# Bulldog Rocketry

# Flight Readiness Report

**2016-2017 NASA Space Grant Midwest High-Power Rocket Competition**

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# Executive Summary

The Minnesota Space Grant Consortium operates and organizes the Space Grant Midwest High-Power Rocket Competition, of which draws teams throughout the Midwest United States to test and display their engineering abilities in the form of rocket science. The University of Minnesota-Duluth team, Bulldog Rocketry, plans to attend and compete with a fully designed and thoroughly tested high-power rocket. The team consists of 50 active members, some of whom are outlined in the team summary.

The purpose of the competition is to develop a high-power rocket with an adaptable motor system which allows an I-class and J-class or J-class and K-class motor to reach the same altitude. Bulldog Rocketry will be utilizing an Aerotech J-135 and Cesaroni K-2045 to prove the adaptable motor design. The avionics package will include a custom-built pitot tube which will act as an active velocity measurement device. The rocket will be fitted with an on-board, downward and upward facing cameras, providing visual data of deployment events during flight. The flight scoring will focus primarily upon the accuracy and precision of the rockets ability to reach similar altitudes with different motors.

A full recovery package, consisting of a dual deployment parachute mechanism (integrated with on-board avionics) will allow the rocket to safely descend from its peak flight altitude to land and be collected. The recovery altimeter is commercially made and has documented performance characteristics.

A full test-flight took place April 23rd and April 29th 2017, where a complete, comprehensive performance analysis of the rocket was conducted. Both test flights resulted in anomalies which caused the rocket to only complete part of the flight. The test flight data aided in further design and mechanical enhancements to make the rocket flight ready for the competition. Analysis of the test flight are outlined in this flight readiness report which will prove the rockets flight worthiness. On May 21st, the rocket will be flown at the competition in North Branch.

The combination of manual calculations, computer aided simulations on SolidWorks, OpenRocket, and test flight data are used by Bulldog Rocketry to design the best possible rocket. By using analytical engineering methods, the team is able to determine the rockets most essential dimensions including body length, nose cone design, and fin length.

Throughout the design and testing phase, team and public safety has been, and always will be, of the utmost concern.

# Bulldog Rocketry Team Summary

The Bulldog Rocketry Team is a registered student organization at the University of Minnesota Duluth that includes students from the mechanical engineering, industrial engineering, electrical engineering, computer science, civil engineering, and physics departments. Only the team leads are included since there are so many active members.

President and Project Manager: Ethan Vought (vough004@d.umn.edu)
Air-Brake: Chet Peterson (Lead)
Airframe Design: Stefan Nelson (Lead)
Avionics Design: Logan Hotek (Lead)
Recovery: Jake Gartzke (Lead)
Video: David Ries (Lead)
Simulation: Evan Boncher (Lead)
Aesthetics: Paul Cerar (Lead)
Financial: Kalli Anderson (Lead)

**Figure 1: Bulldogs approaching the launch pad.**

# Rocket Design Objective

Design and construct an "adaptable" single stage, dual deploy high-power rocket system that will fly to the same highest possible altitude on two motors that are as different as possible from one another. The rocket must be recovered safely and in flyable condition. Each team must predict the rocket's flight performance and construct a non-commercial on-board data collection package for the rocket that will directly measure velocity versus time, for comparison with data collected by a commercial rocketry altimeter. The team must also log airframe separation and parachute extraction from the airframe for both drogue and main parachute deployments, and also collect up and down video from outside the airframe to certify expected drogue and main parachute full deployment.

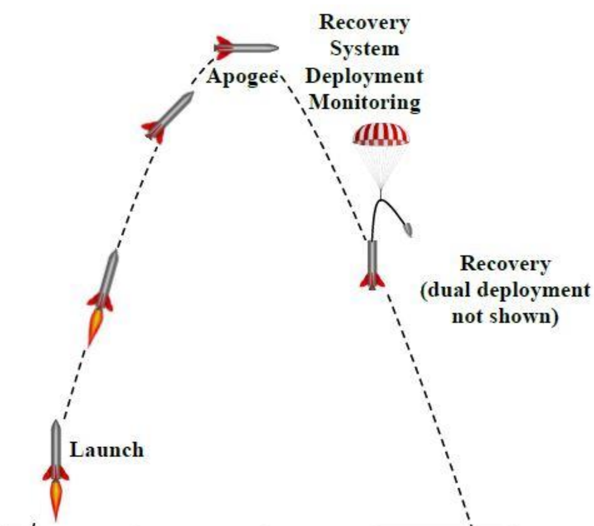



**Figure 2: Events during rocket flight.**

# Mechanical Design

Precision and accuracy are absolutely essential in high powered rocketry construction to ensure not only proper functionality but safety as well. The location of the fins and the lengths of the body tube were designed to place the center of gravity and pressure where they would provide proper stability. Observing the rocket from tail to nose, the center of gravity should be in front of the center of pressure. The fins consist of G10 Fiberglass and a Carbon Fiber prosthetic to transition the airfoil shape to the air-brake. The transition is essential for keeping the air-brake stowed until it needs to be engaged.

The air-brake is designed to rest underneath the fins, completely out of the air-flow until one of two servo motors allows it to rotate into the air-stream. The second servo, when energized, allows the brake to rotate back into a stowed position before apogee. Both servos and the recovery system are controlled by the avionics bay, which calculates the estimated apogee ten times a second. It uses this information to activate the servos and initiate recovery. The drogue chute will deploy shortly after apogee using a gunpowder charge and a piston. Once the rocket is 650 feet above the ground a chute release will release a full-sized parachute. In the event that the blasting caps do not ignite, the delayed ejection charge of the engine will force out the parachutes.

## Dimensional Specifications

The critical dimensions of the rocket were determined using OpenRocket simulations and SolidWorks part models. All lengths, thicknesses, weights, and general locations of parts were selected to optimize the overall performance of the rocket. After construction, the total length of the rocket was measured to be 52.75 inches and the total weight of all components was 6.81 pounds. The dimensions were comparable to the estimated values of 52.4 inches and 6.87 pounds from the final OpenRocket simulation. The weight discrepancy can be attributed to the epoxy used to secure components. The root and tip lengths of the 3-D printed fin set were 5 and 2 inches, respectively. Both fin and airbrake dimensions were developed simultaneously so the airbrake could be stowed underneath the fin profile while not in use. The length of each airbrake leg was chosen to be 2.96 inches. The width of the legs varied from root to tip to match the fin starting from 0.6 inches at the root to 0.53 inches at the leg tip.

## Stability Analysis

The center of pressure for the rocket is located near the top of the motor casing approximately 41.94 inches from the nose of the rocket (see Figure 3). Based upon the OpenRocket simulations, caliber values of 1.69 and 1.72 were found for the K2045 and J135, respectively. After each motor has burned out, the caliber increases to 2.64. The caliber values confirm that the rocket will be stable throughout its flight.

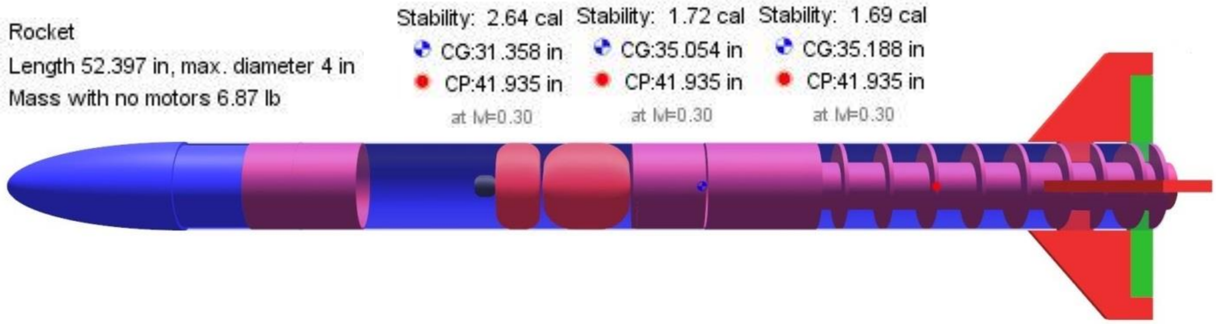



**Figure 3: Rocket render with stability data.**

## Airframe

Designing the general airframe for the rocket took careful consideration, with many different approaches to the design; research was required to complete it. Previous UMD rockets were analyzed to aid in determining how the drag system should be designed. Every component starting from the nose cone to the fins needed to be specially made in order to meet the requirements and constraints for the rocket.

After a significant analysis using computational fluid dynamics the optimal nose cone shape was determined for the flight that the simulations predicted. Simulations showed that the rocket would approach mach 1 but only very briefly. For this reason it seemed most reasonable to design a nose cone which performed best at subsonic speeds. An optimal elliptical shape proved to be the best aerodynamically. The nose cone was 3D printed so that the optimal shape could be used.

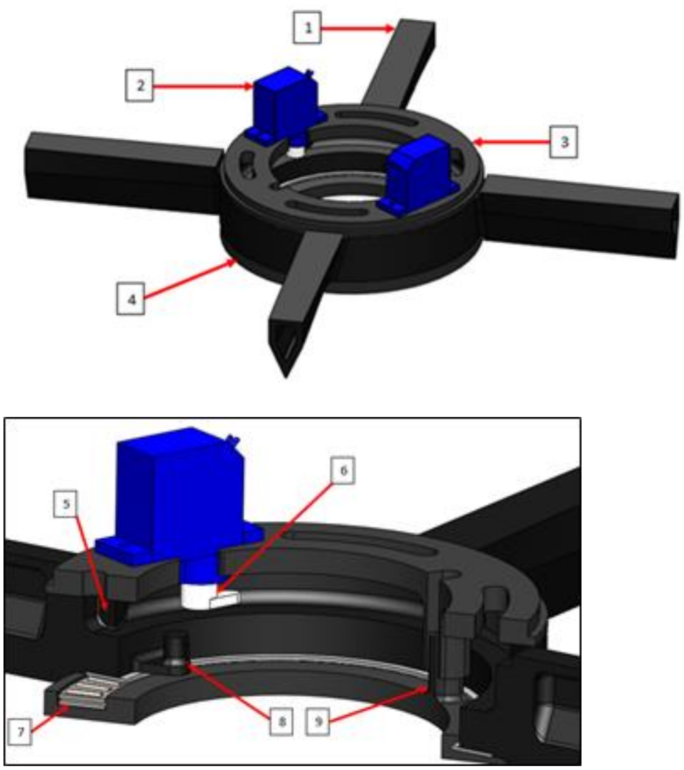
The body material had to be chosen for this rocket. Recent years showed that blue tube performed well, therefore this year's rocket was made with the high strength blue tubing. Next, the fins were in consideration. In order to accommodate for the air-brake system, fiberglass and a 3-D printed prosthetic will be used to form a fin. Again, computational fluid dynamics was used to find the optimal fin design which would be the most aerodynamic and stable for flight. The 3-D printed portion of the fin tapers from 3/16" to 1/2" thick making it easier for the air brake to hide behind. The design was chosen to reduce drag when the airbrake was stowed. A four fin design was selected because it would be the easiest to take measurements due to the 90-degree separation. Since the design is simple, this made finding the center of pressure and gravity relatively easy. After the design was finalized, the ideal motor for the flight was chosen. 5,000 engine combinations were calculated with the figure of merit equation to determine which combination would earn the team the most points possible. The Cesaroni K2045-Vmax and Aerotech J135W motor combination was chosen because it provided one of the highest figure of merit levels while still giving time for the air-brake to be effective.

## Air Brake Design

The air-brake is designed to control the rocket altitude by inducing drag forces on the rocket. By controlling the drag forces, the team is able to control each motor to the same altitude. The air-brake assembly consists of a top and bottom retaining ring, a center brake ring, a thrust bearing, two extension springs, and two servo motors (Figure 4). All three rings are manufactured from Carbon Fiber filled Nylon 11 using a 3D printer.

The entire assembly sits on the aft end of the rocket around the engine casing and is secured to two Aluminum threaded rods which run parallel to the airframe through seven birch centering rings. The top retaining ring fits inside the body of the rocket doubling as a centering ring and holds two servo motors firmly in position above it. The bottom retaining ring has a column which nests inside of a similar column on the top retaining ring acting as a spacer and making it possible to securely fasten the assembly to the aft end of the rocket without putting any pressure on the center brake ring (Figure 4). In this way the center brake ring is able to spin while still being safely secured.

The thrust bearing is recessed into the bottom retaining ring with the center brake ring resting on the top side of the bearing. The bearing system works to minimize axial friction within the braking system. Any repairs or maintenance to the air-brake assembly will be easy because the entire assembly was designed to be removable from the tail of the rocket by removing two lock hex nuts.




**Call-out components:**

1. Center brake ring
2. Servo
3. Top retaining ring
4. Bottom retaining ring
5. Internal riser
6. Custom servo horn
7. Thrust bearing
8. Spring peg
9. Second spring peg and nested columns as spacers

**Figure 4: Air brake components.**

Extension springs located inside the assembly provide the torque to activate and stow the air-brake. The springs must be put in tension by clocking the brake ninety degrees where the servos will then hold it in place. To avoid unintentional drag, the brake is stowed behind the fins when it is inactive. Once the avionics determines that the brake should be activated, the first servo rotates ninety degrees, moving the servo horn out of the path of a riser on the center brake ring and allowing it to rotate forty-five degrees before hitting the second servo horn. The air-brake is now activated; introducing four flat faces into the air stream causing drag. Once the avionics determines that velocity has been reduced sufficiently, the second servo will rotate ninety degrees and allow the center brake ring to rotate another forty-five degrees to a stowed position.

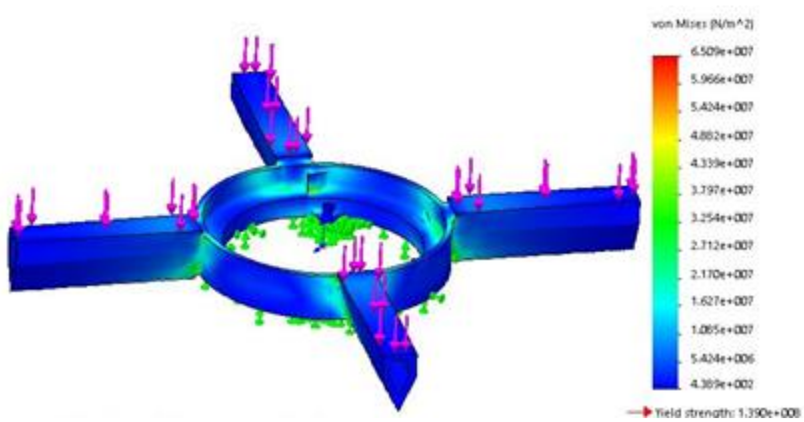



**Figure 5: Air brake FEA.**

An FEA analysis was done on the center brake ring to determine the strength of the design. An analysis of the drag system determined that the center brake ring would never withstand any more than 40 lbs. of drag force due to the projected velocity of the rocket and the geometry of the brake system. When a non-linear stress analysis was performed (Figure 5) it determined that the brake had a factor of safety of around 2.5, which the team deemed sufficient for flight.

## Recovery System

The recovery portion of the flight commences when the rocket reaches apogee. The recovery system is a dual deployment system. One ejection cap is filled with 1.2 grams of black powder as primary source for ejection. In the event of the primary ejection charge failing to ignite, the backup engine deployment charge will fire and force out the parachutes. The main chute is folded by a chute release from jolly logic that deploys the parachute at a predetermined altitude (seen in Figure 6). A piston constructed from coupler tube is used in the deployment of the parachute. The piston will protect the parachute from any burns caused by the charge and will also help harness the explosion from the ejection cap. The drogue parachute is an 18” Compact Elliptical parachute from fruity chutes with a coefficient of drag of 1.5 and a descent rate of 50 ft/sec. The main parachute equipped is an Iris Ultra

**Figure 6: Chute release.**

Compact 48 inch from Fruity Chutes with a manufacturer given drag coefficient of 2.2 and a descent rate of 15 ft/sec. A 25 ft Kevlar shock cord, rated for 1500 lbs. of force, attaches the upper and lower sections of the rocket. The cord will be anchored to the lower end of the rocket with a Kevlar loop through the top two centering rings, and attached to the top with an “i” bolt.

### Propulsion System

The Cesaroni K2045-Vmax and Aerotech J135W were the two motors selected for use in this competition. Burn times for these motors were 0.7 seconds for the K2045 and 7.1 seconds for the J135. Thrust curves for these motors can be seen below in Figure 7. The short burn time of the K2045 will allow plenty of time for the air brake to deploy and reduce the apogee to that of the J135. Based on OpenRocket simulations, the predicted apogees for these motors are 4,486 feet for the K2045 and 4,298 feet for the J135.

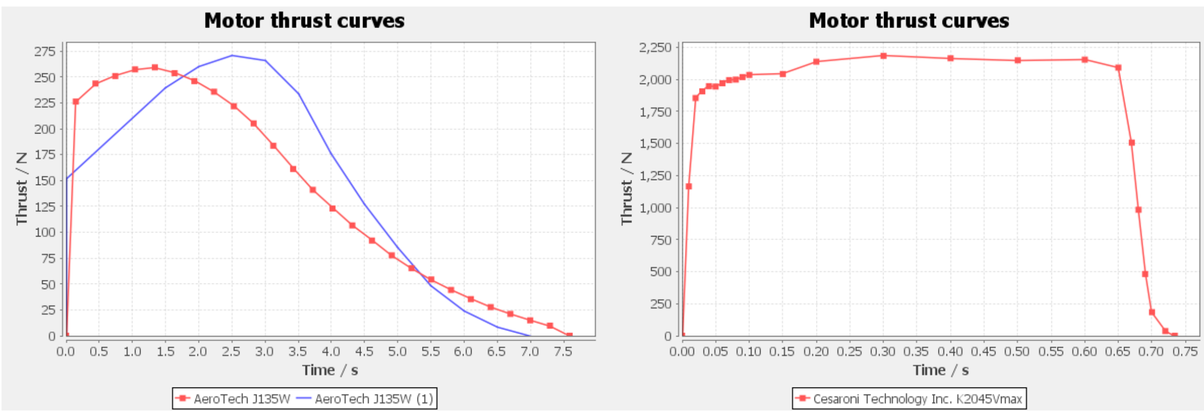



**Figure 7: AeroTech J135 and Cesaroni K2045 thrust curves.**

## Avionics Design

The avionics payload features two micro controllers: one is an Arduino Feather MO with a built-in radio packet and an Arduino Feather MO data logger. The avionics payload also features two Inertial Measurement Units (IMUs ), a standard mV output pressure sensor, and an 8 GB SD card reader/writer. The IMUs record gyro, acceleration, barometric pressure, altitude, and temperature. The pressure sensor records differential pressure using mV output readings. Together the components collect, calculate, and record data. Along with recording data, the Arduino Feather MO with a built-in radio packet was specifically chosen for its live telemetry capabilities. The Arduino Feather MO data logger records data on board the rocket and to operate the drag deployment system. The avionics payload also includes a Stratologger parachute deployment altimeter and an Altimeter Two for standardizing each team’s flights.

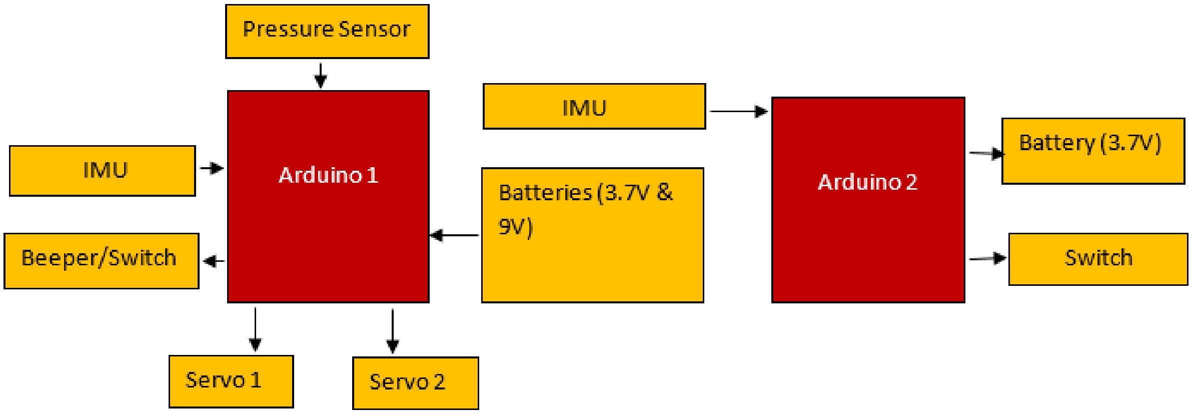



**Figure 8: Avionics control design.**

## Arduino Control Design

While the Arduino Feather MO data logger is recording the flight data and measuring the rocket's velocity, acceleration, and altitude to determine drag system deployment, the Arduino Feather MO with a built-in radio packet sends data back to the ground station through a uFL antenna setup. To determine the best time to actuate the drag system, the Arduino Feather MO data logger will take 10 measurements per second. When the statements written in the Arduino's code determine the rocket has ended boost phase, the Arduino will send a signal to the servo motors to activate the drag system on the second flight. Using the current altitude, velocity, and drag, the Arduino Feather MO data logger will then determine when to recover the drag system to be closest to the first flight altitude. In addition to the flight operations, the Arduinos will also perform pre-flight checks to determine that all functions are operating correctly. The pass/ fail checks will be audibled by a set of beeps that can be heard from outside of the rocket. Using the beeps the team can address any anomalies before flight takes place.

The direct velocity measurement will come from a custom-built system that is built within the avionics package. There will be a one eighth inch in diameter piece of aluminum tubing that protrudes from the top of the nose cone. The tube will be connected to a Honeywell TruStability HSC series pressure sensor. The sensor will output the dynamic pressure reading that is needed for a direct velocity measurement. To get the static pressure the team will use the barometric pressure readings from the IMUs. Figure 10 shows the setup of this custom-built system for the direct velocity readings. Figure 9 is a picture of the Honeywell TruStability pressure sensor. The pressure sensor will be integrated into the avionics package to directly record the velocity.

**Figure 9: Honeywell pressure sensor.**

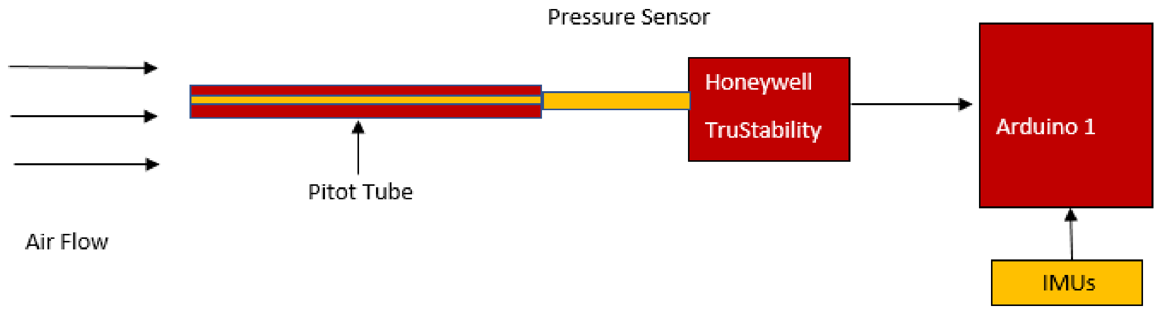



**Figure 10: Diagram of the custom-built system for the direct velocity recording.**

To ensure accessibility of the avionics payload, all electronics are connected to a single board so the electronics bay can be removed from the rocket. Two plunger switches are used so the pins can be removed on the launch pad to access and turn on the Arduinos.

## In-Flight Video

The cameras role is to sense and log airframe separation and parachute extraction from the airframe for both drogue and main parachute deployments. The cameras also collect up and down video from outside the airframe to certify expected (i.e. primary, not backup) drogue and main parachute full deployment. In order to record quality reliable video, two 1080p cameras were selected, each with built in battery and enough memory to operate independent of the other electronics. The reason for using two cameras is to have redundant recording and to balance the rocket. Having no wires running to the camera allows the video to be taken from almost any location on the rocket. The view angle and distance were selected based on the camera's field of view and the aerodynamics team's choice of location. Figure 11 shows the upward and downward views. The picture on the left is when the bottom portion of the rocket passed over the nose cone (yes it's strange but the team will discuss it later) and the picture on the right is of the downward camera on the launch pad.


**Figure 11: Upward and downward facing camera views.**

## Changes since Preliminary Design Report

Several significant changes were made to the rocket design between the time of the Preliminary Design Report and the Flight Readiness Report and they are the addition of a "vein" on the airframe, removal of the vein after testing, removal of the exterior doghouses, relocation of the cameras, a mirror housing addition to the outer airframe, and two additions to the avionics. The vein sits on the outer surface of the airframe and is half an inch tall with a semi-circular cross section. Two quick disconnects at the separation point between the upper and lower end of the rocket allow the wires to separate with ease when the parachute is deployed. With the vein it was possible to run wires from the avionics bay to the servos without running wires down the length of the shock-cord. The vein method was chosen because it significantly reduces the length of wires necessary and decreases the chances of wires being damaged by ejection charges or recovery complications.

Unfortunately, after the test flight which went awry due to aerodynamics instability, the vein was removed from the rocket because the team believed it caused instability. The vein was not balanced on the opposite side by any object with a similar frontal area. This likely caused uneven drag on the surface of the rocket which contributed to the pitching and turning that the rocket experienced in the second test flight.

The doghouses which originally held the cameras on the outer surface of the airframe were also removed. The team believes that the slightly different profiles of the upward and downward camera housings caused uneven drag on the rocket just as the vein did. To avoid the pitching and rolling which occurred in the second test flight, the cameras have been moved to the inside of the rocket. One camera is mounted to the top of the piston in a protective casing which will prevent unwanted stresses on the camera due to any impact with either the bottom of the avionics bay or anything in the recovery bay upon ejection. This will allow the team to view both the drogue and main chute deployment. The second camera is mounted in the avionics bay with a small window to the outside. A small doghouse holding a mirror is mounted to the airframe to reflect images directly into the lens of the camera. This will act as the team's downward facing camera.

Two significant changes was made to the avionics package design. In construction and further testing of the avionics package, it was found that the pressure sensor was not going to work. The chosen pressure sensor was too complex to integrate with the Arduino. Instead, the team decided to get a new pressure sensor. This sensor is easier to integrate into the existing avionics package. The second change was to reinforce the mounting hardware and wire connections. The change will ensure that the avionics will not have any more issues with the battery supply.

## Construction Methods and Pictures

The construction of the rocket was completed over the course of over three hundred man hours of which many members of the Bulldog Rocketry team contributed. Below are pictures of the construction process with descriptions of what tasks were performed and how they were executed.

**Figure 12: Centering rings being waterjet cut from aircraft grade 3/16 inch birch wood. The 3D printed parts made from Carbon Fiber filled Nylon 11.**

The engine mount consisted of seven centering rings and two aluminum threaded rods. The team manufactured centering rings from 3/16 inch thick aircraft grade birch wood. The wood is very light and contained no imperfections which made it ideal for rocket construction. The centering rings were slid onto the threaded rods and secured in their proper location by aluminum nuts. Red Loctite was used to ensure that the nuts would never move. The fins were test fitted into the centering rings slots multiple times. The entire assembly was test fit into the body of the rocket multiple times before it was epoxied and inserted to ensure precise alignment. The entire exposed body tube of the rocket was filled with body filler and sanded multiple times to hide any of the spirals that come with blue tube.

**Figure 13: Shock cord mounting on engine casing.**

The engine mount was coated in epoxy, slid into the body, and then the fins were inserted into the slots. To add the camera doghouses, a custom designed jig was used to ensure alignment, then a plum-bob was used to ensure that they were equidistant between the fins and each other. The vein was epoxied on to the body on the side opposite of the rail buttons and a plum-bob was used to ensure proper alignment.

**Figure 14: The rocket body being weighed after the body filler has been applied and sanded. Nick and David assembling the rocket work stand.**

**Figure 15: Logan (future President) inspecting the alignment and spacing of the centering rings and fin tabs before inserting the engine mount into the body. Courtney clamping the fin prosthetics together after epoxying them.**

The electronics were tested in a pressure vessel to verify that the programs and sensors were working properly. These series of test were performed multiple times with varying pressures and conditions to ensure operation. The rocket was spray painted in a properly ventilated area with proper protective equipment. The avionics were assembled and soldered in a clean and functional layout to simplify field repair. Externally removable arming pins were added to ensure that the rocket could be armed in a safe and quick manner on the launch pad.

The rocket was assembled and many successful ground tests of the recovery system followed.

## Overview of Test Flights

Two separate test flights were performed on the April 23$^{nd}$ and April 29$^{th}$ in North Branch, MN under the supervision of Gary Stroick. Both flights resulted in catostrophic failure due to various anomolies discussed later in the report. Throughout both days the temperature was hovering around 50 degrees Fahrenheit. On April 23$^{nd}$ the wind was coming out the south at a speeds up to 10 mph. On April 29th the wind was coming out of the north at speeds up to 13 mph. Both days the team set up a work station and began to go through the preflight checklist. Each step in the list must have a signiture confirming that the step has been completed properly. Once the checklist was completed and the team had confirmed that every procedure was done properly the rocket was presented to the RSO and then brought to the launch rail. Arming pins extending out of the airframe ensure that the avionics and parachute ejection sytems are not armed until the pins are pulled. Once the rocket was on the rail and oriented upwards the pins were removed and the engine was wired for launch.

**Figure 16: Flight one cato immediately after ignition.**

The first flight was using the AeroTech J135 which resulted in a total catastrophic failure of the forward closure which immediately ejected the nose cone on the launch pad and ruined the flight (seen in Figure 16). The rocket went approximately 13 meters in the air and completed 2 complete flips before landing on the ground and lighting on fire. The shock cord burnt when the exhaust nozzle pointed at the cord which caused the nose cone to separate and thus safely

**Figure 17: Flaming rocket after test flight one.**

descend to the ground under the drogue shoot. The nose cone, avionics, parachutes, and cameras were not damaged due to the separation, the rest of the rocket was completely destroyed by hot fire. The hot fire can be seen destroying the airframe in Figure 17.

The team worked diligently to completely rebuild the rocket in 5 days so they could complete yet another test flight on April 29th, unfortunately the second flight didn't go much better. The second flight was with a Cesaroni K2045. The first half of the boost phase went well, but as you can see in Figure 18 the rocket began to pitch downwards due to aerodynamic instability caused by the doghouse. After the rocket was perpendicular to the ground the nose cone separated at 116 meters due to a pressure differential created by the massive change in direction during the boost phase. The shock cord passed by the nozzle and separated the upper and lower portion of the rocket but not before zippering the lower portion of the rocket. The lower portion of the rocket free fell back to earth and hit the ground causing the fins to separate from the airframe. The avionics bay deployed under a tangled main parachute but landed softly. The progression of the flight can be seen in Figure 18.

**Figure 18: Flight two aerodynamic instability causes early deployment.**

Although nether test flight reached anywhere close to the predicted performance, valuable lessons were learned and it gave the team the opportunity to remanufacture the rocket and problem solve / troubleshoot the design.

## Launch Analysis

Although each test flight had its respective complications, the team can still make conclusions from the collected data.

### Test Flight One

In the first launch the boost phase lasted for 0.41 seconds and provided a maximum acceleration of 13.32 g's. With this acceleration, the rocket was able to reach a maximum velocity of 53.56 m/s according our data package. During the boost phase of the first test flight, the forward enclosure was destroyed corrupting the rest of the boost phase.

### Test Flight Two

In the second launch the boost phase lasted about 0.6 seconds and provided a maximum acceleration of 23.8 g's. With this acceleration, the rocket was able to reach a maximum velocity of 282 m/s according to our data package, approaching Mach 0.82. Unfortunately, after the rocket ended its boost phase it became unstable. The instability caused the rocket to go horizontal at which point the avionics package experienced a great amount of force. This caused the mounting hardware and wire connections to the electronics to fail. Thus the avionics package lost power and stopped recording data.

## Coast Analysis

The coast phase of the first two flights began with engine burnout and ended with parachute deployment. Since both flights had their respective complications, the coast phase of both flights was changed. That being said, conclusions can still be drawn from the collected data. Also, the air brake was not deployed on the first two flights.

### Test Flight One

For the first flight the coast phase lasted 1.6 seconds and had a starting velocity of 53.56 m/s. The acceleration decreased almost immediately due to the engine failure, but overall for the coast phase had a max negative acceleration of around 20 g's.

### Test Flight Two

The second flight coast phase lasted 1.5 seconds and had a starting velocity of 282 m/s. During the second flight the amount of force on the avionics made its mounting hardware and wire connections fail. This caused the StratoLogger and the Feather MO data logger to lose power and stop recording data. Thus, the team cannot get an accurate coast phase acceleration measurement.

## Recovery System Analysis

During both test flights the rocket failed to reach apogee. Because of this, the recovery system of the rocket was never truly deployed, however it did go through many stresses that pushed its components to the limits. On the first test flight due to the forward closure failure that caused the engine to burn upwards, the piston, parachutes and nose cone were all deployed. The piston successfully protected the parachutes from seeing any flames that could have destroyed them. The temperatures and created by the engine failure were much higher than the black powder charge would have been that was supposed to deploy the recovery system. On the second flight, the forces that the shock cord experienced were way also stronger than it would normally experience on a standard flight. The rocket turning horizontal while going at a very high velocity caused the shock cord to zipper the body tube twice and tear the cord. The cause of the Kevlar cord tearing is not known however.

## Pre-flight / Post-flight Procedure Analysis

The pre-flight and post-flight procedure includes all steps necessary to safely prepare and assemble the rocket for launch and recovery. Each step in the procedure requires the signature of two members of the team before the rocket is launched. This year's procedure was taken largely from the procedure used by the Bulldog Rocketry team in previous years, however a few modifications were made. Most of the additions were made to the recovery section because of the new system that was implemented this year. Some of these changes include filling the PVC ejection charge with the proper amount of black powder, inserting the nichrome igniter into the wire connector and black powder, and securing the main parachute with a fully operational chute release. The team followed all steps to the procedures which cause pre and post flight procedures to go smoothly and without hiccup.

### Data and Video Collection Analysis

Bulldog Rocketry performed extensive tests of both the avionics and video collection packages before the test flights to ensure best practice and operation. From the data that was recovered, the team was amazed to see how closely the data lined up with the Altimeter Two and Stratalogger. After both test flights the avionics package was tested after impact and everything functioned properly. The team plans to make the fastening equipment and wire connections more robust to handle the amount of force it receives on takeoff.

The video from the first two test flights turned out great. Bulldog rocketry is changing the way the cameras are mounted to help fix the stability problem. The first camera will be mounted on top of the piston to capture the parachute deployment event. The second camera will be mounted inside the rocket and attached to the nose cone. The camera will use a mirror to capture a downward facing video of the rocket.

#### Test Flight One

During the first test flight, both the avionics and video collection packages worked seamlessly. On the first flight the avionics package had a hard impact with ground which made the avionics restart. This is likely due to a voltage spike. Although this impact made the avionics package restart the team was successful in recovering all the data.

#### Test Flight Two

Unfortunately, during the second test flight the data and video collection had issues. The upward facing camera was not turned on correctly. This issue will be resolved by following the pre-flight procedures more closely and checking the cameras operation by using a provided phone app from the manufacturer. During the second flight the amount of force on the avionics made its mounting hardware and wire connections to fail. This caused the StratoLogger and the Feather MO data logger to lose power and stop recording data.

## Test Flight Predicted vs. Actual Performance

The data for the test flights can be found below compared against the predicted results. The test flights were clean flights meaning that no drag system was deployed. The reason for the two clean flights is because the internal calculations to deploy the air brake depend heavily on the coefficient of drag of a clean rocket. The performance of both flights will be shown in both graphical and Numerical form below. Discrepancies in the data will be described below each graph.

### Test Flight One

**Table 1: Numerical data of test flight one vs predicted.**

| Flight One: Aerotech J135 | Flight One | Flight One Predicted | Flight Accuracy |
|---|---|---|---|
| **Mass (kg)** | 3.54 | 3.54 | 100% |
| **Max Alt AGL CD (m)** | 13.7 | 1367.6 | 1% |
| **Max Alt AGL Alt2 (m)** | 15.2 | 1367.6 | 1.1% |
| **Max Alt AGL SL (m)** | 16.6 | 1367.6 | 1.2% |
| **Max Velocity CD (m/s)** | 53.6 | 149.4 | 35% |
| **Max Velocity Alt2 (m/s)** | Corrupt | 149.4 | 0% |
| **Max Velocity SL (m)** | 55.0 | 149.4 | 36.8% |
| **Max Acceleration Alt2 (g's)** | Corrupt | 5.2 | 0% |
| **Boost Time (sec)** | 0.41 | 7.6 | 13.1% |
| **Coast Time (sec)** | 1.6 | 9.5 | 16.8% |
| **Descent Rate (m/s)** | 1.2 | 15 | 8.1% |

*CD denotes the custom data package, SL denotes StratoLogger, and Alt2 denotes the Altimeter 2.

### Test Flight Two

**Table 2: Numerical data of test flight two vs predicted.**

| Flight Two: Cesaroni K2045 | Flight Two | Flight Two Predicted | Flight Accuracy |
|---|---|---|---|
| **Mass (kg)** | 3.47 | 3.47 | 100% |
| **Max Alt AGL CD (m)** | 116.1 | 1311.0 | 8.8% |
| **Max Alt AGL Alt2 (m)** | 115.5 | 1311.0 | 8.8% |
| **Max Alt AGL SL (m)** | 120.3 | 1311.0 | 9.1% |
| **Max Velocity CD (m/s)** | 282.6 | 309.12 | 91.4% |
| **Max Velocity Alt2 (m/s)** | Corrupt | 309.12 | 0% |
| **Max Velocity SL (m/s)** | 286.1 | 309.12 | 92.5% |
| **Max Acceleration Alt2 (g's)** | 23.8 | 51.5 | 46.2% |
| **Boost Time (sec)** | 0.59 | 0.75 | 78.6% |
| **Coast Time (sec)** | 1.5 | 13.8 | 10.9% |
| **Descent Rate (m/s)** | Corrupt | 15 | 0% |

*CD denotes the custom data package, SL denotes StratoLogger, and Alt2 denotes the Altimeter2.

After the test flights, it was determined that the Altimeter two was reporting erroneous data in some cases. Bulldog rocketry also lost data in the first flight likely due to hard landing. The team also lost data in the second flight likely due to the failure of the battery supply mounting hardware during the high speed ejection. The team does not predict that to be a problem at a normal low speed ejection.

## Graphical Data of Test Flight

### Test Flight One

The first flight did not achieve its predicted altitude. Subsequently, there is a massive amount of error in the graph. This is due to the fact that the rocket had a catastrophic failure of the forward enclosure of the rocket engine. This caused the flight altitude to be nothing close to that of the predicted altitude. With a successful rebuild now complete, the team plans to achieve the predicted altitude of 1367 meters.

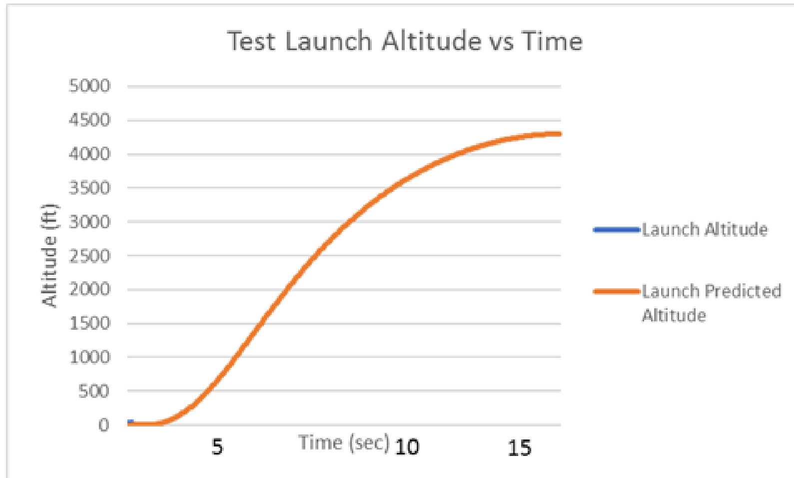



**Figure 19: Test flight one altitude vs predicted altitude.**

The first flight did not achieve its predicted velocity. Subsequently, there is a massive amount of error in the graph. This is due to the fact that the rocket had a catastrophic failure of the forward enclosure of the rocket engine. This caused the flight velocity to be nothing close to that of the predicted altitude. With a successful rebuild now complete, the team plans to achieve the predicted max velocity.

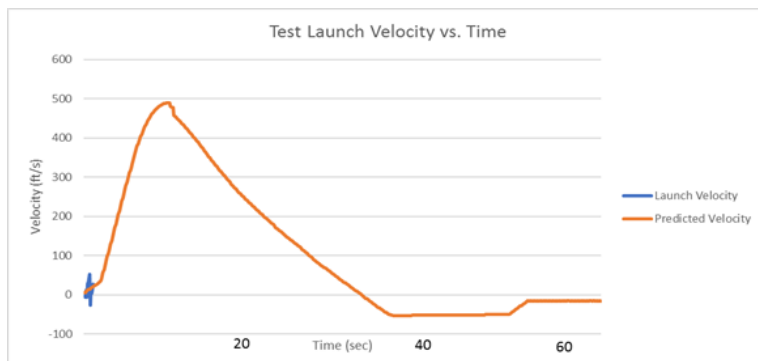



**Figure 20: Test flight one velocity vs predicted velocity.**

### Test Flight Two

The second flight did not reach its predicted altitude. Subsequently, there is a massive amount of error in the graph. This is because there was an instability in the design of the rocket. Also, the amount of force caused the avionics package's mounting hardware and wire connections to fail. This caused the loss of power and subsequently the loss of data. Going forward with both issues being fixed the team plans to achieve the predicted altitude of 1311 meters.

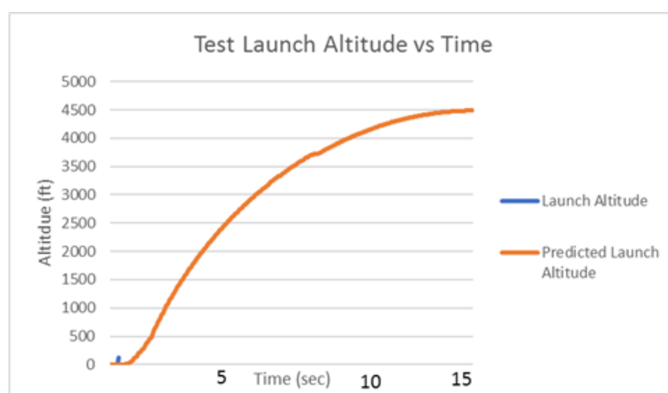



**Figure 21: Test flight two altitude vs predicted altitude.**

The second flight did not reach its predicted altitude. Subsequently, there is a massive amount of error in the graph. This is because there was an instability in the design of the rocket. Also the amount of force caused the avionics package's mounting hardware and wire connections to fail. This caused the loss of power and subsequently the loss of data. Going forward with both issues being fixed the team plans to achieve the predicted max velocity of 309 meters per second.

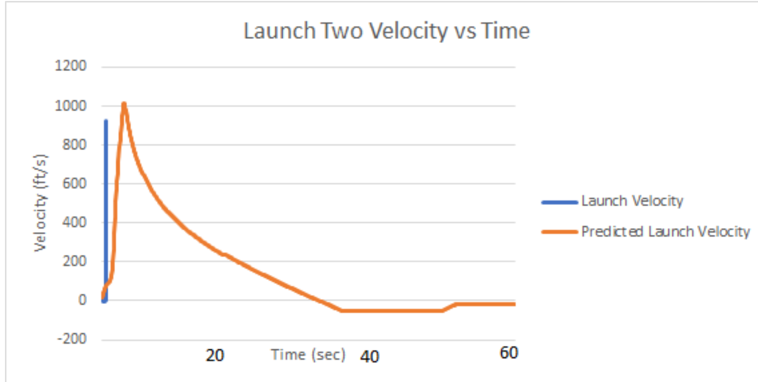



**Figure 22: Test flight two velocity vs predicted velocity.**

## Rebuild One – Trial By Fire

On 4/23 the UMD rocketry team performed a test flight using an AeroTech J135W-14A as the first of two potential test flights. Immediately upon ignition on the launch pad an engine failure caused the rocket to separate and burn from both the top and bottom of the engine. The team believes this was due to a failure of the forward end closure of the AeroTech motor (23). This caused the engine to burn both downwards and upwards which forced the piston to eject the recovery system and avionics bay. The entire lower portion of the rocket needed to be rebuilt, including the entire engine assembly, the center brake ring of the air-brake, and the recovery system housing tube. The fins, avionics, top and bottom centering ring for the air-brake, the drogue parachute, and the main parachute were all salvageable. The team was able to rebuild the entire rocket in only 72 hours. This swift recovery time is attributed to the team's quick action to salvage parts and their foresight in planning material purchases for this possibility. Twice the amount of necessary building materials was purchased ahead of time in the event that something disastrous like this were to occur.

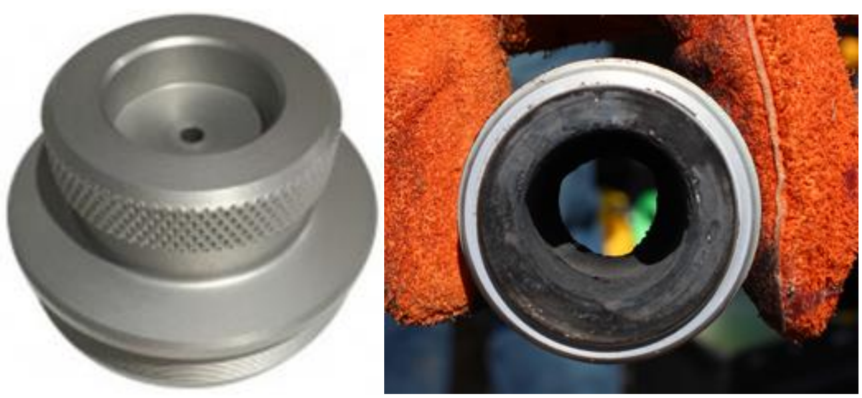


**Figure 23: AeroTech Forward Closure (Left), AeroTech failed Forward Closure (Right).**

After considerate flight analysis it was determined the failure was due to a defect in the forward closure of the AeroTech motor itself and not to any failures in the teams design. For this reason, no additional changes were made to the original design when the rebuild was done.

## Rebuild Two– Trial By Impact

On 4/29 the UMD rocketry team traveled to North Branch to perform the second test flight with the new rebuilt rocket. The team chose to test the Cesaroni K2045 because, aside from a second forward closure failure for the AeroTech, the Cesaroni motor would cause greater strain on the rocket due to the extremely peak thrust. The rocket flew straight right until the coast stage which came 0.7 seconds after ignition. Once the rocket reached the coast stage it began to tumble and turned horizontal. The nose cone ejected soon after the rocket turned horizontal and the shock cord zippered up the side of the rocket before breaking. The avionics, nose cone, and parachutes were ejected from the system and, once again, survived unscathed. On the lower portion, however, three of four fins broke off, a majority of the body tube was zippered, and one fin on the air-brake center ring was cracked. The team believes the crash was caused by a severe aerodynamic issue. The doghouses, although very similar, were not identical and the team believes this discrepancy caused one side of the rocket to experience more drag than the other which caused the initial tumbling of the rocket.

Once moving horizontally, it appears that the velocity of the rocket caused a boundary layer of air around the airframe which was much lower in pressure than the internal pressure of the recovery bay. This pressure differential must have been high enough to shear both of the small shear pins holding the upper and lower section together and causing a deployment. The team is confident this was not an engine or recovery system problem because the charge under the piston was recovered still packed full with gunpowder, the pre-flight checklist which included shear pin insertion was followed perfectly, the avionics never recorded sending a deployment signal, and the back-up motor ejection charge was recovered in the motor tube entirely un-spent. Therefore, because no on-board system ejected the nose cone it must be assumed that an issue with differential pressure caused the separation.

In 24 hours the team was able to rebuild the rocket for a second time and resolve all of the issues that caused the failure in the second test attempt. The changes to the design are outlined in the following section.

## Planned Changes before Competition

Several design changes were made after the events of the second test flight. All exterior features which the team felt could have caused the aerodynamic issues were removed. The cameras were moved to the inside of the rocket. One camera was placed on top of the piston so that the drogue and main chute deployment could be clearly witnessed. The second camera was placed on the inside just below the avionics bay. A small mirror housing was designed and epoxied to the outer body of the avionics bay to reflect the outside images through a small hole in the airframe to the second camera mounted on the inside. The vein, which covered wires that ran down to the air-brake, was also removed from the design. In the future, the wires will be covered with tape which will secure them to the airframe while eliminating any stability problems that the vein may have been causing while not altering the functionality of the air-brake.

To solve the pressurization issue two 1/16 inch holes were drilled into the top of the recovery bay so that pressure within the rocket can equalize. One 1/8 inch hole was also drilled slightly above the piston so that pressure can be relieved in the event that pressure build up in piston begins to move it up the recovery bay. The hole also prevents any issues with expelling the gases created by the ejection charge when the piston is actually supposed to eject the parachutes.

The team is confident that these design changes will end the aerodynamic and pressure issues that originally caused the failed test flight on 4/29. No design changes were made as a result of the 4/23 flight because an unavoidable motor failure was determined to be the cause.

## Key Findings/Potential Design Improvements

The vein and doghouse design caused aerodynamic instability but the team would like to implement these designs in the future. More testing and analysis will be required to alter the design so that all instability problems can be resolved. The doghouse and vein design has significant advantages that the team feels are worth looking into.

## Budget

**Table 3: Total budget of rocket.**

| **Team:** | **Item:** |
|---|---|
| **Part:** | **Cost:** |
| **Air-Brake** | |
| Servo x 2 | $80.00 |
| Bearing | $10.00 |
| Air Brake | - |
| Tabs for fin | - |
| Fins | |
| Misc. Hardware | $15.00 |
| **Simulation** | |
| 4" Nose cone (3D Printed) | |
| **Avionics** | |
| 2 Arduino transmitters | $69.90 |
| Straight Pitot Tube | $158.00 |
| Pressure Sensor | $50.00 |
| 10 DOF Sensor | $30.00 |
| Misc. Hardware | $40.00 |
| Avionics Board (3D Printed) | - |
| Batteries | $30.00 |
| **Recovery** | |
| Iris Ultra Compact Chute 48" | $168.00 |
| Compact Elliptical Chute 18" | $60.00 |
| Shock Cord | $11.00 |
| Ejection Canisters (5 pack) | $10.00 |
| Piston | - |
| Black Powder | - |
| Chute release | $129.00 |
| **Aesthetics** | |
| Paint | $50.00 |
| **Airframe** | |
| Blue Tube | $95.85 |
| Coupler (Blue Tube) | $10.95 |
| Motor Mount Tube (Blue Tube) | $23.95 |
| Epoxy | $24.00 |
| Engine Casing | $70.00 |

| | |
|---|---|
| Aft Closure | $42.75 |
| Spacer | $14.00 |
| Threaded Rod -3ft | $5.68 |
| Nuts | - |
| Bulkhead/Centering rings x 7 | $14.00 |

| | |
|---|---|
| **Video** | |
| 2 Camera's | $140.00 |
| | |
| **Total** | $1,352.08 |

## Conclusion

Bulldog Rocketry will fly the same rocket at least twice during the competition while meeting or exceeding all competition requirements. The team will use two different motors, an Aerotech J135, and Cesaroni K2045 to reach the same altitude. Students, with the help of mentors and faculty, used simulation analysis, extensive testing, and applied engineering to build a safe, quality, and innovative rocket. Students have put hundreds of man hours into this design purely due to a passion for high power rocketry and the satisfaction that comes from creating an elegant design. Although Bulldog Rocketry has faced great adversity during test flights, they will have a competitive and successful rocket for the 2017 Space Grand Midwest High-Power Rocket Competition.