ISS Space Grant Team

Exocoetidae

Illinois Space Society

University of Illinois at Champaign-Urbana

May 9, 2018

Flight Readiness Report

Faculty Advisor: Diane Jeffers (dejeffer@illinois.edu, 217-898-5888)

Team Lead: Shivani Ganesh (ssg3@illinois.edu, 309-912-8457)

Team Mentors: Mark Joseph, Jonathon Sivier, Connor Latham

Team Members: Linyi Hou, Avery Moore, Jake Hawkins, Noah Henricks, Spencer Murdoch, Hunter Schoff, Matthew Zhang, Courtney Steele, Lydia Kurtz

Table of Contents

1 Summary of Design

1.1 Structures

1.1.1 Design and Dimensions

The dimensions of the large rocket structures did not change significantly, but may have been slightly altered due to human error while cutting and assembling the components. Once the rocket was assembled, the large structures were measured to get more accurate values that could be entered into Open Rocket to output more accurate simulations. The largest design variation was the change of the coupler tube length from 10” to 16” to better organize the avionics bay.

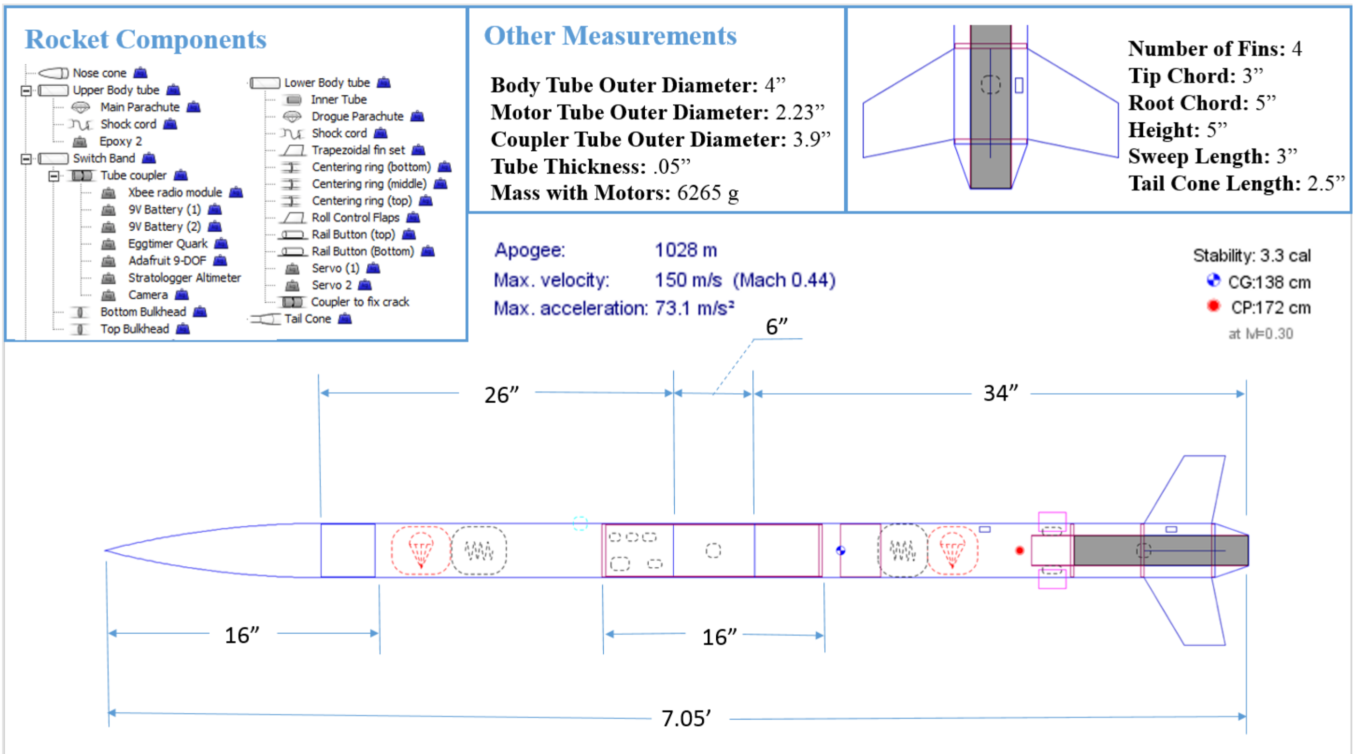

Figure 1: Open Rocket Dimensions

All of the updated dimensions are represented in Figure 1. Any changes represented were due to the iterative design process as issues were encountered by the team. An example of this occurred once the coupler tube length had been increased by 2 inches, the overall rocket height increased, which changed the placement of the CG and CP. The estimated weight during the initial stages of design when the PDR document was submitted was around 10 pounds. The final weight of the rocket ended up being 13.8 pounds. This large difference was due to underestimating the weight of the avionics section of the rocket. This underestimate was made up of epoxy weight, wires, and the mass of the mounting supports for the avionics. This mass significantly affected how both the drogue and the main parachute were selected. The remainder of the rocket’s structures were consist with the initial design.

1.1.2 Safe Flight and Recovery Systems

1.1.2.1 Parachutes

One of the important constraints of the competition is the final descent speed of 24 ft/s or less. The team had to select a combination of drogue and main parachute that would allow the rocket to descend fast enough that it would not drift far away but also, once the main parachute is deployed, be travelling at a speed of 24 ft/s or less.

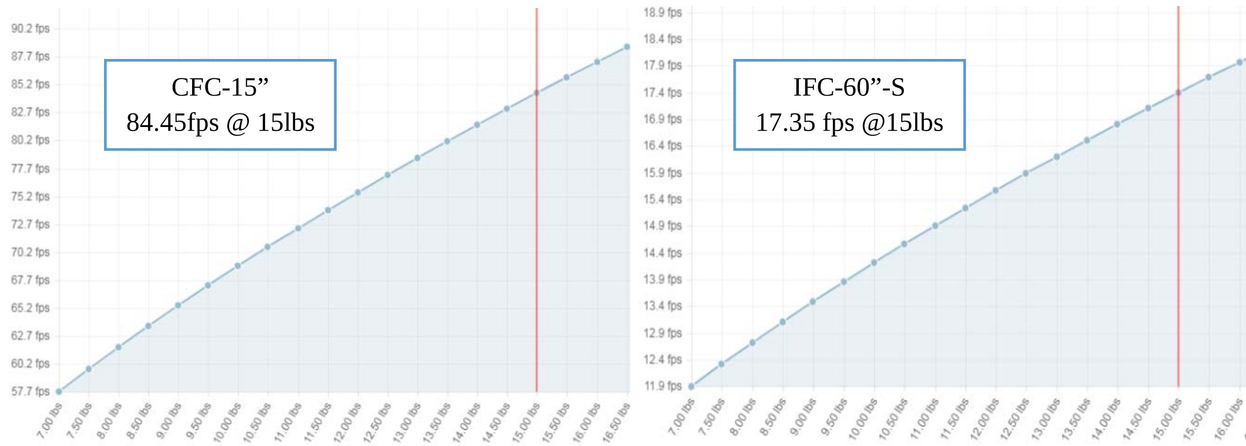

Figure 2: Fruity Chutes Descent Speed Analysis; Drogue Parachute (Left) & Main Parachute (Right)

Figure 2 depicts the graphs created by Fruity Chutes for the two parachutes that the team selected. The left graph represents the 15” elliptical drogue parachute descent speed for a 15lb mass. The team chose 15lbs because when the parachutes were selected, the avionics bay was still being constructed, so they overestimated to ensure that the rocket would be recovered safely. The descent speed obtained from this data at 15lbs is 84.5ft/s. This speed would allow for the rocket to have time after apogee to travel down quickly without drifting significantly before main parachute deployment. The right graph represents the 60” main parachute that the team selected. At 15lbs, the descent speed would be 17.4ft/s, which is safely recoverable and follows the competition constraints.

1.1.2.2 Shock Cord

The team decided the length of their sections of shock based on the positioning of the rocket components during the decent portion of the flight. The team used two 20 foot sections of shock cord. The shock cord was tied on either side to a quick link and knotted 1/3 from one end of the cord to attach to the parachute. One quick link will then be attached to a U-bolt on the bulkhead of the coupler. The other quick link will be attached to an eye bolt mounted on a centering ring of the motor mount tube assembly for the first separation (reference Table 1 for separation details). The remaining quick link will be attached to the nose cone for the second separation. The lengths of cord are outlined in Figure 3 to ensure that none of the components would collide during their descent.

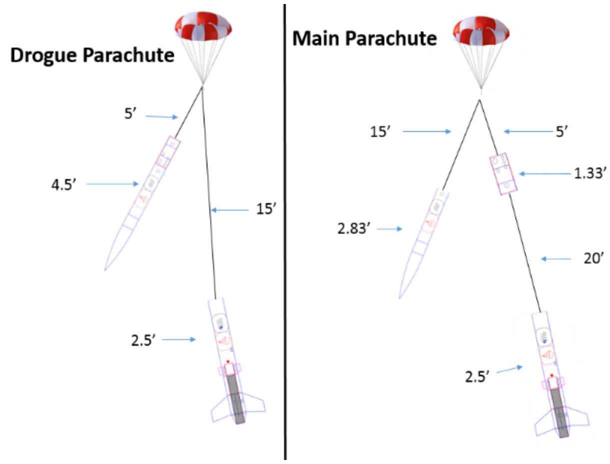

Figure 3: Shock Cord Calculations

1.2 Payload

1.2.1 Avionics Bay

The team decided to design an avionics bay that is fully removable from the coupler tube to streamline the assembly process while improving accessibility. The main structure of the bay is a 1/8" rectangular wooden sled that almost all of the electronics lay on. The sled was laser cut to be 3.5" by 16". In the middle of the sled, there will be a rectangular cutout which will be replaced by a solder board bolted to the sled that is accessible from either side of the sled. One 9-DoF magnetometer/gyro/accelerometer sensor (henceforth referred to as 9-DoF) and the multiplexer will be soldered directly onto the solder board to reduce the number and length of wires required. Two threaded rods run down the entire length of the coupler tube. The two rods are 2.5" apart from each other, lying on a plane perpendicular to the bulkheads and 1.25" from the center of the bulkhead to offset the board and maximize the space available for the electronics. The sled attaches to these two rods via 3D printed thread guides, which are bolted onto the sled. The sled/bulkhead/threaded rod assembly can be seen in Figure 4. All 3D printed parts were tested for strength and accuracy before used in the test launch.

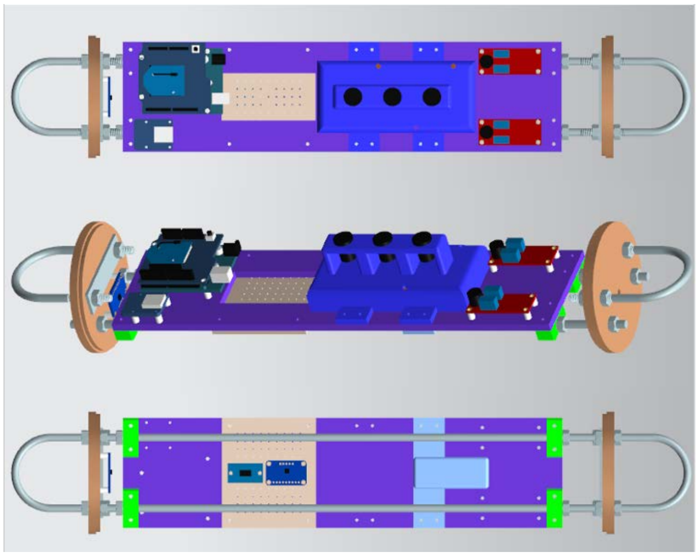

Figure 4: Avionics Bay

All of the electronics are bolted down onto the board except for one magnetometer, which is bolted down onto the bottom bulkhead. The Arduino (with XBEE Shield and XBEE Pro attached), SD card reader, three 9V batteries, one 7.4V Li-Po battery, and the two StratoLogger CF's lie on the front of the sled. One 9-DoF, the multiplexer, and the Altimeter Two lie on the back side of the sled. The four batteries and the Altimeter Two have 3D printed covers to secure them onto the sled. The battery cover holds all four batteries horizontally and is bolted down onto the sled. A frame exists on top of the battery cover that holds the three rotary switches. This allows the rotary switches to be removed from the coupler tube without having too many excessively long wires sticking out of the tube. Holes were made to allow the wires to reach the batteries. The Altimeter Two cover went onto the back of the sled and used the same nuts and bolts as the battery cover to secure it onto the sled.

The two StratoLogger CF's lie at the top of the sled. Directly below them is the battery cover. The three 9V batteries lie in the top three slots of the battery cover with the Li-Po battery on the bottom. The top two 9V batteries power the two separate altimeters and the third and lowest 9V powers the Arduino Uno. This allows the wires connecting the batteries and the electronics to be as short as possible. The Arduino Uno sits at the bottom just below the solder board. The SD card reader sits next to the Arduino Uno since it only needs to be connected to the Arduino.

1.2.2 Active Roll/Orientation System

The active roll/orientation system (detailed in Section 4) consists of two 9-Dof sensors and a multiplexer. Two sets of magnetic measurements are made from the two 9-Dof sensors that are mounted perpendicular to one another, and compared against known magnetic field coordinate systems to compute the z-axis rotation (roll orientation) of the vehicle. The multiplexer is used to expand the limited pin space of the Arduino UNO to allow access to data from both sensors. A PID controller is implemented to translate measured orientation values into servo commands that deflect two control fins and control roll.

A 3-LED system mounted on the coupler of the vehicle is used to signal the roll "intent" of the vehicle. An onboard camera (Mobius) is mounted on the upper airframe 14.5 inches from the LED's. The camera is positioned to capture LED signals and fin movements, and to provide ground reference to analyze performance.

2 Post-PDR Design Changes

2.1 Structures

The main structural changes between the test launch and the Preliminary Design Report pertained to the integration of payload, namely the location of the servos and the sizing of the coupler tube.

In the original design, the servo mounts rested on the top centering ring and were wired up to the coupler tube's bottom bulkhead. After studying the booster tube's structural integrity, members found that the servos would be more susceptible to the motor's backup ejection charge, the system would have less space in addition to the wadding, shock cord and parachute, and the servo mounts would be more likely to break due to the force during drogue deployment. Therefore, the team decided to rest the servo mounts on the middle centering ring and wire through the top centering ring to avoid the aforementioned issues. More information can be found in 3.1.3.2.

In similar hopes for optimizing space, the payload sub-team rethought the avionics bay. Due to sizing issues with the avionics bay (as described in 2.2.1), the structures team cut the overall coupler to be 16 inches as opposed to 14 inches with the same switchband length.

2.2 Payload

2.2.1 Avionics Bay Layout and Additional Hardware

As previously stated, the *Exocoetidae* changed most in its avionics bay organization, camera system, altimeter choice, and the positioning of the flaps. Firstly, the "H" configuration of the avionics bay did not realistically allow for the Arduino-XBEE module to fit inside the coupler tube, as seen in the right side of Figure 6. Therefore, to allot space for that module and still preserve a horizontal spot for the 9DOF, the team pursued the model depicted on the left diagram of Figure 6. In this model, the avionics bay is on top of a singular board, instead of the original plan that entailed the bay on two separate boards. In putting all the avionics on one board, all of the necessary electronics now properly fit in the tube. In the original layout, not all of the electronics fit in the tube because the CAD did not transfer as expected in reality. Once the CAD was revisited, it was determined that a single board will fit everything properly. All of the needed batteries in the new layout will be in a 3D-printed casing located to the right of the center of the board. Since it is not in the absolute center, this design idea allows for wires to be strung through to the left of the battery casing effectively. In addition, both the primary and backup altimeters, one on the left and one on the right, fit perfectly at the top of the board. The Arduino Uno is located at the bottom left of the board; as a result, the battery casing is in a perfect position for its purpose. Since the batteries need to power the altimeters as well as the Arduino Uno, having the batteries in between them make the most logistical sense for wire placement. For the Arduino Uno, it is located at the bottom because one of its wires needs to reach all the way down to the servos. The servos are located in the body tube, which is below where the avionics bay is; consequently, having the Arduino Uno at the bottom of the avionics bay proves most efficient in terms of space. Since the Arduino Uno must be at the bottom, the two altimeters are at the top.

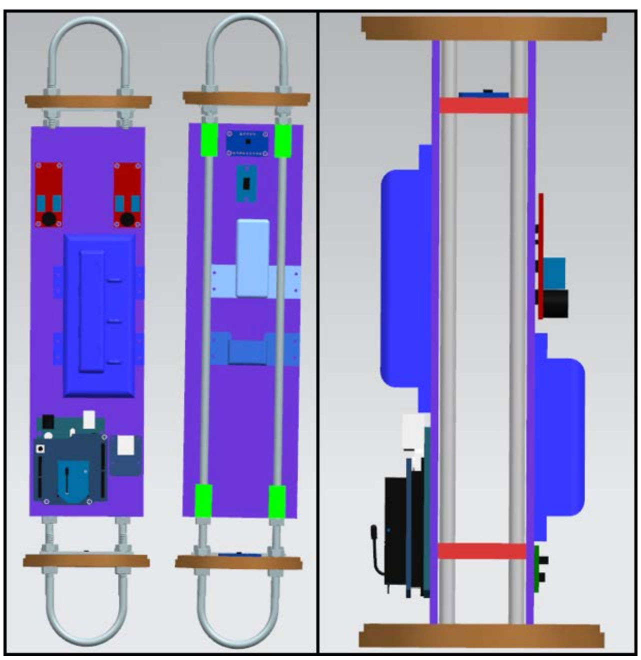

Figure 5: Test Flight Avionics Bay (Left), Original Avionics Bay (Right)

Due to supplier hurdles, the team had to omit the Mobius Mini camera. In place of it, the team settled on the Mobius Basic ActionCam for the video-logging purposes. Coming in at 1.38 by 2.40 by 0.72 inches, the device records with 1080p video quality and a 16GB card. In light of reducing build time, the team also purchased a Mobius Video Camera Shroud from Additive Aerospace to mount on the outside of the upper airframe, as seen in Figure 6.

Figure 6: Camera Mount (Left), Camera (Middle), Multiplexer (Right)

Upon soldering the original altimeter, the EggTimer Quark, the team quickly realized that the time and skill required for the soldering proved too great. As a result, the main and backup altimeters are Stratologgers. Due to changes in the roll control algorithm, the team also introduced a new magnetometer and a multiplexer. For further explanation, reference 1.2.1 and Figure 6.

3 Construction of the *Exocoetidae*

3.1 Structures

3.1.1 Construction Techniques

In order to easily access the servos' connections to the avionics bay and in turn the avionics bay as well, members had to find an avenue to connect the servos to the Arduino Uno in a way that the wires extended fully out of the coupler tube. With some innovative brainstorming, the team determined that soldering together several wires that connected the servo extension wires to the avionics bay was the best course of action. The payload sub-team connected the wires using the Lineman splice soldering technique – a process approved by NASA workmanship standards – that entails stripping the ends of both wires. After, individuals intertwined the two ends several times and then soldered them to secure their connection. Implementing this technique with the servo extension wires allowed for them to extend out of the coupler tube with connecting wires. Once completed, the team successfully accessed the avionics bay, along with its servo connection.

3.1.2 Upper Airframe

3.1.2.1 Nose Cone

As addressed in PDR, the rocket uses a 4" plastic, ogive nosecone from Apogee Rockets. Since the main parachute's shock cord connects the top of the coupler tube and the nose cone, the structures sub-team drilled two ¼'' holes along the diameter of the bottom of the nose cone and looped a piece of thin rope to create an attachment point for the main shock cord. For further illustration, see Figure 23.

3.1.2.2 Shear Pins

In order to attach the nose cone to the upper airframe, the team used shear pins. The team drilled four holes near the top of the upper airframe 90 degrees apart. Four locations, each 90 degrees apart, were marked on the inner shoulder of the nose cone. Then, the team cut out four circular brass backings and epoxied one at each mark on the nose cone. Four holes were cut into the brass backings and through to the inside of the nose cone. The process for determining the number of shear pins used is outline in Table 1.

Table 1: Shear Pin and Ejection Charge Calculations

<table>
<tr><td colspan="3">Separation 1: Drogue Deployment; Separation of Booster Tube and Coupler Tube</td></tr>
<tr><td>Tube Diameter</td><td>4”</td><td rowspan="5">Note: During actual launch using minimum may not completely shear the pins connecting the airframe.</td></tr>
<tr><td>Tube Length</td><td>19.0”</td></tr>
<tr><td>Desired Pressure</td><td>12 psi</td></tr>
<tr><td>2-56 Nylon Screws Shearing Force</td><td>64.24 lbf</td></tr>
<tr><td colspan="2">Results: Use 4 2-56 Nylon Screws
Use Minimum of 1.48 grams of 4F Black Powder</td></tr>
<tr><td colspan="3">Separation 2: Main Deployment; Separation of Nose Cone and Upper Air Frame</td></tr>
<tr><td>Tube Diameter</td><td>4”</td><td rowspan="5">Note: The main parachute size may differ the pressure inside the tube, so more black powder is recommended to completely shear pins</td></tr>
<tr><td>Tube Length</td><td>17.25”</td></tr>
<tr><td>Desired Pressure</td><td>12 psi</td></tr>
<tr><td>2-56 Nylons Screws Shearing Force</td><td>64.24 lbf</td></tr>
<tr><td colspan="2">Results: Use 4 2-56 Nylon Screws
Use Minimum of 1.34 grams of 4F Black Powder</td></tr>
</table>

3.1.3 Integration of Payload

3.1.3.1 Coupler and Switch Band Assembly

Figure 7: Coupler and Switch Band Tubes

A section of 4” blue tube that was 6” long was centered on a section of 4” coupler tubing that was 14” long leaving 4” of coupler outside of the switch band on either side. The tubes were connected with rocket epoxy and left to cure for 24 hours. This arrangement is depicted in Figure 7. This section of tubing would house the avionics bay with a bulkhead on either side of the coupler tube.

3.1.3.2 Centering Rings & Bulkheads

The centering rings and bulkheads were laser cut from aircraft plywood and epoxied together. The centering rings consist of two layers of 1/8” plywood. The bulkheads consist of three layers of 1/8” aircraft plywood. The top two layers have a diameter matching the outer diameter of the 4” coupler tubing. The bottom layer has a diameter to match the inner diameter of the 4” coupler tubing. This bulkhead design will allow the avionics bay to be completely sealed from ejection charges. The final bulkheads and centering rings can be seen in Figure 8.

Figure 8: Centering Ring and Bulkhead Laser Cut and Glued

3.1.4 Booster Tube

3.1.4.1 Fin Jig

In order to epoxy the fins to the motor mount tube, a fin jig was laser cut from plywood so the fins could be properly spaced at 90 degree angles from each other. The CAD file of that fin jig can be seen in Figure 3.

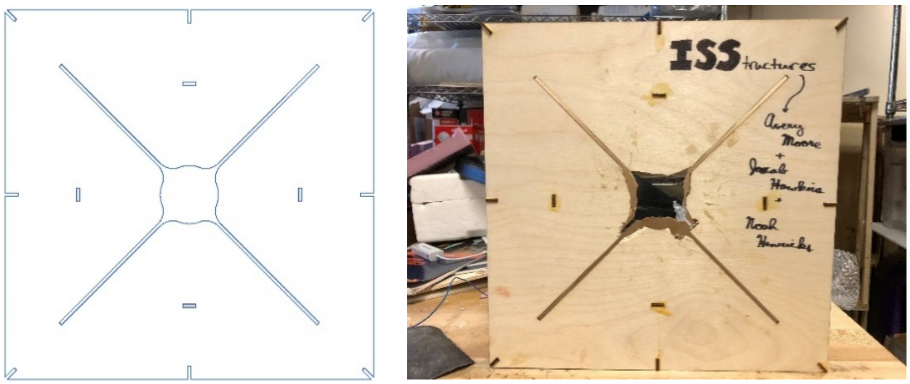

Figure 9: Fin Jig Template (Left), Constructed Fin Jig (Right)

During construction, team members realized that the fillets put in place near where the fin contacts the motor mount tube were too small and did not leave enough space to complete the epoxy fillets between the fins and the motor mount tube. To fix this, individuals cut out pieces around the center of the fin jig. The final version of the fin jig can be seen in Figure 9.

3.1.4.2 Fins

In order to create the fins, the outline of each fin was drawn on garolite. In order to minimize waste, all four fins were drawn on one sheet of garolite. The fins were then cut out with a diamond tile saw. In order to dull the sharp edges of each fin, the edges were sanded while team members wore respirators. The cut fins and original sketches can be seen in Figure 10.

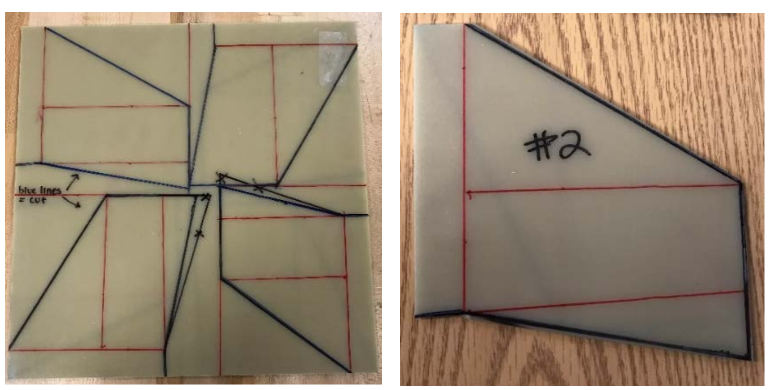

Figure 10: Fins Drawn on Garolite Sheet and Cut

3.1.4.3 Fin Slots

In order to attach the fins directly to the motor mount tube, slots had to be cut into the booster tube. To line up the slots properly, the radius of the booster tube was used to calculate the arc length required between fins so that each fin was 90 degrees from its neighbor. Using a piece of string with this arc length marked on it, the locations for the slots on the booster tube were marked. These slots were then cut using a dremel.

3.1.4.4 Rail Buttons

In order to properly mount the rail buttons onto the blue tube, small wooden blocks were used. A hole was drilled 1/8" into the block to match the diameter of the t-nut. The T-nut was then epoxied into the block and the block was epoxied to both a centering ring and the inner wall of the blue tube. This arraignment allow for the rail buttons to sit flush with the blue tube on either side as well as create a stronger joint as the wooden block was epoxied to a centering ring and the tubing. The wooden block and sunken t-nut can be seen in Figure 11.

Figure 11: Rail Button Backing

3.1.4.5 Motor Mount Assembly

In order to assemble the motor mount, the team first epoxied the lower centering ring to the motor mount tube. Then, the team used the fin jig they created to hold the fins in place while they were epoxied to the motor mount tube. The fin jig being used to align the fins can be seen in Figure 9. The team epoxied the fins two at a time and set the tube in a horizontal position overnight to dry so that gravity would pull the epoxy into a fillet shape. Then, the middle centering ring was epoxied to the motor mount tube above the fins, and the top centering ring was also epoxied onto the motor mount tube. The epoxied fins and centering rings can be seen in Figure 9.

The entire motor mount assembly was then slid into the booster tube, and the fins were then epoxied to the booster tube. The fins were again epoxied two at a time, and allowed to dry in a horizontal position overnight so that the epoxy formed fillets. The bottom and top centering rings were also epoxied to the booster tube. The booster tube with the fins epoxied on can be seen in Figure 12.

Figure 12: Motor Mount Assembly Process

3.2 Payload

3.2.1 Avionics Bay

The sled was laser cut as a rectangle with sides of 3.5 and 12 inches. The team mapped out the electronics. Once the team decided on the desired placement of the electronics, holes were drilled out to put bolts through. The electronics were held down by 4-40 and 2-56 bolts and nuts. To prevent the electronics from being smashed against the board, ¼” standoffs were used for all electronics. A 3D printed cover was used to hold all three 9V batteries and one 7.4V Li-Po battery. The top of the battery cover also has a frame to hold the three rotary switches. Two other 3D printed pieces hold down the Altimeter Two and a small solder board onto the back of the sled. Several holes were drilled into the sled to allow wires to run from one side of the board to the other. The assembled sled can be seen in Figure 8.

Two all-thread rods run down through the entire coupler tube. Four 3D printed thread guides were epoxied onto the sled to attach the sled to the all-thread. Nuts were tightened down on both ends of the sled to secure it in place on the all-thread as seen in Figure 9. The all thread is attached to the two coupler bulkheads by nuts and washers on the outside to compress the bulkheads down tightly to the coupler tube. Terminal blocks were epoxied onto the outsides of the bottom and top bulkheads. A hole was drilled into each bulkhead to allow the wires to connect to the terminal blocks. The wires that ran to the servos in the booster tube also ran through the terminal block hole in the lower bulkhead. Putty was placed over the holes and around the wires to seal off the holes.

Figure 13: Fully Assembled Avionics Sled (Left), Avionics Sled Attached to All-Thread (Right)

On the coupler tube, three holes were drilled out in a horizontal line for the three LED’s. The LED’s were positioned through the holes and epoxied 180 degrees from the center hole. Three vent holes were drilled into the coupler tube in a vertical line. A fourth vent hole was drilled below the LED holes. The above mentioned three vent holes were also used to access the rotary switches.

3.2.2 Electronics

In determining the placement of the Mobius camera, members implemented several trials of videotaping the view of LEDs from several different points on the rocket. After review, the team determined upon the camera’s “mode 1,”since it better captured a moving object compared to “mode 2.” Mounting the camera 14.5 inches from the LEDs gives an optimal view, as well as a panoramic sight of the ground (seen in Figure 14). Individuals epoxied the camera mount accordingly, which allows for easy access to the camera and serves as a secure spot for flight.

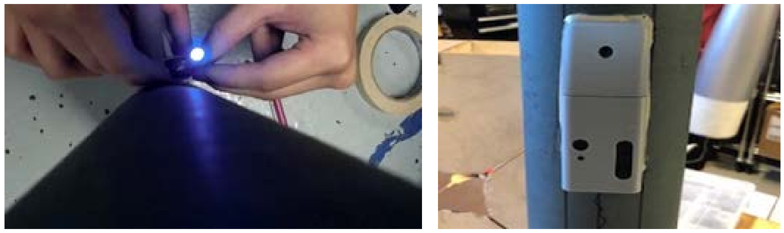

Figure 14: Camera Testing Footage (Left), Epoxied Camera Mount (Right)

4 Final Implementation of Active Roll Angle Monitoring System

4.1 Experimental Logic and Simulations

4.1.1 ANSYS

ANSYS is a software suite that enables physics simulations across a wide variety of engineering fields. The team specifically employed the computational fluid dynamics (CFD) tool to simulate lift and drag induced by fins and control flaps.

By varying the simulated wind speeds and angles of attack, detailed force responses by both the flaps and control fins were modeled. These aerodynamic models were then transferred into MATLAB, where interactions between the control code and the vehicle were further explored.

4.1.2 MATLAB

A custom MATLAB simulation was scripted to simulate the aerodynamics of the vehicle. In particular, the forces and moments induced upon the vehicle by fins and control flaps were modeled by equations derived from the aforementioned ANSYS simulations. Furthermore, the in-flight procedure (described below) was converted into MATLAB code which was then combined with the aerodynamic simulation in order to simulate the vehicle's rolling behavior in-flight.

A number of variables were tweaked to simulate different flight conditions. It was demonstrated that the code was able to handle roll conditions of over 2700 degrees per second while achieving a settling time of under 1 second. The control code could withstand intrinsic roll, varying off rail velocities, and perturbations due to sensor inaccuracies. Unfortunately the test launch rendered it nearly impossible to verify the simulation or aerodynamics, as explained in section 6.2. From the limited fin movement in the flight footage it is plausible to reason that the effectiveness of control fins were near their simulated performance.

4.2 In-Flight Procedure

A custom console interface was designed in Arduino to enable a streamlined setup process for both flights. The user would enter a password and be prompted to select Flight 1 or Flight 2.

If Flight 1 is selected, the vehicle would immediately begin its code loop, starting with standby mode to detect launch via acceleration measurements. If Flight 2 is selected, the user is then prompted to enter commands for the flight. At any time in this process the user may choose to restart from the beginning or skip all subsequent entries. For convenience, the command list was initialized with default commands provided by the competition, such that if bonus challenge A were not attempted, no modifications would be necessary. Completion of the entry process would begin the control loop similarly to Flight 1.

4.2.1 Roll Control Loop

The previously mentioned control loop is shown in Figure 12.

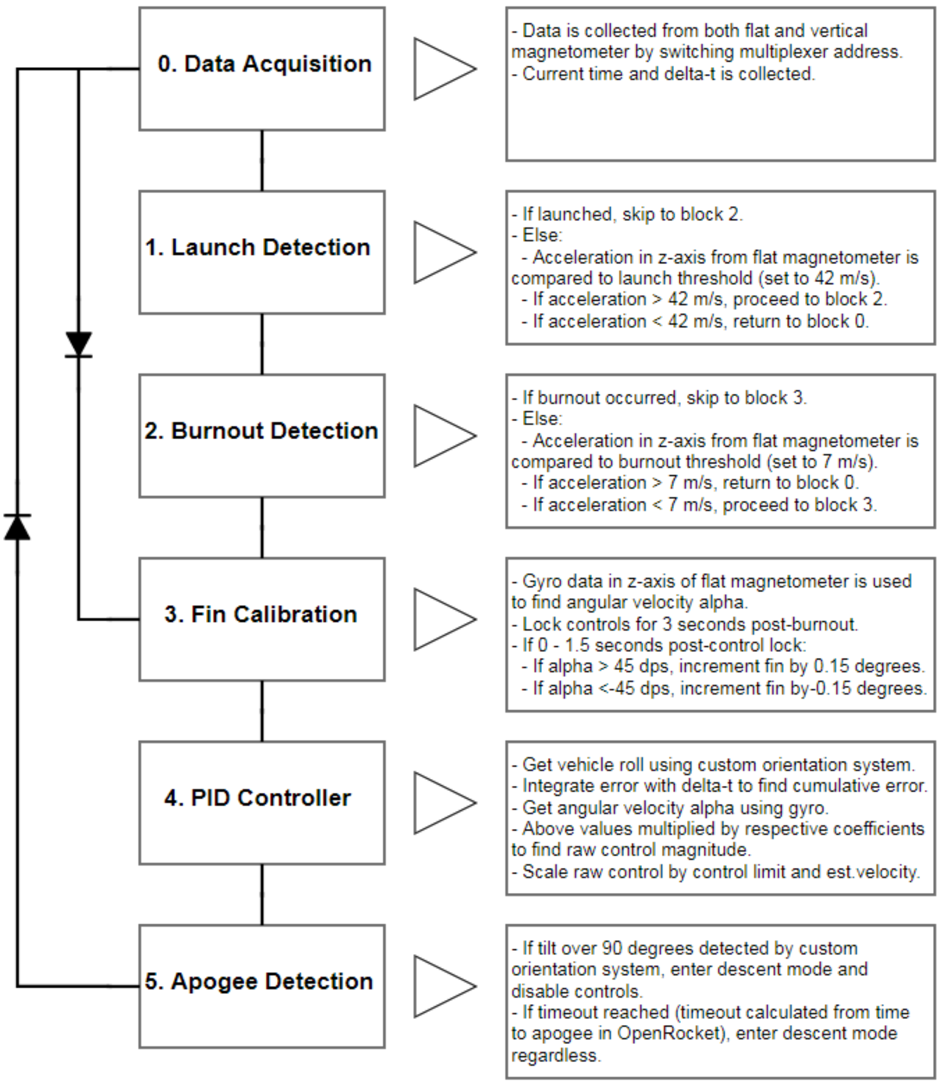

Figure 15: Roll Control Code Block Diagram

Data is collected at the beginning of each loop before any operations are performed. If launch has not been detected, the code will loop over Block 1 until z-axis acceleration exceeds the detection cutoff value (42 m/s^2). Similarly, Block 2 would continue to loop and check for burnout until z-axis acceleration is below the detection cutoff value (7 m/s^2). Following burnout, Block 1 and 2 are permanently disabled. A mandatory waiting period occurs. Then, Block 3 analyzes the intrinsic roll of the vehicle and attempts to adjust control fins to cancel intrinsic roll. This step is executed for 1.5 seconds after the end of the waiting period, and then permanently disabled. The control code then begins PID control and apogee detection. Once apogee is achieved (detected via magnetometer tilting or forced timeout), the vehicle enters descent mode where all controls are neutralized and disabled, and LED's initiate a flashing sequence.

For Flight 2, target angles are fed into the PID controller in Block 4. If Flight 2 is chosen, a segment of code in Block 4 would be activated to alter target angles according to command entries. This segment is also responsible for determining roll direction, hold time, and signaling to LED's.

4.2.2 PID Controller

Block 4 of the roll control loop utilizes a PID controller to compute the appropriate force response from the control fins. The PID controller takes into account the orientation / angular displacement (**P**roportional error), cumulative angular displacement (**I**ntegral error), and angular velocity (**D**erivative error), multiplies each term by their respective coefficients, and sums up the quantities to produce an output. The output is then normalized and scaled according to maximum deflection (derived from simulations), servo mapping (servos take 0 to 180 degree inputs but only rotate from 0 to 115 degrees), and vehicle velocity, before being sent to the servos.

The PID controller coefficients are tuned using MATLAB simulations mentioned in section 4.1.2. Each set of coefficients would be tested under varying conditions to find the most robust combination, such that tolerance is maximized while settling time and oscillation is minimized. The final coefficients utilized were kp = 2.50, ki = 0.40, kd = 0.50.

4.2.3 Orientation Sensing

Orientation of the vehicle is attained by using a pair of magnetic measurements from two 9-DoF sensors. On the pad, a pair of measurements would be taken automatically in order to construct a reference frame. Since the two 9-DoFs are perpendicularly mounted, a cross product would be taken to define a third axis. Subsequent measurements would be taken in-flight to determine the rotated frame, the rotation of which is caused by the rolling of the vehicle. Comparing the rotated frame to the initial reference frame to find a rotation matrix, roll orientation may be derived.

An alternative approach has been formulated in case magnetic interference from onboard electronics incapacitates the magnetic sensing system. Angular velocity measurements from the gyroscope of the 9-DoF would be integrated over time to find angular displacement. Integration errors are difficult to account for – a bias value measured on the pad would be subtracted from each measurement to minimize the effects of integration error.

For Flight 1, the code's main goal is to figure out the orientation of the rocket. In order to do this, the Arduino Uno on board of the rocket sends information regarding the flaps to the computer. This information is in the form of angles according to where the flaps are currently located. The code is a step function made up of testing multiple angles to determine which one is the neutralized position. Once neutralization is reached, the code holds the position with the PID algorithm.

For the second flight, the same code is used to put the rocket into a neutralized position. Once this is completed, the code will run a series of different commands for a certain time to complete the requirements of the second flight.

5 Test Flight

5.1 Completion of Rocket

Figure 16: Avionics Bay in the Coupler Tube (Left), Upper Airframe with Camera Mount, Nose Cone, and Main Parachute (Right)

Figure 17: Team on Launch Pad (Left), Completed Rocket on Launch Rail (Right)

5.2 Pre-Flight Procedures

To confirm that the different parts of the rocket will separate during flight, the team must perform ejection charge testing at least 24 hours before launch. The rocket is fully stacked up and assembled with parachutes and shear pins. The black powder charges are prepared and placed in the rocket as they would be at the launch. Instead of using the altimeters to set off the black powder charges, a controller is used to remotely set off the charges. The team leaned the rocket onto a box on the quad then set off each charge in the order that they would go off during the launch. The first charge separated the booster tube with the coupler and upper airframe. The second charge separated the nosecone and upper airframe. During this testing, the structures sub-team folded the parachutes, packed them in parachute protectors and used them during ejection charge testing. This particular round, members put rubber bands around the packed parachutes and only removed them upon attaching and placing them inside the rocket before launch.

Figure 18: Ejection Charge Testing (Nose-Cone and Upper Airframe)

Before the flight, the altimeters have to be tested. In order to do this, the altimeter will be hooked up to the computer and the program that was sent with it will be ran. The altimeter must be connected to a battery source. Once connected, the altimeter will set off a series of beeps that relay various information about previous flight data logged and battery voltage.

At the launch site, the team followed the launch procedures laid out in the Preliminary Design Report (changes have been made, however, as detailed in 5.5). Firstly, the payload sub-team connected electronics in the avionics bay, checked for accuracy and securement, slid the bay into the coupler tube and tightened the all-thread to secure the unit. Structures concurrently attached the packed parachutes to the shock cord, locked quick links to their respective eyebolts and U-bolts and connected sections of the airframe. Next, members inserted shear pins between the nose cone and upper airframe points, as well as between the coupler tube's lower shoulder and the booster tube. Machine screws were fastened into the respective t-nuts between the upper airframe and the coupler tube's upper shoulder. Lastly, the camera was slid into its mount, turned on, and secured.

After undergoing safety inspections and mounting the rocket onto the launch rail, members individually tested all three rotary switches – for the main, backup, and Arduino – and listened for the correct settings. After completing this step, the rocket was prepared for launch.

5.3 Flight Analysis

5.3.1 Launch and Boost Phase

During the launch and boost phase, the rocket performed as expected. The motor burned for the expected 3.5 seconds and sent the rocket on a nearly vertical flight path. As seen in Figure 19, the rocket did initially turn about 5 degrees from the vertical axis during the first second of flight, but from that time until the end of the boost phase, the rocket ceased turning and flew on a straight flight path.

Figure 19: Rocket Shortly After Liftoff

5.3.2 Coast Phase

During the coast phase, the rocket barely rolled, which was the goal for the test launch. However, based on the video recorded by the camera on the rocket, it is unlikely that the active roll control prevented any roll. From the camera's perspective, the rocket appeared to naturally rotate clockwise. Yet, when the flaps rotated, they rotated in the direction that induced clockwise rotation. This means that the rocket's overall design was slowing the rotation of the rocket, not the active roll control system. Additionally, the LED lights did not blink during the coast phase. This was later determined to be caused by an error on the control code, specified in Section 6.

5.3.3 Descent and Recovery Phase

At apogee, the drogue parachute successfully deployed and the rocket began its descent. The shock cord successfully held the booster tube and upper airframe/coupler tube together during descent. Under the drogue parachute, the rocket fell as expected. However, the main parachute did not successfully deploy at the primary height of 600 ft above the ground, or the backup height of 500 ft. Figure 20 shows the rocket about to hit the ground with only the drogue parachute deployed.

Figure 20: Camera View immediately prior to Landing (Left), Recovered State (Right)

With only the drogue parachute to slow it, the rocket hit the ground hard, causing the booster tube and coupler tube to crack. The payload bay also sustained damage in the form of a hole in the battery holder, and the mounts holding the all threads to the board breaking off. None of the electronic components in the payload bay sustained any damage. Two of the fillets holding the fins to the booster tube cracked, but none of the fins sustained damage.

Because the main parachute did not deploy, the team was not sure if the ejection charges had gone off. So, the team approached the rocket carefully and did not touch it until the team was reasonably confident that the ejection charges had gone off. The team saw that the shear pins holding the nose cone to the upper airframe were partially broken, which meant that the ejection charges had gone off. Some members of the team slowly removed the shear pins and the nose cone. Looking inside the rocket, the team confirmed that the ejection charges had gone off. When this inspection ended, the team carried the various pieces of the rocket back to the work area.

Since the ejection charges had gone off, the reason the main parachute did not deploy was that the ejection charges did not have the force to give the parachute the speed to break through the shear pins. The most likely explanation is that the parachute was not packed tightly enough, which increased the pressure of the parachute against the inside of the body tube. The extra friction this produced slowed the parachute when it tried to exit the upper airframe and prevented it from having the speed necessary to break the shear pins.

5.4 Post-Flight Procedure

Following the first test launch, the team followed the original launch procedures (particularly from Post-Flight 1). Due to the level of damage, members decided not pursue a second test launch that day. Subsequently, the motor and its casing were removed and the rocket was dismantled into the upper airframe, nosecone, coupler tube (with avionics bay inside), and booster tube.

5.5 Pre-and-Post Flight Procedure Assessment

Whilst writing PDR, the team formulated a primary set of launch procedures to use during the test launch. As the day progressed, however, members gained actual experience on launching routines, leading the team to reevaluate and formulate a set of launch procedures for the actual competition.

Table 2: Revised Launch Procedures

Phase of Flight	Actual Task	Completion
Pre-Flight 1		
1.1	Connect all electronic systems and assemble coupler tube	
1.2	Turn off electronic systems in preparation for charges	
1.3	Attach, fold, and pack drogue and main parachute	
1.4	Attach parachutes with quick links to shock cord	
1.5	Attach shock cord between booster tube to coupler	
1.6	Attach shock cord between coupler to upper airframe / nose cone	
1.7	Attach tracker to booster tube shock cord	
1.8	Place black powder charges on terminals	
1.9	Assemble rocket airframe	
1.10	Put in shear pins and coupler tube / upper airframe screws	
1.11	Run through last checks with team mentors	
1.12	Insert motor into lower airframe	
1.13	Set rocket on launch pad	
1.14	Turn on rotary switches	
1.15	Listen for appropriate altimeter settings and check tracker	
Post-Flight 1		
2.1	Check for unexploded black powder charges	
2.2	Assess rocket for damage	
2.3	Remove motor from lower airframe	
2.4	Decide on pursuit of flight 2 (dependent of outcome of flight 1)	
2.5	Implement repair measures (if needed)	
2.6	Download camera and sensor data, submit to judges	
Pre-Flight 2		
3.1	Charge batteries and camera as needed	
3.2	Repeat steps 1.1 to 1.15	
Post-Flight 2		
4.1	Repeat steps 2.1 to 2.6, omitting 2.4	
4.2	Turn off all electronic systems	
4.3	Detach drogue and main parachutes	
4.4	Disassemble and store rocket airframe	

6 Discussion of Results

6.1 Flight Characteristics – Predicted vs. Actualized

Table 3: Flight Characteristics

Quantity / Characteristic	Predicted (if applicable)	Actualized (if applicable)
Mass	10.0 lbs	13.81 lbs
Maximum Altitude	3372.7 ft	3271 ft
Maximum Velocity	492.12 ft/s	508 ft/s
Maximum Acceleration	239.83 ft / (s^2)	211.062ft/(s^2)
Drogue Parachute Decent Speed	80.4 ft/s	76.5 ft/s
Main Parachute Decent Speed	16.7 ft/s	N/A
Time to Motor Burnout	3.54 s	3.51 s
Time to Apogee	14.6 s	14.5 s

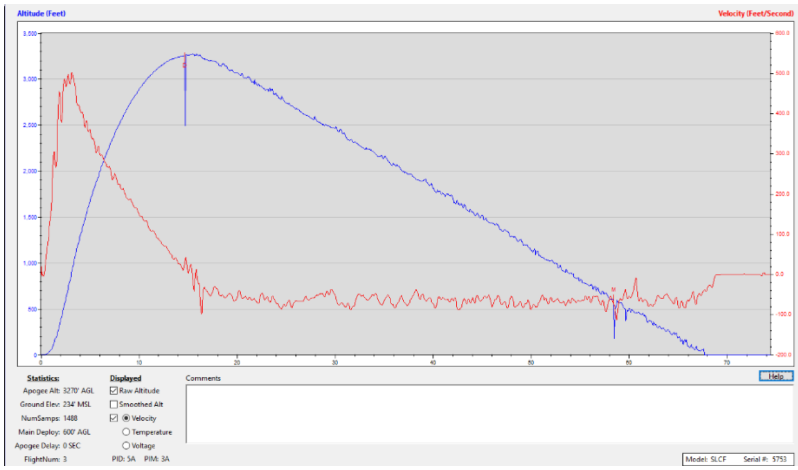

Figure 21: Primary Altimeter Data

Only the primary altimeter data is represented in Figure 22 as the backup altimeter data collected was nearly identical. Both altimeters collected data accurately and effectively. The altitude data extracted from the Stratologger was imported into excel and analyzed to create approximations for the velocity and acceleration functions. Then these functions were analyzed to extract an approximate maximum acceleration and velocity of the rocket during the test flight. The data from the Stratologger can be seen in Figure 21 and the extracted data is in Table 3.

6.1.1 Predicted vs. Actual Apogee

As detailed in the original table, the test launch OpenRocket simulations predicted an apogee of 3372.7 ft. The actual rocket attained a peak altitude of 3271 ft. The team attributed the 100 ft decrease to the margin of error with computer simulations, as discussed with the team's mentors. Furthermore, the wind speed reached up to 14 mi/h the day of launch – as even seen above in Figure 18 – which impacted the otherwise straight flight. Such a force in the horizontal direction could have altered the trajectory and, in turn, the apogee. Lastly, in addition to the significant epoxy fillets on the fins, various portions of the rocket had epoxy fillets – namely, the top and bottom centering rings, the sides of the servo mounts, and the switchband to the coupler tube. While members did add mass in those sections to account for the extra epoxy in OpenRocket, this may have contributed to the lowered peak altitude.

6.1.2 Predicted vs. Actual Peak Velocities and Accelerations

The predicted peak velocity, based on OpenRocket simulations, was 492.12 ft/s. During flight, the rocket reached 508 ft/s, which produced a minimal margin of error. Predicted maximum acceleration was 239.83 ft/(s^2), while actualized acceleration was 211 ft/(s^2). The slight difference, however, can be explained by the impulse of the motor. This rocket has been and shall be using a J415W AeroTech motor for all flights. As detailed by *ThrustCurve*, the average thrust is 415.0 N (of which OpenRocket bases calculations on). The maximum thrust, however, is 732.8 N. Due this significant upward range, the rocket could have possibly experienced a thrust anywhere between 415.0 N and 732.8 N, contributing to the increase in peak velocity and acceleration.

6.1.3 Predicted vs. Actual Descent Speed

The predicted descent speed, calculated through the Fruity Chutes descent speed calculator based on rocket mass and parachute Cd, came out at 16.7 ft/s. The actual descent speed recorded by the altimeter was 76.5 ft/s, depicted in Figure 18 and Figure 19. These two values were drastically different for the test launch, primarily because the main parachute did not deploy. The predicted drogue descent speed was 80.4 ft/s, which is much closer to the 76.5 ft/s descent speed. Therefore, the rocket performed as expected between liftoff, apogee, and drogue deployment. For further explanation and analysis on this quantity and period of flight, reference 5.3.3.

6.2 Payload

6.2.1 Avionics Performance

Two StratoLogger CF altimeters, one as primary and the other as backup, were used for altitude sensing, data logging, and parachute deployment. The primary altimeter was set to deploy drogue at apogee and deploy main at 600ft AGL. The backup altimeter was set to deploy the main chute at 500ft AGL, while backup drogue chute charge was handled by the motor ejection event.

The recovered avionics bay showed that both altimeters functioned nominally, and all three black powder charges were set off. The team was able to acquire flight data from both altimeters and their data closely matched one another.

6.2.2 Overall Performance of Roll Control System

Roll control code was set to neutralize roll for the first test flight to simulate the conditions for competition flight 1. The vehicle would detect and lock on to a specific orientation, then eliminate any roll. Expected behavior would then be compared to footage from the onboard camera to analyze performance.

From returned XBEE data, the team concluded that the orientation system malfunctioned during flight. XBEE orientation data suggested that the vehicle was perfectly aligned and not rolling throughout the flight, but this was not possible since ground testing showed measurement inaccuracies in even the most ideal conditions. Video footage further confirmed that upon launch the vehicle rotated 90 degrees clockwise, which was not reflected in the orientation data. The team concluded that code behavior was abnormal due to a timer error. The timer was used to find delta-t, which was then used to integrate angular velocity to find angular displacement. The error caused delta-t to exceed the Arduino floating point limit, which in turn caused angular displacement to overflow and return zero. Additional testing post-launch revealed sensor malfunctions in addition to the timer error.

Further analysis revealed another bug in the control code which reset the vehicle’s state in each Arduino loop, causing the vehicle to enter calibration mode every 25ms. Coupled with the sensor malfunction, it was determined that the flap servos never received commands to rotate away from their neutral position. However, from video footage it could be seen that control flaps exhibited slight twitching occasionally, which may be a byproduct of the above mentioned timer bug. Further testing is underway to mitigate these issues before the competition flight.

7 Post Test Flight Steps

7.1 Pre-and-Post Competition Timeline

Considering new workload additions in regards to rocket repairs, the team will undergo this schedule for the weeks leading up to the competition. Seen as the week of May 6th to the 12th encompasses many of the team’s finals, members plan to complete work before and after that week.

Table 4: Timeline

Week	*Hours Spent*	*Task List (# of Meetings)*
4/22 – 4/28	15	**-Test Launch** -Launch Analysis and Timeline Meeting -FRR Writing Session (1)
4/29 – 5/5	10	-FRR Writing Session (3) -Mentor Meeting
5/6 – 5/12	5	-FRR Writing Session (2) **-Submission of FRR** **-**Oral Presentation Session (1)
5/13 – 5/18	10	-Oral Presentation Session (4) -Assembly Practice (4) -Preparation of Supplies and Rocket Meeting (2)
Competition Weekend	TBD	**-Oral Presentation** **-Competition Flights**
5/20 – 5/26	9	-PFPR Writing Session (4) -Unpacking of Supplies Meeting (1)
5/27 – 6/2	5	-PFPR Writing Session (2) **-Submission of PFR**

7.2 Structures

Due to the significant impact upon landing, the rocket requires several reparations before reaching flight-ready status. Moving up the rocket, the structures sub-team will mend a fin fillet, repair the booster tube, rebuild the coupler tube, and replace part of the nose cone shear pins.

Firstly, upon landing, two fins on the same side cracked slightly, as seen in left of Figure 22 below. Since the fillet was solely affected, members will sand down the epoxy to the root of the crack, sand and scratch the new surface, and set another layer of epoxy to cure.

Due to the same cause, the top of the booster tube was fractured in two points opposite of each other, found in the right of. The team will be cutting the top of the current booster tube by five inches with a miter saw. Secondly, the team will cut the same five inch piece of regular body tube and epoxy a 3 inch coupler tube within one side, allowing for 1.5 inches to be suspended outwards. Lastly, the suspended piece will be epoxied flush to the top of the current booster tube.

Figure 22: Cracked Fin Fillet (Left), Fractured Top of Booster Tube (Right)

The coupler tube was fractured on the bottom. In hopes to increase structural integrity, the structures sub-team plans to reassemble the coupler tube. The overall length of the tube will increase in addition to a two-inch extension to the switch band, while the various holes on the switch band and bulkheads will remain the same. Bulkheads do not need to be redone and shall not be.

Lastly, as a result of the nose cone's incomplete ejection, one of the four brass backings – meant for the upper airframe's shear pins – chipped off during flight. Therefore, the team will adhere a new brass backing to the singular shear pin location using the same method found in 3.1.2.2.

Figure 23: Chipped Brass Backing (Left), Regular Brass Backing (right)

7.3 Payload

Since the avionics bay and coupler were damaged during the test flight, the team took the opportunity to fix all of the mistakes made during the first assembly of the avionics bay. The first change the team decided on was to increase the avionics sled length by two inches. To fit the new avionics sled, the coupler length will increase by two inches also. To keep the shoulder the same length of 5 inches, the switch band will increase two inches. The LED's and rotary switch holes will require minor adjustments to match their new positions. This would be done on a new coupler so no patching would be required. New LED's will be used since it will be extremely difficult to remove the old LED's from the old coupler tube.

To streamline building the avionics sled, all of the holes will be laser cut. New thread guides were designed to take up less space while being structurally stronger. Instead of epoxying the thread guides onto the sled – which was the point of failure during test launch landing - each new thread guide will be bolted down by two nuts and bolts. The new point of failure in the attachment of the thread guides is now the wood board, which is substantially stronger than the bond between the wood and epoxy.

In the initial prints for the battery and Altimeter 2 holders several dimensions were incorrect. The team used a drill and dremel to fix the mistakes. The modified pieces became quite messy, but there was not enough time to reprint the pieces before test flight. Upgraded pieces have been designed and will be 3D printed ahead of time to allow for iterations if necessary.

8 Revised Budget

8.1 Finalized Budget

Table 5: Revised and Finalized Budget

Item	Per unit cost	Quantity	Total Cost	Item	Per unit cost	Quantity	Total Cost
Full Scale Rocket							
2-56 Screws (1/2", Pack of 25)	$1.10	1	$1.10	Mounting Screws for Flaps	Owned	14	$0.00
4-40 Screws (1 1/4" and 3/4")	$1.28	4	$5.12	Multiplexer (Adafruit TCA9548A)	$6.95	1	$6.95
54 mm Seal Disk	Owned	1	$0.00	Nose Cone	$21.95	1	$21.95
54mm Blue Tube (Motor Mount)	$23.95	1	$23.95	Nuts and Washers (1/4")	$2.36	1	$2.36
98 mm Blue Tube (Body)	$38.95	1	$77.90	Nylon Spacers	$0.12	25	$3.00
98 mm Coupler Blue Tube	$39.95	1	$39.95	Parachute Protector	Owned	2	$0.00
9V Battery Clip	$0.57	8	$4.56	Position Terminal Strip	$0.76	2	$1.52
Adafruit 9-DOF Accel/Mag/Gyro+Temp Breakout Board - LSM9DS0	$24.95	2	$49.90	Quicklinks	Owned	1	$0.00
Aircraft Plywood	$19.50	1	$19.50	Rail Buttons (1010)	$3.22	1	$3.22
Arduino UNO	$22.00	2	$44.00	Resistors	Owned	3	$0.00
Backup Altimeter (Eggtimer Quark)	$20.00	1	$20.00	RocketPoxy	$38.25	1	$38.25
Bluetooth XBee Shield (Gikfun for Arduino)	$9.58	1	$9.58	Rotary Switches	$9.93	3	$29.79
Cable Ties	$7.67	1	$7.67	SD Card	$11.89	1	$11.89
Copper Wire	Owned	1	$0.00	Servo Extension Wires	$1.32	4	$5.28
Coupling Nut (Set of 2)	$1.24	1	$1.24	Servos (HobbyKing HK15298B)	$20.45	4	$81.80
Drogue Parachute (15")	Owned	1	$0.00	Shear Pins (Set of 20)	$3.10	1	$3.10
Duracell Procell 9V (x6)	$10.59	1	$10.59	Shock Cord (Set of 2, 21')	Owned	2	$0.00
Electrical Tape (Set of 6)	$5.49	1	$5.49	Spray Paint	$2.95	3	$8.85
Eye Bolts (Set of 2, 1/4")	$1.18	1	$1.18	Stainless Nuts	$0.05	16	$0.80
G10 Fiberglass (1/8", 12" x 12")	$19.36	2	$38.72	Stainless Round Head Screw	$0.04	16	$0.64
G10 Fiberglass (1/8", 6" x 6")	$10.59	1	$10.59	Standoffs (discounted set)	$0.35	50	$12.07
J Motor (Aerotech J415W-L)	$79.04	2	$158.08	Stratologger Altimeters	$49.46	2	$98.92
Lipo (Turnigy Nano-tech 450mAh 2S 65C)	$5.30	2	$10.60	T-Nuts (Set of 4)	$1.18	1	$1.18
Lockwashers (1/4")	$4.55	1	$4.55	Tailcone Retainer (Aero Pack 54L/3.9")	$57.78	1	$57.78
Machine and Sheet Screws (Set of 2)	$1.18	2	$2.36	Threaded Rod (1/4" - 20)	$1.97	2	$3.94
Main Parachute (60")	Owned	1	$0.00	U-Bolts	$4.96	3	$14.88
MicroSD Breakout Board	$7.50	1	$7.50	USB Cable Standard A-B	$3.95	2	$7.90
Mobius Basic ActionCam 16GB (with 16GB SD card)	$89.95	1	$89.95	USB Data Transfer Kit	$22.46	1	$22.46
Mobius Video Camera Mount (4", 98mm body tube)	$19.95	1	$19.95	Voltage Regulators (3.3V 950mA, 12 Pieces)	$8.99	1	$8.99
Motor Adapter	Owned	1	$0.00	XBee Pro Module (Series 1, 60mW with Wire Antenna)	$37.95	2	$75.90
Motor Casing (54-2560)	Owned	1	$0.00	XBee USB Adapter (TTL Adapter)	$11.95	1	$11.95
Mounting Brackets for Flaps	Owned	2	$0.00			Total:	$1,199.40

8.2 Post-PDR Budget Changes

The ISS Space Grant team has a general budget of $1,000 to encompass all technical expenses needed for the full-scale rocket. The actual distribution is detailed in Table 5. The team plans to expend approximately $750 for travel purposes in addition to the $400 registration fee. These do not fall under the technical project expenses. During the building process, the team purchased various additional nuts, bolts, and screws as a result of the evolving avionics bay. More information can be found in 1.2.1 and 3.2.2.