer; and the Measurement Specialties MS5611-01BA high-resolution barometer. All three sensors connect to the Arduino via the I^2C bus, which is overclocked to run at 400 kHz (100 kHz is nominal) to allow for faster data rates. The data from the sensors is interpreted using a customized version of the FreeIMU library, developed by Fabio Varesano. The library uses data from the magnetometer and gyroscopes to project the accelerations from the body frame onto the Earth inertial frame, and then performs sensor fusion of these corrected accelerations with the barometer to obtain extremely precise altitude measurements. The system is capable of measuring AGL altitude accurate to within a few centimeters at a rate of 200 Hz. The sensors, mounted on an Arduino Proto Shield, are shown in Figure 14.

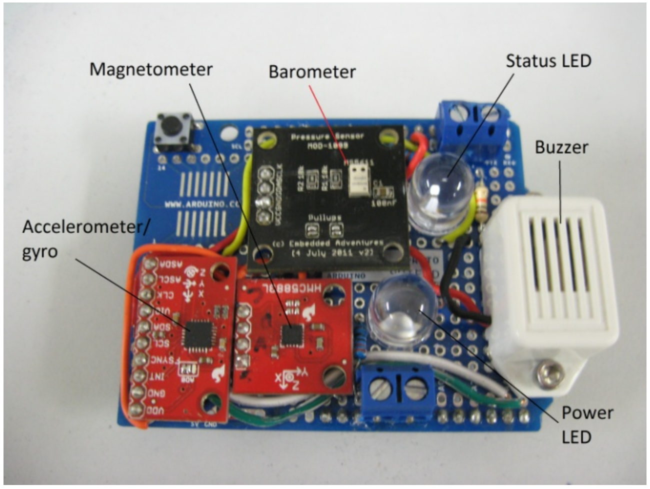

Figure 14. Arduino shield with sensors and sensory feedback from LEDs and a buzzer.

Once the controller decides that it needs to actuate the airbrakes, it does so by using a logic-level MOSFET to close the solenoid valve. A MOSFET was selected instead of a relay since it can be switched much faster. The pneumatic system is very fast as well, and can complete one full open-close cycle of the airbrakes in under 150 milliseconds. In addition to the airbrake control, the Arduino has one additional function. On the AIM XTRA, two ejection lines are used (both on the same black powder charge). One line is programmed to fire during the ascent phase at an altitude of about 2,950 feet. The second line is programmed to fire at apogee detect. However, the E-match for the first line is run through a relay connected to the Arduino. If the Arduino determines based on its sensor data that the airbrakes have failed, or that the apogee cannot be limited to 3,000 feet no matter how much airbraking is done, then it will close the relay, effectively "arming" the first ejection charge, allowing it to fire during the ascent. If it does not close the relay, then the AIM will still fire the pyro line, but the E-match will not be triggered. A full schematic of the electronic systems is shown in Figure 15. The entire system runs on two lithium 9-volt batteries. The two batteries are connected in series and run through a 12-volt regulator to produce the 12-volt supply needed for the solenoid valve, and the Arduino and the AIM XTRA are each powered by one of the two batteries. Since the MOSFET requires that the 12-volt supply and the Arduino both have the same ground reference, the battery from 0 to 9 volts must be used for the Arduino, and the battery from 9 to 18 volts must be used for the AIM

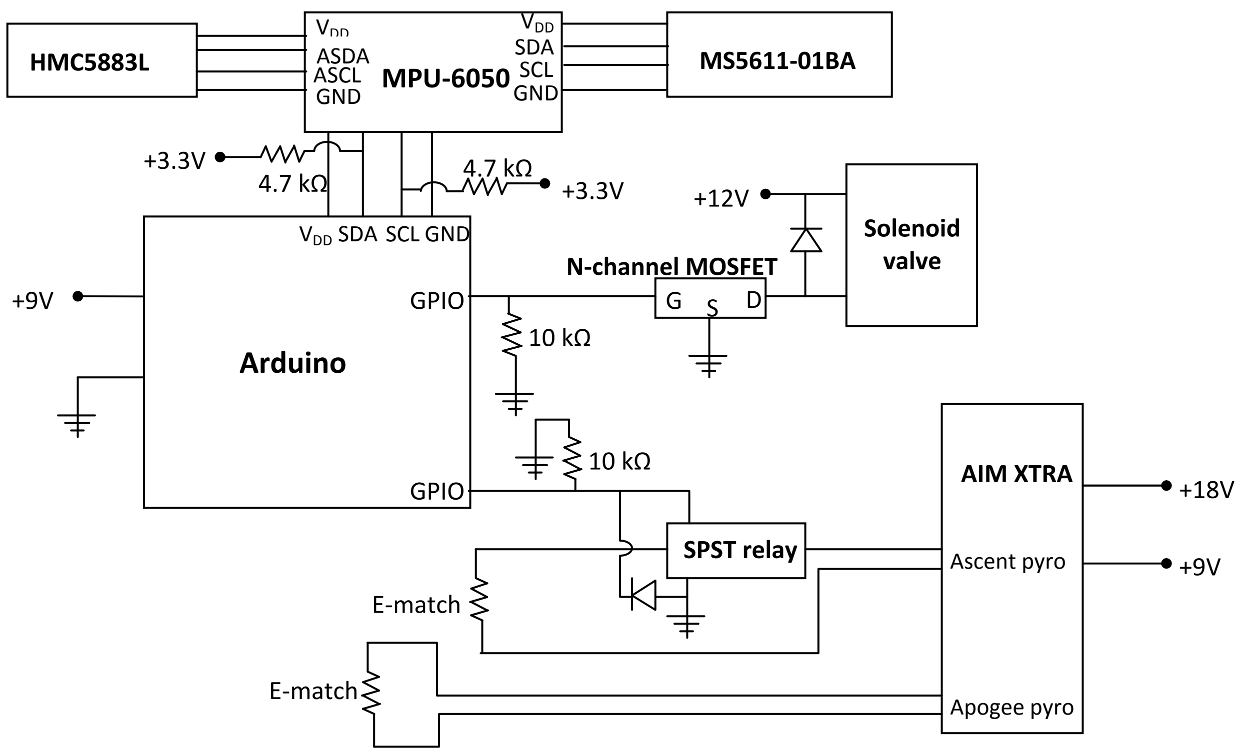

Figure 15. Full schematic of electronics, including airbrake control system with sensors, altimeter, and E-matches for parachute ejection.

In the avionics bay, the airbrake control electronics are mounted on one side of a sled and the AIM XTRA is mounted on the other side. Since both systems use barometers, two static vent ports were drilled through the airframe, one on either side of the avionics bay. The size of the holes was determined based on the requirements of the AIM XTRA as stated in its manual. One of the holes also serves as an access point to the DPST power switch which activates both the Arduino and the AIM. The switch can easily be pressed using a small screwdriver. The avionics bay can be seen in Figure 16.

Figure 16. Close up of avionics bay. The AIM XTRA is mounted on the opposite side of the sled.

Stability

The locations of the center of gravity and center of pressure are located about 39.7 and 43.1 inches, respectively from the tip of the nose cone. These locations are evaluated when the rocket is at its maximum weight, including the motor. When the rocket is on the launch pad, the static margin is 0.85 in terms of the diameter of 3.95 inches. After motor burn out, the static margin is changed to 1.4. This makes the rocket more stable after its initial flight characteristics. This degree of stability is well within acceptable bounds.

Flight Characteristics

Our rocket can travel up to a maximum speed of about 350 miles per hour, with a launch acceleration of about 20g and an ejection acceleration of about 6g which was determined from our test flight which is discussed in detail in its section. Under normal weather conditions with medium to high winds, our prediction shows that the rocket will have an apogee altitude of about 3,100 feet without airbrake actuations. The time to apogee is about 15 seconds and the total flight time is about 120 seconds. Drift distance is dependent on weather conditions. The expected distance will be within half mile radius from the launch pad due to our rockets somewhat rapid descent rate.

Test Flight

Our first test flight occurred 3 weeks before the competition on April 7th. The main purpose of this flight test was to ensure our rocket is aerodynamically stable and performs as a normal rocket without any air breaking. Before the actual flight test, several ejection tests were performed on the ground to make sure the main parachute would deploy. After a few trials, the amount of black power needed to separate was about 2 grams. The main parachute was damaged during our ground tests due to improper parachute protection and preparation. There were also some field modifications to the avionics as at the time we were unsure how to get the AIM XTRA to run on one battery. These issues have since been fixed. During the launch, our main concern was that the main parachute would not come out of the nosecone during deployment due to the ejection charges pushing the parachute in rather than out; however, these issues did not manifest. The launch was successful with no damage to the rocket airframe, but the main parachute was badly damaged from ground ejection tests as was discussed earlier. We are planning two future tests for airbrake evaluation which have been delayed due to scheduling and weather. The first of these tests will have a nominal braking procedure where the airbrakes are actuated on a timer to evaluate their effectiveness and to ensure no damage occurs during flight. The third and final test flight will use our full air braking logic to evaluate its effectiveness.

Recovery System

Our primary recovery system is a single 5 foot Rocketman Parachute made of ripstop nylon which should give us a descent rate of about 20 feet per second which is sufficiently slow for a safe landing according to the supplied manufacturer's documentation. This descent rate is backed by Rocksim and field testing. The parachute is stored in our parachute bay, located just below and within the nosecone and is connected to the rest of the rocket through an eyebolt mounted to the G-10 fiberglass topmost bulkhead which is glued in place with DP-460 epoxy. The parachute is protected from the exhaust gasses with a sheet of Nomex fire resistant cloth that is attached to the shock chord. The shock chord is a tubular nylon strip 10 feet long with 6 feet being before the parachute to ensure the nosecone does not hit the rocket after ejection.

Figure 17. Parachute attachment eyebolt and charge holder (left) and full parachute setup (right).

There are a total of 3 ejection triggers in use with our ejection system. There is the chemical motor backup as part of the I540 motor which is required by the completion regulation. This charge is set on a maximum length timer to ensure it goes off after apogee and after our other ejection charges are attempted. The ejection gasses are directed through two small tubes from the motor to the parachute bay to minimize the damage done to the internal electronics and pneumatics systems. This system has been tested both in small scale controlled tests with electronically deployed charges and during flight tests with no signs of pressure damage or other wear. There is one electronically deployed 2 gram black powder charge which is placed in the parachute bay and can be set off by two separate pyro lines from our AIM XTRA altimeter to the E-matches placed within. The first of these E-matches is set to go off slightly before 3,000 feet altitude if the altitude control system is not functioning properly. The second charge is set to go off slightly after apogee under all circumstances.

Our AIM XTRA altimeter has an onboard GPS and real-time telemetry to the base station. This will allow us to track and recover the rocket during its descent. Given the low altitudes involved, we are confident about our ability to find the rocket after landing.

Simulations

We used several simulation tools to understand the expected behavior of our rocket. We did initial sizing and basic design such as length, weight, and fin size using Rocksim. The rocket exterior is very standard in terms of dimensions and distributions, so this seemed like a sound tool to do the basic analysis. This allowed us to determine the size and dimensions of a stable rocket that overshoots the goal of 3,000 feet by a substantial margin of around 100 feet under even the worst wind conditions. This was done via an iterative design process to find the target mass and fin sizing while the overall body size was determined by our internal component requirements. See our design descriptions for details of our sizing and dimensions.

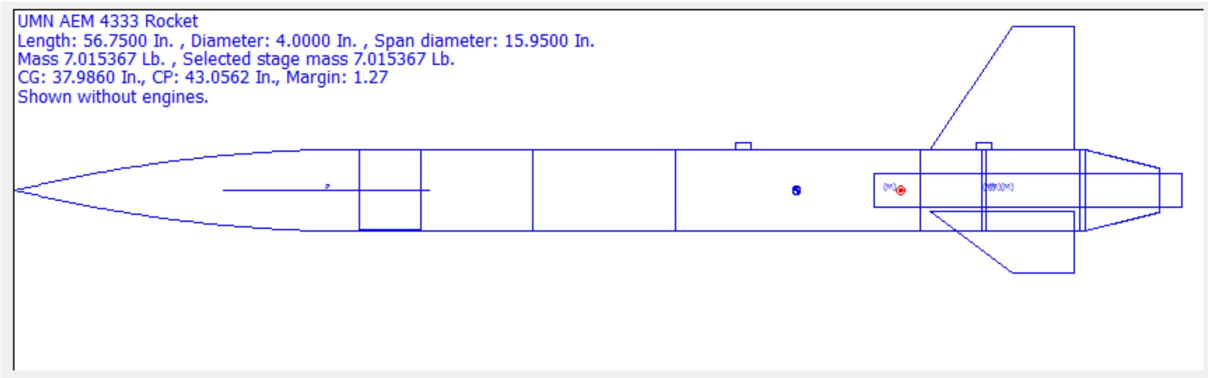

Figure 18. Rocksim Model.

Only the most basic analysis of our air braking system can be done in Rocksim, primarily in the form of approximating the change by removing the boattail. This method is unlikely to be at all reliable or accurate. One of our team members spent a significant part of the 2012 fall semester figuring out how to do basic computational fluid dynamics in ANSYS. This is unlikely to be the most accurate simulations due to our inexperience in doing good analysis of this type but it gives us a good idea of the general effectiveness of our design. Our analysis indicates that the drag coefficient of our rocket when the airbrakes are deployed will be around 4 times that of the rocket without airbrakes. This high differential allows us a great deal of freedom in designing and testing our control model. The overall drag coefficient of the rocket without deployed airbrakes was found to be around 0.7.

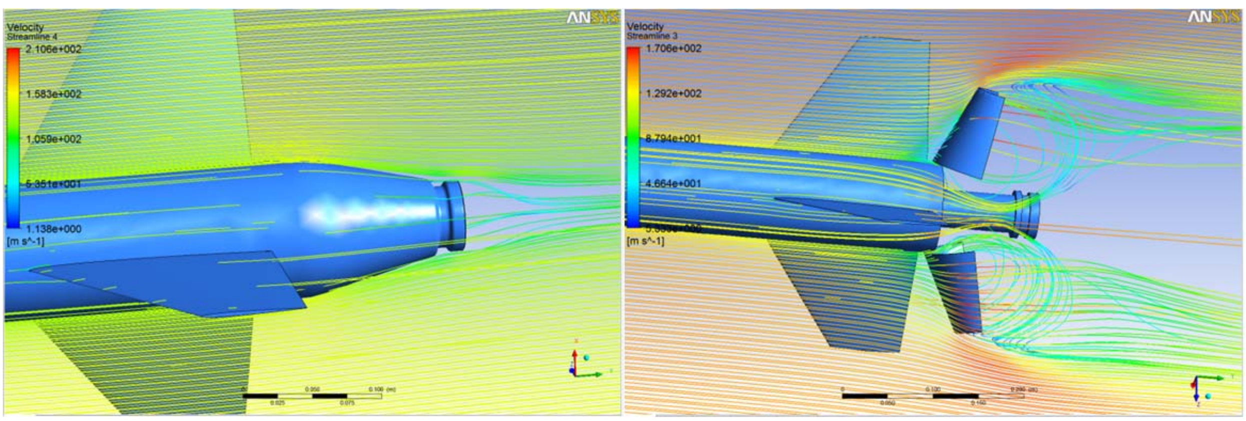

Figure 19. ANSYS analysis of air braking system.

From these airbrake values and the other parameters of the rocket, a model for the control of the airbrakes needed to be developed in a simulated launch environment. Given that we lacked access to an existing simulator of this type we developed one using MATLAB and Simulink. This was primarily a linear simulation of the altitude change using the expected drag and gravitational forces to determine the behavior of the rocket after motor burnout when it is in a ballistic trajectory. The initial conditions were taken from our Rocksim simulations. This simulator allowed us to test several different models of control until we settled on our current method which makes use of an algebraic estimation of the final altitude given the rockets history of altitude change. The remaining altitude after the target height is divided evenly into equal regions based on our allowable number of airbrake actuations.

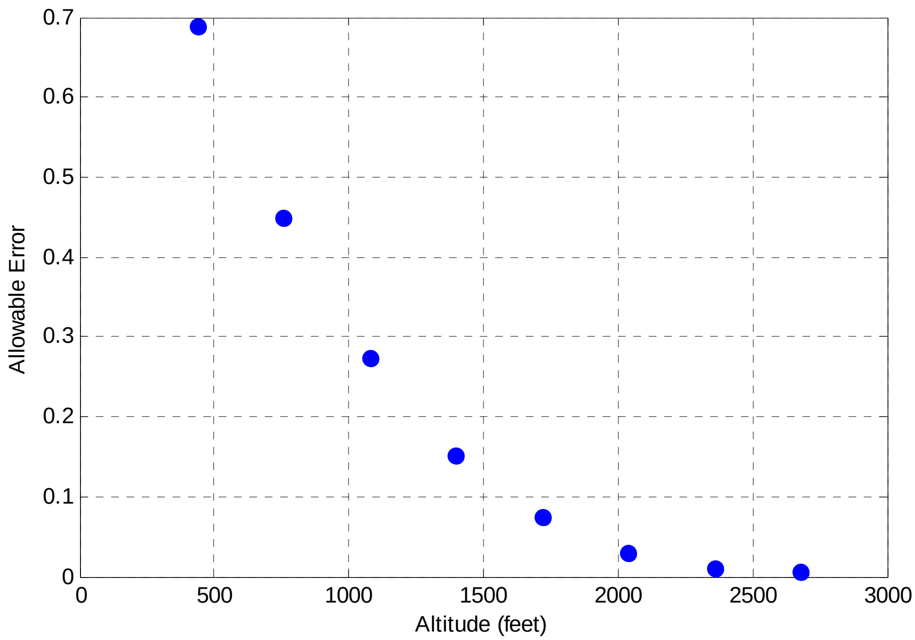

Figure 20. The allocated amount of excess altitude as a function of the total amount of altitude.

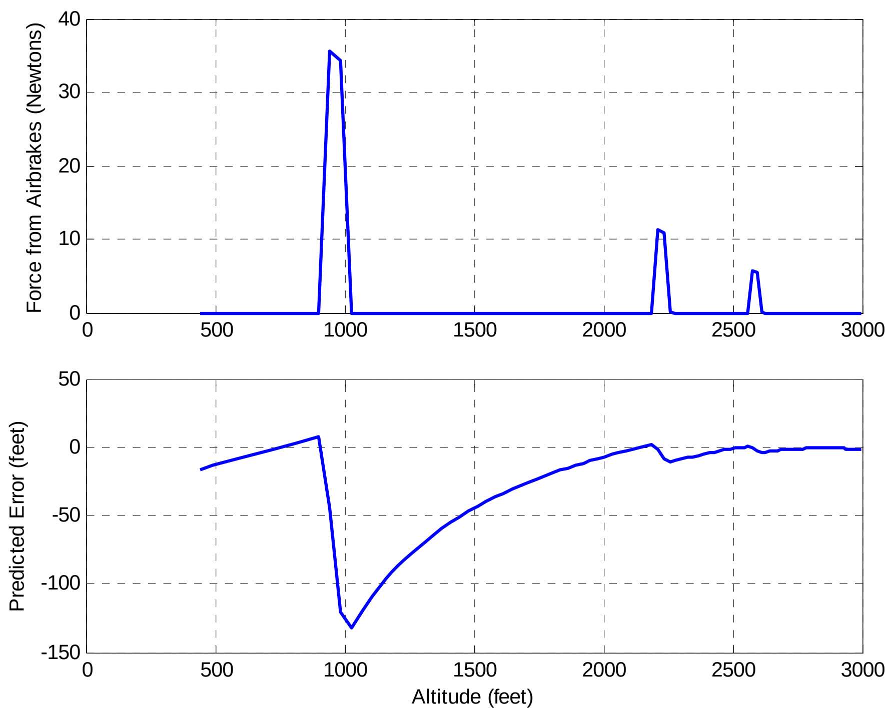

Figure 21. Projected Airbrake Behavior

The difference between the expected altitude and the desired altitude is determined and this initial difference is allocated to the different segments as a quadratic function with the high values at lower altitudes when the airbrakes are most effective. The airbrakes gave accuracy to within a foot during simulations, but real world complications will likely significantly reduce this accuracy. Within 10 feet is a much more reasonable estimate for the accuracy of the altitude reached with the airbrakes.

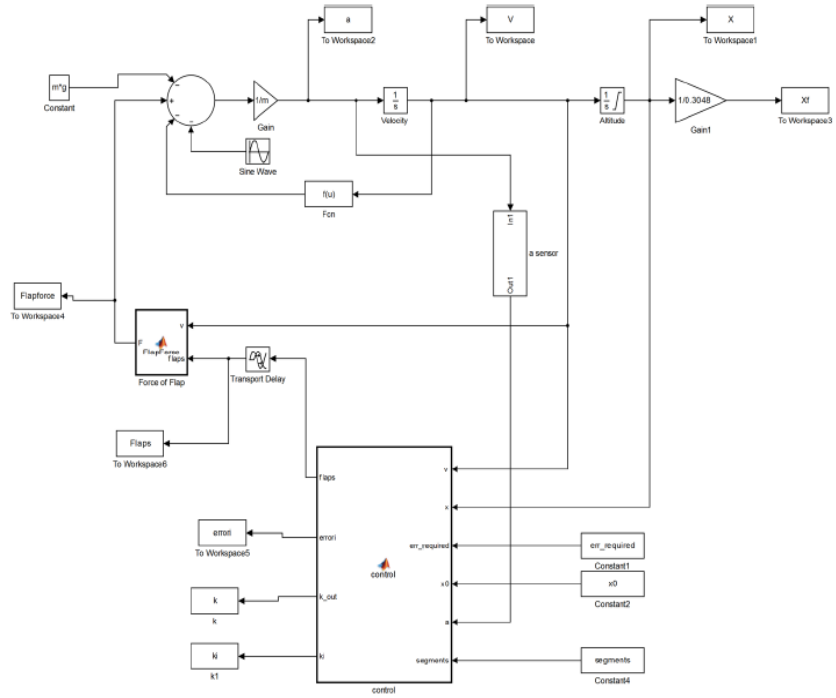

Figure 22. Simulink model of Simulator.

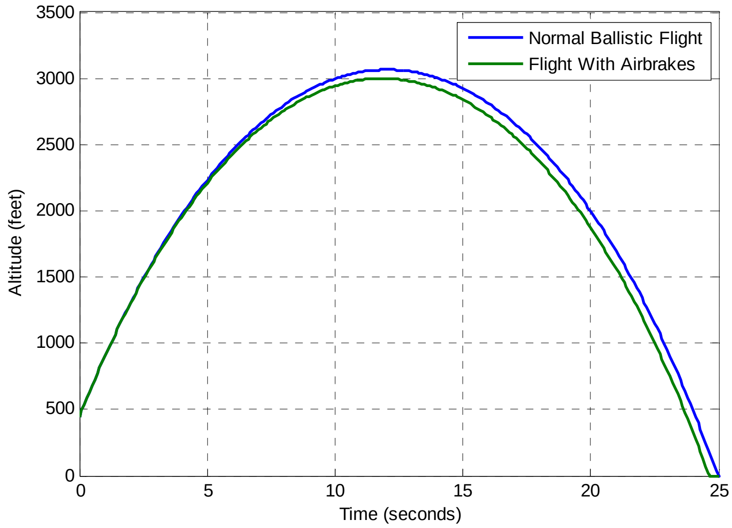

Figure 23. Predicted differences in performance.

There was also significant structural analysis using the 20g loading maximum condition we expect given the flight characteristics of the rocket and the motor used. The primary components analyzed were parts of the air braking system and internal structure to ensure that no failures will occur during worst case scenario conditions.

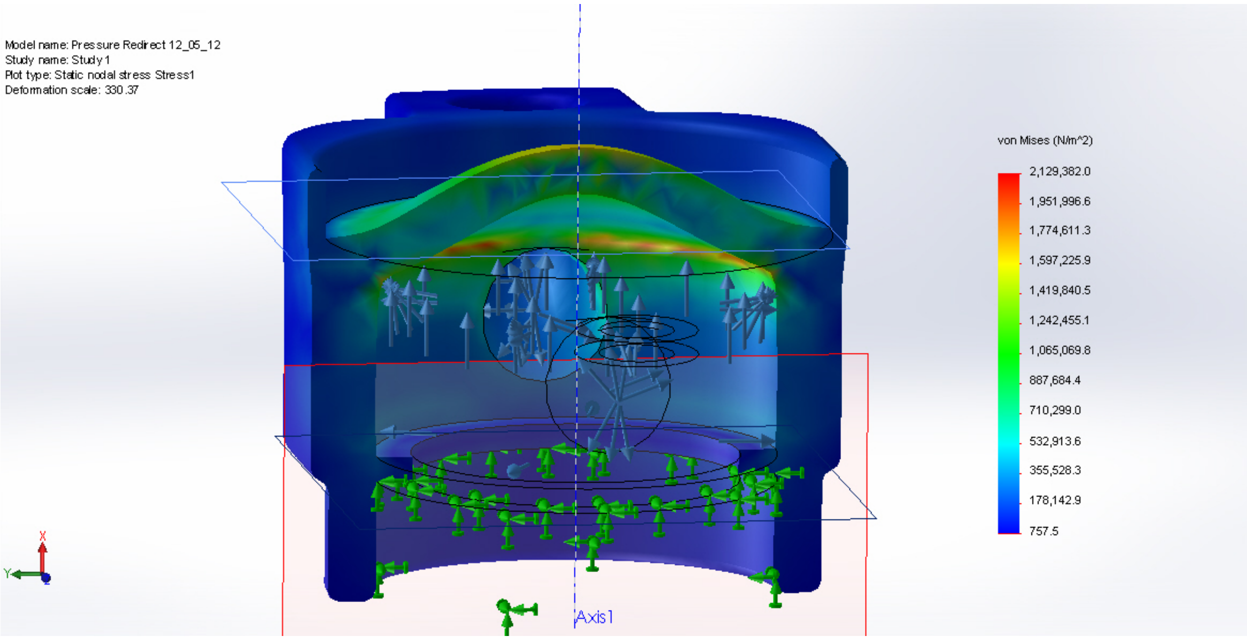

Figure 24. The properties of the pressure redirection component under simulated pressure. Forces are within expected tolerances.

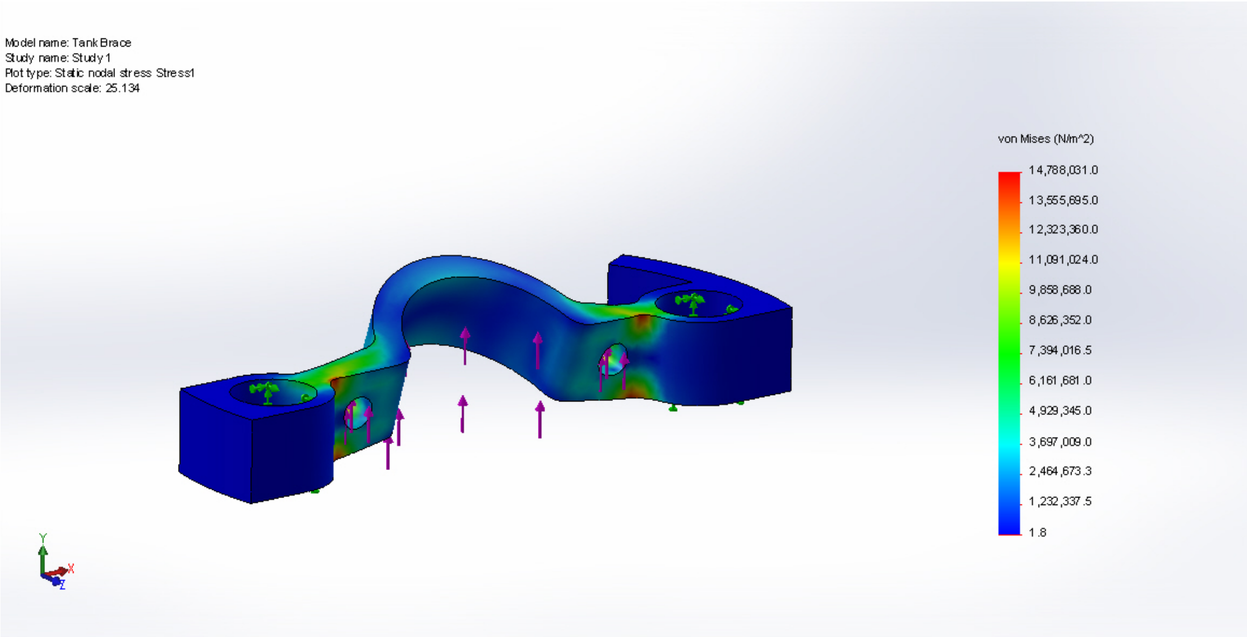

Figure 25. The tank brace for the pressure tank. The forces involved imply that this piece should take over 1,000 launches before failure.

There was also some basic stress analysis done on the composites used in the rocket's construction. This was primarily focused on the main upper body tube section, as a failure in that component is where the safety of the rocket as a whole would be compromised. The body tube itself appears to have a safety factor of 161 using a tensile stress of carbon of 570 GPa under 20g loading conditions. So if failure would occur, it would be due to stress concentrations in the rivets connecting to the lower body tube which will bear the whole weight of the rocket during deployment under impact loading. Given the complexity of this failure mode, simulations were not attempted and physical testing was done using test pieces of carbon in a tensile testing machine which demonstrated the pull out stress for the rivets to be 60 pounds. With 6 rivets used, there should be little risk of failure in that region and all other body tube components have loads which are well distributed and should not fail before the rivets.

The stresses on the internal structure, besides the components mentioned before, were not analyzed to a great degree of accuracy as the materials used were, in many senses excessive, for the application we used them. Aluminum 1/8 inch thick and G-10 fiber glass, also 1/8 inch thick, were used in the lower body tube which will take the entire weight of the rockets internal structure, but our physical testing and test launches have demonstrated that these materials are more than strong enough for the applications we used them for and are significantly stronger than the carbon body tube and would not fail before it.

Motor Selection

The competition requirements allow only the five grain I540 Cesaroni motor; thus, that is what we used and designed around. This motor is a relatively forceful and brief motor with a 1.2 second burn time and outputs a total impulse of 634 Newtons with a maximum thrust of 625.9 Newtons. The initial mass of this motor plus the case is 1.68 pounds and at the end of the burn this is reduced to 1 pound. These characteristics were primarily accounted for through the use of Rocksim simulations.

Launch Check-Off List

The launch procedure to successfully launch our rocket is as follows. This is the responsibility of our team lead.

1. Remove rocket from protective transport casing.
2. Inspect rocket exterior for damage
3. Inspect avionics and internal structure for defects or loose parts.
4. Insert motor and secure using our motor retaining ring.
5. Hook up the two E-matches to pyro lines one and two on the AIM XTRA and secure them in the pressure redirection tube.
6. Insert, secure and attach the pneumatics air tank and valve.
7. Hook up computer to verify avionics are functional and test the airbrakes to ensure functionality.
8. Secure avionics batteries and competition altimeter.
9. Turn on the AIM XTRA and attempt to get a GPS Lock.
10. Replace upper body tube and secure with bolt and rivets and attach the rail button.
11. Activate the avionics and check telemetry.
12. Measure and prepare ejection charge of 2 grams and attach both E-matches to this charge. Check for continuity from the AIM XTRA.
13. Pack parachute tightly and have methodology inspected by at least 2 team members. Package in nosecone with protective Nomex cloth. Inspect knots during this process for looseness or fraying. Check to make sure that the parachute slides smoothly in the nosecone reapply lubricant if this is not the case.
14. Secure nosecone in place with 3 shear pins.
15. Ask everyone on the team to inspect the rocket one final time for potential issues.

Safety Plan

Building the Rocket Safely

When designing our rocket around the given requirements, we always made sure to keep safety at the forefront of our minds. Before building anything, during our design process, we calculated all the forces and stresses expected during the rocket flight and chose materials and planned the structure of our rocket accordingly. This was done so that the rocket would not tear itself apart during flight, possibly sending high speed debris and causing injury to spectators. This analysis was done using SolidWorks and ANSYS by modeling all the components of the rocket we planned to use, assembling them together and applying all the appropriate forces through SolidWorks motion analysis tool. Once all our components were thoroughly tested in SolidWorks they were approved for use in building the rocket. No component of our rocket had a safety factor below 1.5.

Next up was safely designing a pneumatic system that would fit inside of our rocket and actuate the airbrakes. Obviously, having an air tank holding pressurized air at 3,000 psi in the near vicinity of rocket motor can be extremely dangerous, so we made sure to take all the necessary precautions. Firstly, we figured out how much force we would need from the airbrakes to achieve a sufficient angle to slow the rocket down. Determining this lead us to how many psi of air pressure we would need. Once this was determined, we picked out cylinders, tubing, a solenoid valve, regulator, and air tank that were all industry rated for the air pressures we would be using so that no ruptures would occur. Also, since the motor will be properly contained inside the motor casing and motor mount tube, no significant heat or pressure should reach the air tank or any other parts and cause problems. The tank is also fitted with pressure disks which will rupture and vent all of the air long before an explosion of any sort is an issue.

Lastly, the most potentially dangerous part of the rocket is the motor. There is only one motor that can be used at the competition and it is the Cesaroni I540 so the only thing we needed to do was buy an appropriate sized motor mount tube and casing to house the motor which are all meant to be used in that fashion and have been industry tested and rated and should present no safety concerns that we can avoid. For safety during the build process we made sure to take the necessary precautions so no one would be harmed during building of all the components. When handling the carbon fiber used for our rocket we would always wear gloves when doing layups to not get resin on our hands. When cutting or sanding the carbon fiber, safety glasses and face masks were worn so we would not inhale any carbon fiber particles or get any shards in our eyes. The other parts of the build process were simply putting things together, applying epoxy, and surface finishing/painting so no serious safety precautions were needed.

Testing the Rocket Safely

The two things we did testing on for the rocket was a tensile test on the rivets we would be using to connect the body and coupler tubes and an explosion test on our pressure redirect system to make sure it could handle the explosion from the motor backup parachute eject charge. In order to do the tensile test on the carbon fiber and rivets, we used the tensile testing machines at our university under the supervision of one of the faculty, making sure everything was done safely. For the testing on the pressure redirect, we took black powder charges and ignited them under the redirect from a safe distance away simulating the forces that would be experienced during flight. The component was able to withstand a charge over twice the size we would be using so it was deemed safe. When doing our actual test flights for the rocket we had Gary Stroick, a level 3 certified Tripoli member, supervise all of our flights. He had the all the pieces needed to run an effective launch and made sure we followed all the safety precautions while doing our test flights. These included doing an ejection test, identifying where our cg and cp were, properly mounting the rocket on the rail, properly inserting the ignition wires, and maintaining a safe distance away during the launch among other things.

Launching the Rocket Safely

When launching our rocket as explained in the previous section we had a level 3 Tripoli member supervise our launch and he made sure we followed all the necessary safety rules. To make sure recovery of our rocket was safe we used a parachute that was rated by Rocketman for the weight of our rocket and used an appropriate shock cord and packing method so the parachute would unfold properly. We also did ejection tests on the ground to make sure the black powder charge was sufficient and so that we could see if the parachute was coming out properly. All safety decisions shall be overseen by our safety officer Malcolm DeBoer.