ISS Space Grant Team

Exocoetidae

Illinois Space Society

University of Illinois at Champaign-Urbana

March 9, 2018

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Table of Contents

1 Summary

1.1 Executive Summary

The Illinois Space Society (ISS) team designed the *Exocoetidae* to compete in the 2017-18 Midwest High Power Rocketry (MHPR) competition. This year's competition consists of two flights, each with different parameters. Both flights are to be flown on either an I class or J class AeroTech or Cesaroni motor, but the rocket must use the same reloadable motor for both flights. The objective of the first flight is to minimize the overall roll of the rocket. The second flight's objective is to orient the rocket's roll position according to the assigned commands. In doing so, the team must manipulate the applied forces during flight. The bonus challenge involves an XBEE radio module, which will be incorporated into the avionics to receive, transmit, and interpret the data in order to angle the rocket in the specified orientation prior to the actions being performed during flight.

The ISS team consists of 10 undergraduate freshmen from the University of Illinois at Urbana Champaign. Shivani Ganesh, a freshman in aerospace engineering, serves as the team lead and manages the project. A sophomore ISS member and the 2016-17 ISS Space Grant team lead, Connor Latham, will guide the team through his role as ISS technical director. He will aid the team through design, construction, and testing to ensure the rocket is completed safely and efficiently. The team is broken down into two sub teams; structures and payload. The structures team – led by Avery Moore, a freshman in aerospace engineering – will focus on the physical build of the rocket, as well as making sure the rocket will fulfill the competition objectives that solely rely on the aerodynamic and structural design. The payload team – led by Linyi Hou, a freshman in systems engineering and design – will configure the avionics and electronics that will control the rocket's roll and collect data during flights. Throughout the year, these sub-teams will collaborate to create a rocket capable of meeting all of the challenges in this year's MHPR.

Through research and testing, the team decided to approach both roll-control challenges with a pair of 4 in^2 flaps on the lower airframe of the rocket and run by servos following the Arduino code. In the first flight, the rocket will hold for the required three seconds post-burnout, spend one and a half seconds calibrating based on angular momentum data as collected by the gyroscope and magnetometer, and optimize for little to no roll. The second flight requires two main sectors of code. Upon inputting the provided commands, the rocket will follow a similar flight path until burnout. After the mandated waiting period, the gyroscope and magnetometer collect data every 0.05 seconds, check for data uplink/downlink, and depending upon whether the rocket reached the preprogrammed angle for the correct time period, it will continue along said loop until apogee. Once these ideas were formed, the team began design and construction of the rocket to complete these tasks.

1.2 The Illinois Space Society (ISS)

The Illinois Space Society (ISS) is a professional and technical student organization at the University of Illinois at Urbana-Champaign. The registered student organization manages six technical projects; NASA Student Launch, Hybrid Rocket Engine, NASA Space Grant, NASA Micro-g NExT, RASC-AL, and the High Altitude Balloon. This wide variety of technical projects allows the ISS members to become involved with a diverse set of technologies and challenges. ISS also serves to build its members' networks with prior members and professionals in the job market. ISS does this by organizing an array of space-related events, whether it be by attending the annual

Goddard and Von Braun National Symposiums or hosting a LinkedIn network. Lastly, ISS spends much of their efforts to inspire the surrounding community. Educational outreach extends itself in many different manners, as further detailed in section 5.5. The Illinois Space Society – through technical projects, career connections, and community involvement – has brought together a community of individuals curious about space exploration to achieve greater ambitions.

2 Structures Design

2.1 Mission Statement

The objective of this year's competition is to build a high-power, single-stage rocket that will complete two flights on an I-class or J-class motor. Each flight has a specific set of tasks that must be completed. Between each flight, the rocket must be recovered in a re-flyable condition. The first flight's objective is to minimize the overall roll of the rocket with a roll-orientation device. The second flight's objective is to follow a set of commands regarding the orientation of the rocket and to hold these positions for a given amount of time. Both flights will utilize a downward looking camera to document the rocket's roll by referencing landmarks on the ground. Roll intent will be indicated via LED's mounted in front of the camera.

2.2 Competition Constraints

At the beginning of the competition, a handbook was published that outlines the entire set of rules. The document was the foundation for the team's approach to this competition. It includes several constraints that will guide the team in the process of creating a safe and successful rocket. In order to ensure that the team followed these competition rules, Table 1 was created to compile them all. Once all of the constraints were identified, they were grouped together based on how they affected the competition. These are explained in detail, and are referenced throughout the document to ensure that all of these rules were met.

Table 1: Constraints Outlined in Competition Handbook

Category	Constraint Details	Section Addressed
Pre-Competition Prep	Each team must purchase, fly, and successfully recover a model rocket prior to building their full scale competition rocket.	Section 5.3.1
	Each team must assemble, fly and test their fully functional competition rocket at least once.	Section 5.2
	Each team must participate in the safety review held the day prior to competition.	Section 5.3
	Analysis of non-pre-qualified components must be available at the design safety review.	Section 2.3
Rocket Design	Thrust to weight ratio for each flight must be no less than 3 to 1.	Section 4.4.1
	No activation of external active roll devices until after boost.	Section 2.5
	Rockets must reach at least a 3000 ft apogee.	Section 4.4.1
	Avionics bay can be tough, but must be user-friendly.	Section 3.1.1
	Rocket must be recovered safely in a flyable condition.	Section 4.4.1
	Active roll-orientation single stage high-power rocket system.	Section 3.3
	If there is a main parachute, it must be deployed between 1500ft and 500ft above ground after apogee.	Section 2.5
	Rocket must have a descent speed less than or equal to 24ft/sec.	Section 4.4.1
	Teams must provide an easily accessible space for the altimeter two that will be provided at competition.	Section 3.1.1
	Rocket fin-stabilization with a static margin greater than 1 and less than 5 during entire flight.	Section 4.3

Construction	All fabrication work on rocket must be performed by students excluding machined parts ordered for the rocket.	Section 5
Parts	Roll-orientation device must be able to detect roll orientation along compass headings.	Section 3.3.1
	Two flights on an I-class or J-class Cesaroni or AeroTech motor.	Section 2.3
	Motor must have a built in ejection charge.	Section 2.3
	All components and materials must be ordered from a reputable high power rocketry vendor or chosen with thorough engineering analysis.	Section 5.4
	Down-looking video will be captured with a camera to view the LEDs, external airframe, and landmarks on the ground as reference to roll orientation.	Section 3.1.5
	Motor ejection backup is required.	Section 2.5
	Electronic ejection of recovery system must occur after apogee using a commercial rocketry altimeter.	Section 2.5 and 3.1.2
Competition	Teams must prepare rocket for flight within one hour to avoid penalty.	Section 5.3.3
	Teams must complete at least two flights on competition day between 9am-4pm.	
	Rockets must be ready for RSO inspection within one hour of the range opening on competition day, or after rocket recovery, post flight inspection, and after the flight data is recovered.	
	Teams must pass the Range Safety Officer's inspection the day of competition prior to flight.	

2.3 Material and Design Decisions

Through the first semester with this project, the team brainstormed and researched to develop the skeleton of the rocket. As a congregation of newcomers, a starting point seemed difficult to find. Mark Joseph and Jonathon Sivier, two rocketry veterans and ISS mentors, highlighted the primary decisions needed to move forward with any aspect of execution – diameter and material of body, method of controlling roll, material of the fins and hypothetical flaps, and type of motor.

In regards to the rocket body, the team analyzed the benefits and shortcomings of fiberglass and blue tube. The former, despite an impressive strength demonstrated in past launches, did not fit the use-case scenarios. Considering the team's composition of all freshmen, using a versatile material such as blue tube made the most sense. Along the same line of reasoning, the team opted for a 4 inch body tube instead of a 3 inch body tube. Since the competition's objectives depend heavily on the payload's performance, a larger body tube offered greater maneuverability and flexibility to experiment with the avionics bay.

Upon deciding the structural airframe, both the structures and payload sub-teams debated several approaches to the overarching challenge of controlling roll. Amongst the rather grand ideas was a pressurized set of tanks from which a fast, tangentially directed stream of air would escape to turn the rocket in the predetermined direction. Alternately, members thought of a two-flap system – 180 degrees apart and suspended above their respective pairs of fins – which would counter the roll with a simpler solution. As per opinion of older members of ISS, the team leaned towards the latter concept.

Upon deciding the approach, the structures sub-team debated upon the material of the primary fins and roll-control flaps, as illustrated in Table 2. Much contention surrounded carbon fiber, which was a pursuit of many past technical projects in ISS. Although a promising material, carbon fiber and its strengths could not justify the cost. Afterwards, plywood and fiberglass were among the remaining options. The team eventually settled upon G-10 Garolite fiberglass due to its sturdy nature. Although heavier than plywood, G-10 has proven to be exceedingly strong in past competitions. Full descriptions of each candidate material as well as its price are included in Table 2.

Table 2: Series of Proposed Fin and Flap Materials and Approaches

Materials	**Description**	**Price (approximate)**
Carbon Fiber	High strength-to-weight ratio, high tensile strength, easy to work with	$120 for 12” by 36” sheet
Carbon Fiber Honeycomb Sandwich Panels	Similar to Carbon fiber but with a higher compression strength and lower core density. Tough to work with because of the uneven honeycomb core	$177 for 12” by 24” one ply with .125” thick core
Carbon Fiber Foam Sandwich Panels	Less strength than honeycomb but more than regular panels, easier to work with than honeycomb	$155 for 12” by 24” one ply with .125” thick core
Fiber Glass	Higher weight than Carbon Fiber with a slightly lower strength	$33 for 12” by 24” with 0.03” thickness
Fiber Glass Honeycomb Sandwich Panels	Same as with the carbon fiber but with lower strength and higher weight	$103 for 12” by 24” one ply with .125” thick core
Fiber Glass Foam Sandwich Panels	Same as with the carbon fiber but with lower strength and higher weight	$80 for 12” by 24” one ply with .125” thick core

As stated in the competition handbook, the team had to choose between an AeroTech or a Cesaroni motor of I or J-class. The team’s student advisor and mentors both had further experience with AeroTech motors, so ultimately an AeroTech motor was selected out of familiarity and experience. When deciding which motor to choose, two main requirements from the student handbook had to be met; the motor must be reloadable and have a built in ejection charge.

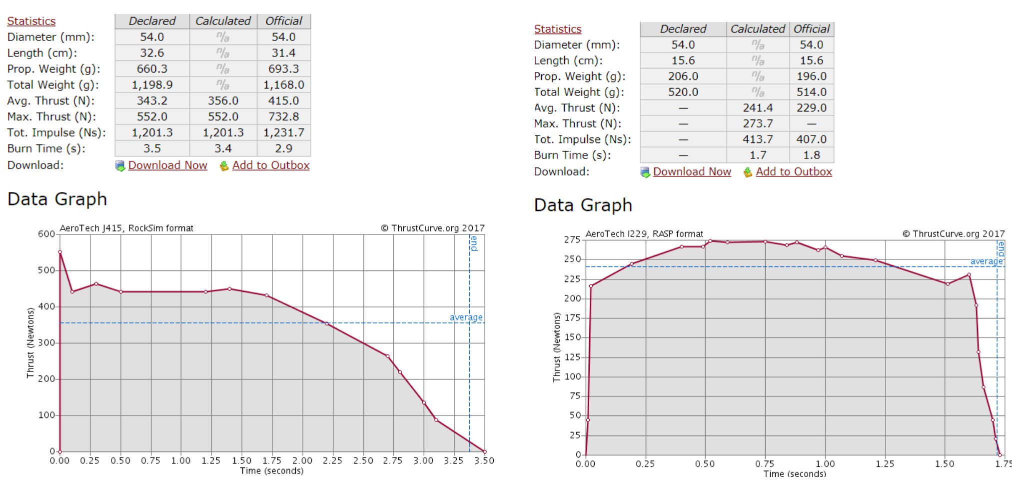

Figure 1: J415W (Left) vs. I229 (Right) Motor Thrust Curves

With these constraints, the team analyzed thrust curves provided for the given motors to review their impulse, burn time, and thrust. Two of these thrust curves, one for the AeroTech J415W motor and one for the AeroTech I229 motor, are included in Figure 1. The AeroTech J415W motor was ultimately selected, since it provides a large amount of thrust in a short period of time, allowing for a longer coast time for the active roll-orientation device to change the rocket’s orientation.

2.4 Dimensions and Weight

The rocket is split into a booster tube containing the motor mount, the coupler and avionics bay, the upper airframe, and the nose cone. An image of the full rocket and an exploded view of the rocket are shown in Figure 2. The booster tube and upper airframe are colored blue. The nose cone and tail cone are shown in a bright green. The four fins are red. The motor mount contains a tube colored turquoise and centering rings colored orange. The coupler and avionics bay are two shades of purple.

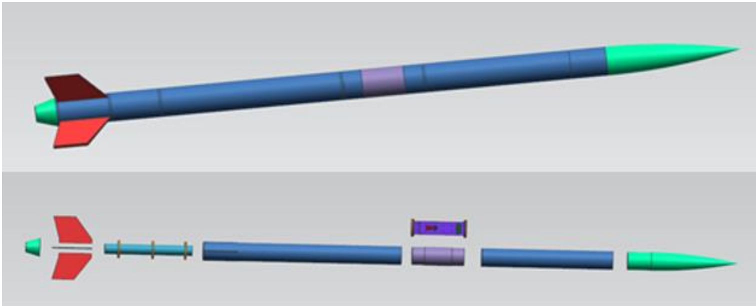

Figure 2: CAD of Full Rocket (Top), Exploded View of Full Rocket (Bottom)

2.5 Recovery System

The rocket will make use of a dual deployment parachute setup. The drogue parachute will be sized such that it will allow the rocket to descend at approximately 100 ft/s to reduce drift distance. The drogue will deploy at apogee on the primary charge. In the event that this charge fails, the motor ejection backup charge will be timed such that it will deploy the parachute within two seconds of apogee to avoid excess velocity. The main parachute will deploy on its primary charge at approximately 1000 ft in order to limit drift distance but still have ample time to open. The backup main charge will deploy at 900 ft in order to once again provide plenty of time for the parachute to fully deploy. Based on OpenRocket calculations, the rocket will land at roughly 16 feet per second - below the maximum descent rate listed in the handbook.

To ensure the team has constant contact with the rocket throughout flight and recovery, a small transmitter will be attached to a shock cord on either the main or drogue chute. This transmitter can be located with a handheld antenna, so the recovery of the rocket may go as fast as possible.

Once the rocket has landed, the team will begin walking to the landing site. The team will make sure all of the charges have gone off before picking up the different sections of the rocket and carrying them back to the launch site. If the rocket is in good enough condition to fly, the team will participate in the second part of the challenge. The second launch will have the same recovery process as the first.

The recovery devices will most likely be one Stratologger CF and one Quark running on separate batteries. Each altimeter is on its own circuit and should not affect the function of the other if there is a failure. The team used the Stratologger CF altimeter on the High Power Rocketry tutorial rockets and will be well-acquainted with them come competition flight. They will also do plenty of testing with the Quark and its associated hardware setup. These altimeters will both be located in the coupler section with the other avionics and will be activated by switches situated on the switchband.

2.6 Structures Mass Statement

Table 3: Structures Mass Statement

Structures Component	Mass	Number Needed	Total Mass
Body Tubing	2793.6 grams	N/A	2793.6 grams
Bulkheads	45 grams	2	90 grams
Centering Rings	21.7 grams	3	65.1 grams
Drogue Parachute	142 grams	1	142 grams
G-10 (12x12)	6046 g/cm^2	2	120492 g/cm^2
J415W Motor	1145 grams	1	1145 grams
Main Parachute	510 grams	1	510 grams
Nose Cone	298 grams	1	298 grams
Quick links	72 grams	4	288 grams
Tubular Shock Cord	16.5 grams/ft	40 ft	660 grams
U-Bolts	30 grams	2	60 grams
Tail cone Retainer	112.9 grams	1	112.9 grams
Epoxy	567 grams	N/A	567 grams

3 Flight Control & Data Systems

3.1 Avionics Hardware

3.1.1 Avionics Bay Configuration

The team iterated through multiple designs for the avionics bay. As designs for the roll orientation system evolved, the team decided the avionics bay must be optimized for the greatest surface area. Key electronic modules were drafted in NX and positioned in various configurations to visually aid the team's design process as shown in Figure 3.

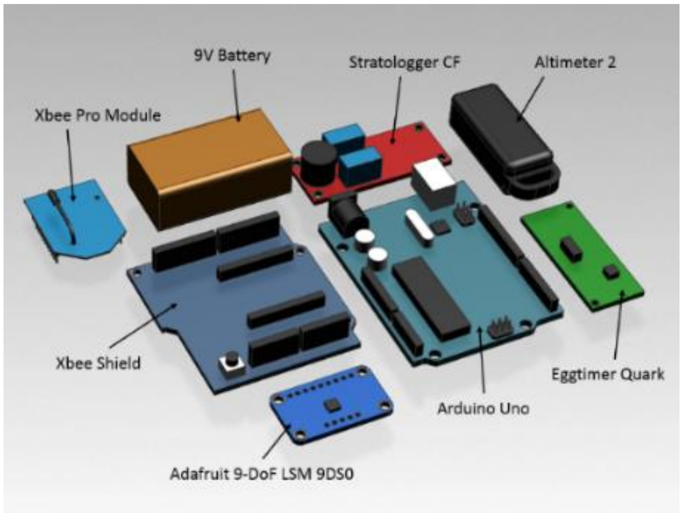

Figure 3: Key Modules in Avionics Bay

Most notably, the Adafruit 9-DoF breakout board (accelerometer, gyroscope, and magnetometer hybrid) should ideally be mounted in a horizontal fashion. Taking these needs into consideration, the team brainstormed several configurations. Firstly, the payload sub-team contemplated a binder, two plywood sleds connected with rings. Such an orientation would be inserted into the coupler with parallel sleds and could be unfolded when removed. As per past iterations of ISS Space Grant rockets, the "sandwich" layout utilized only horizontally mounted, circular sleds. The structures sub-team offered a middle ground with a system resembling a triangular prism, in which a horizontal platform would fall in the center. The overlapping issues of the previously described designs, however, brought the team back to a simpler design. The chosen design – an "H" shaped structure – allows the 9-DoF breakout board to sit in between the two platforms and provides adequate space for the electronics.

One bulkhead with the same diameter will sit on either side of the coupler tube, and each on either end will be connected by two threaded rods. Just outside of the rods are two vertical mounting boards, one on each side, as shown in Figure 4. Two smaller platforms lie parallel to the bulkheads and in between the two boards. Holes in all of the boards and bulkheads to allow wires to easily run between the electronics as well as between the body tubes if necessary.

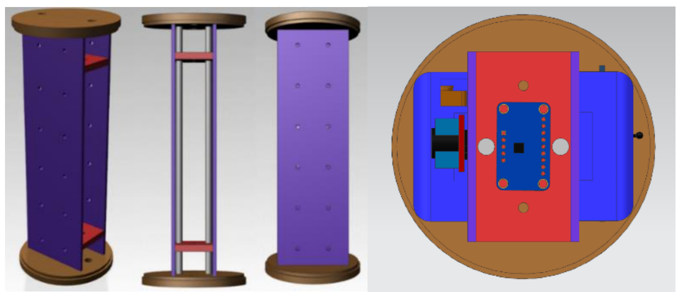

Figure 4: Multiple Views of Unmounted Avionics Bay (Left), Top-Down View of Avionics Bay (Right)

Since the magnetometer should ideally remain horizontal during the flight, the module will rest on the top horizontal platform as seen in Figure 4. All other electronics components are positioned to maximize distance from the magnetometer to reduce magnetic interference. Electronics are organized between the two vertical mounting boards according to their function – one board is designated for altimeters and their battery supplies, while the other board is mounted with payload electronics for roll control, as well as the competition altimeter. 3D printed covers will be used to secure batteries and the competition altimeter to the mounts. The detailed configuration of the avionics bay can be seen in Figure 5.

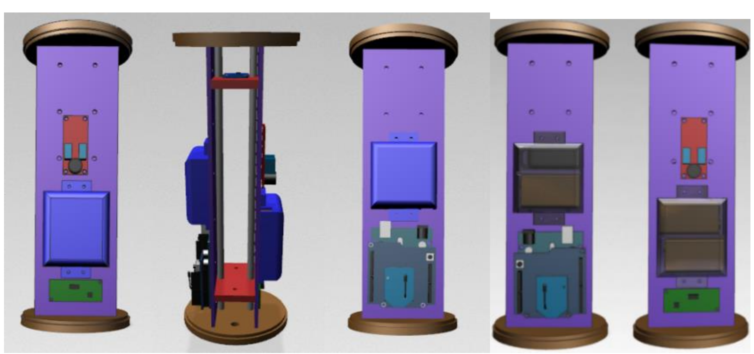

Figure 5: Multiple Views of Mounted Avionics Bay (Left), Translucent Battery Covers (Right)

3.1.2 Altimeter

The primary altimeter chosen, Perfectflite Stratologger Altimeter CF, will be powered by a 9V battery. Its purpose is to directly record highest altitude and speed, highest and average acceleration, booster burn time, and coast to apogee time. Using these variables, the altimeter will be programmed to fire off the parachute at a specific instant during the flight. This altimeter has dual deployment capability; therefore, it will successfully fire off two parachutes during flight. These two parachutes are the drogue parachute, which is released exactly at apogee to ensure the slowest speed, and the main parachute, which is fired at a programmable height. Through firing off two parachutes instead of one, the altimeter further ensures that the rocket will not be damaged in its descent, along with dropping at a location closer to where it was launched. In case of any mishaps, a backup altimeter will also be on board. The EggTimer Quark altimeter contains the necessary applications of the primary one, including dual deployment. The EggTimer will be independently powered by a 9V battery to provide full redundancy. Both altimeters can be seen in Figure 6.

Figure 6: Primary Altimeter – Stratologger CF (Left), Secondary Altimeter – EggTimer Quark (Right)

3.1.3 Arduino

The Arduino UNO R3, based on the ATmega328 chip, is the microcontroller selected for the vehicle. It can be seen in Figure 7. The Arduino UNO will be powered by a 9V battery. Its goal is to power the communications system, orientation system, and control the servo motors. Acting as the processor, it is externally programmed to manage the servos, an essential part of the competition, along with other avionics. In regards to the communication system, the Arduino UNO is responsible for communicating to an external programming source so it may control the avionics and electronics. Through this, the communication system will manage the roll requirements of the competition, along with many other key aspects to the flight.

Figure 7: Arduino UNO

3.1.4 9-DoF Sensor

The team decided to use an Adafruit 9-DoF Breakout Board LSM9DS0 to record roll and acceleration of the rocket. The 9-DoF includes an accelerometer, gyroscope, and magnetometer, each capable of measuring with three degrees of freedom. The team originally considered using only a gyroscope to control roll. After some research, the team found that a combination of magnetometer and gyroscope should be used to improve accuracy and reliability. The gyro will be used to integrate angular velocity over time to determine orientation. The magnetometer will be used to calibrate gyroscope integration error over time. The accelerometer is used in magnetic field calculations to compensate for tilting.

3.1.5 Camera and LED System

The camera chosen for the rocket is the Mobius Mini 1440P HD video camera. Weighing in at .95 oz and having dimensions of 1.93 x 1.14 x 0.55 inches, the camera does not greatly impact the overall weight of the rocket, and can be easily mounted externally. Because of its wide-angle lens and its capacity to record at 720p/60FPS or 1080p/30FPS, this camera will successfully record the flights at the level of video quality desired. In order to keep the camera in place and safe, the sealed Mobius Mini Camera shroud will be utilized to enable simple mounting and protect the camera from ejection charge forces.

A 3-LED indicator system is used to signal the vehicle's current control state. The LEDs will be mounted to the exterior of the coupler horizontally such that each is in view of the camera while not obstructing excessive areas of the video. The central LED is used to indicate holding, during which the vehicle attempts to prevent any roll. The right-hand side LED indicates rolling clockwise. The left-hand side LED indicates rolling counterclockwise. The LEDs will blink at 0.2s intervals after the vehicle goes vertical and before launch. After apogee, the blink pattern will be reestablished at 0.5s intervals.

3.2 Avionics Electrical Setup

3.2.1 Altimeter

The team decided to go with a dual altimeter design in order to ensure accurate readings and successful deployments of both the drogue and the main parachutes. The system is set up so that both altimeters are powered by their own separate batteries and each altimeter is able to deploy both parachutes individually. The main altimeter is the Stratologger CF, which is connected to its own 9V battery, switch, and primary charges of both parachutes. This altimeter will be set to detonate the drogue parachute charge at apogee and the main parachute charge at 1000 ft. In the case that the main altimeter fails to gather data and/or discharge both parachutes, the secondary altimeter, the EggTimer Quark, will be there as a backup. The secondary altimeter is connected to a 4V LiPo battery, the secondary switch, and both of the backup parachute charges. The electrical setups of both the primary and secondary altimeter can be seen in Figure 8. This secondary altimeter is set to detonate the main parachute charge at 900 ft on descent. The motor ejection charge will be used at the backup drogue ejection charge.

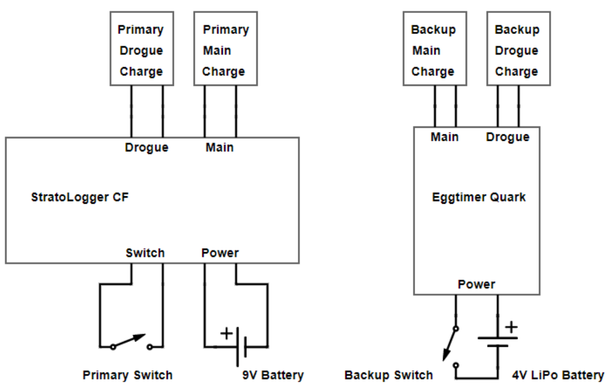

Figure 8: Altimeter Electrical Setup

3.2.2 Arduino

The onboard Arduino will be powered by a 9V battery and will be mounted in the avionics bay. The Arduino UNO supplies power to the 9-DoF and receives input from the 9-DoF via analog pins 4 and 5. It also powers three LEDs used for control signaling via pins 5, 6, and 7. Finally, pins 8 and 9 are used to send signals to two servos which actuate the vehicle's control flaps.

3.2.3 9-DoF Sensor

The 9-DoF breakout board will only be wired to the Arduino while in the rocket. From its 3.3V output, the Arduino will power the 9-DoF. Two signal wires are necessary to connect the 9-DoF to the Arduino. The SDA pin on the 9-DoF will be connected to analog pin 4 on the Arduino, and the SCL pin on analog pin 5. A wire will run from the 3.3V output on the Arduino to the VIN pin on the 9-DoF. The GND pin on both the Arduino and 9-DoF will be connected by a wire as well. To properly read roll data, the 9-DoF will need to sit parallel to the bulkheads. Since the magnetometer of the 9-DoF detects the magnetic field around it, the team decided to isolate the 9-DoF. The breakout board will sit on a flat board perpendicular to the rest of the electronics. The board will sit at the opposite end of the payload bay to minimize magnetic interference.

3.3 Active Roll and Orientation Design

The competition requires the vehicle to perform two flights. The vehicle shall cancel its angular velocity during the first flight and actively roll to preprogrammed directions during the second flight. The team achieves these goals through two servo-mounted flaps that are actuated by a closed-loop control algorithm. Figure 9 illustrates the control schematics of the vehicle.

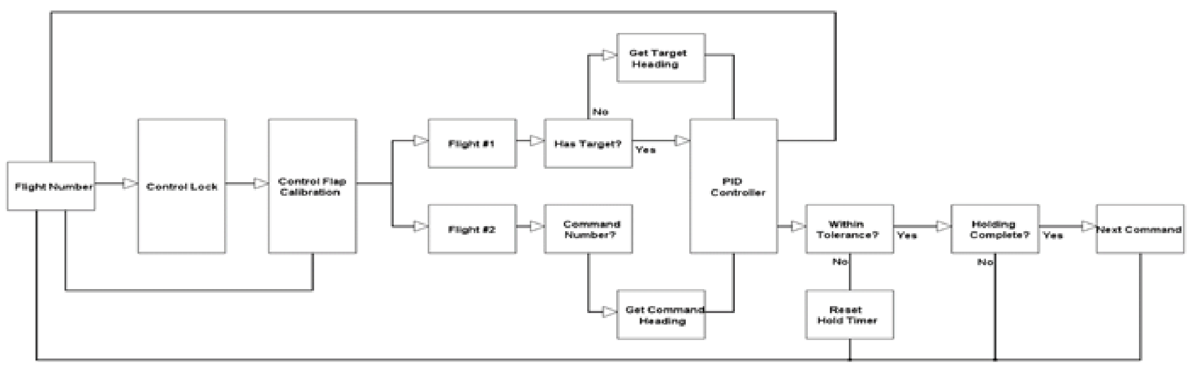

Figure 9: Active Roll Control Program Schematic

3.3.1 Orientation Detection

The team uses the 9-DoF to determine heading. Angular velocity readings from the gyroscope are integrated over time to provide smooth readings. Since the gyroscope has inaccuracies that will accumulate over time, absolute orientation calculated from magnetometer readings is used to recalibrate gyroscope data once cumulative error from the gyroscope approaches a given limit. Raw magnetometer readings, along with accelerometer readings in the x and y axes, are fed into an equation, shown in Equation 1, to produce the tilt-compensated reading value as previously mentioned. Accelerometer readings are used to compensate for tilting of the magnetometer. **B** represents magnetic field measurements, **V** represents compensation for hard iron error, and **ψ**, **θ**, and **ϕ** correspond to heading, pitch, and roll respectively.

$$tan(\psi) = \left(\frac{-B_{fy}}{B_{fx}}\right) = \left(\frac{(B_{pz} - V_z)\sin\phi - (B_{py} - V_y)\cos\phi}{(B_{px} - V_x)\cos\theta + (B_{py} - V_y)\sin\theta\sin\phi + (B_{pz} - V_z)\sin\theta\cos\phi}\right)$$

Equation 1: Tilt-Compensated Heading from Magnetometer Reading

The magnetometer must be calibrated just prior to launch to account for hard and soft iron error. The team must first determine magnetic field strength based on the vehicle's geolocation and then subtract readings from the magnetometer to find the error in all three axes. These values are then accounted for in the aforementioned equation to compensate for error. It is essential to perform this procedure after the vehicle is assembled and at the launch site because hard and soft iron errors are highly dependent on the surrounding environment of the magnetometer.

3.3.2 Control Flaps & Servos

Active orientation control is achieved through two 2”x2” square control flaps symmetrically mounted to the booster tube of the rocket. The two control flaps are independently actuated by HK15298B coreless digital servos, which can each produce 20.0 kg·cm of torque with a speed of 0.16s per 60 degrees of rotation. The two servos are powered by a single 6V LiPo or NiCd battery mounted in the avionics bay and are controlled by signals sent from the onboard Arduino.

3.3.3 Roll Control Algorithm

The active roll control system consists of two feedback loops. The first loop measures angular velocity of the vehicle and incrementally changes the flaps’ angle of attack (AoA) to find a neutral position - where the intrinsic torque from the vehicle is canceled out by control flaps. The resultant neutralizing AoA is used to calibrate the second control loop, which uses a proportional-integral-derivative (PID) controller to actively orient the vehicle. The proportional, integral, and derivative terms are, respectively, angular error, cumulative angular error, and angular velocity. These terms are multiplied by their respective gain constants and summed with the neutralizing AoA to find the desired output AoA to the servo-mounted flaps. MATLAB was used to create mathematical models of the dynamic system to optimized gain constants to minimize settling time and maximize robustness.

The torque generated by control flaps is mainly dependent on the velocity of the vehicle. Theoretically, the amount of lift generated by an airfoil is proportional to the square of the velocity. This effect is compensated via the control code by scaling up the magnitude of control flap deflection over time. The time of flight will be estimated from OpenRocket for test flight, and actual flight data from the test flight will be used to improve upon the simulation. While atmospheric density is also a factor in the lift equation, based on the apogee of the vehicle from OpenRocket simulations, the team believes the effect is insignificant and does not need to be accounted for.

The vehicle needs to be configured before flight. A serial monitor interface is used for setting up the vehicle. First, a password is required for interaction to prevent accidental activation. Then, the flight number will be selected. Selecting Flight 1 will directly lead to activation of the preflight loop where the vehicle awaits launch via measurement of vertical acceleration. Selecting Flight 2 will lead to the command input phase where roll commands, including target heading, roll direction, and hold time, are manually entered and recorded as variables used by the control code. This may be done either wirelessly in compliance with the bonus challenge or completed through a wired connection as a backup solution.

3.3.4 ANSYS Simulations

To expedite the design process and reduce wind tunnel testing time, the team also uses ANSYS to simulate forces on the vehicle’s aerodynamic surfaces. ANSYS is a software suite that enables physics simulations across a wide variety of engineering fields. The team specifically employs the computational fluid dynamics (CFD) tool to simulate lift and drag induced by fins and control flaps.

The force generated by control flaps was simulated under varying wind speeds and angles of attack. Results from the simulations will construct a lookup table used by the MATLAB simulation (addressed below) to accurately model aerodynamics effects. The data would also be compared against wind tunnel data. If similar results are attained by the wind tunnel and ANSYS simulations, the team could then conclude that ANSYS simulations are sufficiently accurate to directly employ. Otherwise, more substantial wind tunnel testing would be required.

3.3.5 MATLAB Simulations

A custom-built MATLAB simulation simulates the performance of the roll control system. The simulation computes the lifting force generated by both the control flaps and the stationary fins under varying conditions. The calculations are performed using lifting forces simulated by ANSYS or determined by wind tunnel testing. Torque is calculated from the lifting force and the moment arm and then applied to a cylindrical body with an estimated moment of inertia. This produces angular acceleration which is integrated twice to calculate vehicle orientation.

A wide range of initial conditions may be set up to simulate multiple potential scenarios. The second part of the simulation contains a translated version of control code from the Arduino program. By iterating over 1 millisecond time steps, a high-fidelity simulation may be created. From the simulation results, control parameters may then be tuned manually in rapid succession. Simulation results indicate that the control mechanism is robust and capable of handling roll conditions of over 2700 degrees per second, which is greater than the gyro's hardware limit of 2000 dps. Desired heading may be achieved with a settling time of under one second. A sample MATLAB simulation is shown in Figure 10 below.

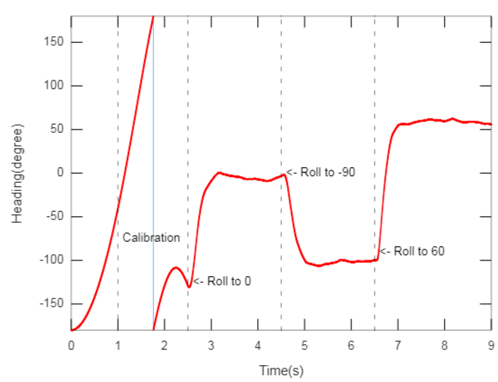

Figure 10: MATLAB Simulation Results

3.3.6 Wind Tunnel Testing

After using MATLAB and ANSYS to provide a basis for the roll algorithm, both sub-teams solidified the approach with testing. Dr. Brian Woodard, the director of aerospace engineering undergraduate programs at the university and an esteemed professor, focuses his research on airfoils; therefore, the team requested his help to model an experiment that tests the roll-control capabilities of the rocket's fins and flaps.

The experiment's independent and dependent variables, the velocity of air speed on the x-axis and the force on a singular flap or fin on the y-axis, were determined first. Based on the model's needs, Dr. Woodard suggested using the 1x1x2 ft wind tunnel in the university's aerodynamics testing facility. Within this piece of equipment, the object would be situated on a metal mount facing the inlet of air. Seeing as the wind tunnel is capable of airspeeds of 100 ft/s, the team plans to take measurements at 10 ft/s increments, which will eventually be used to plot a theoretical graph. Such pursuits will be completed in late March.

3.4 Payload Mass Statement

Table 4: Payload Mass Statement

Avionics Component	Quantity	Total Mass (g)
Voltage Regulator	1	22.68
Batteries	4	287.0
9-DoF Sensor	1	2.30
Arduino UNO	1	25.0
Primary and Backup Altimeter	1, 1	10.77, 5.00
XBEE Shield	1	9.07
Servo Motor	2	132.0
Rotary Switch	3	11.07
XBEE Pro	1	4.30
LED	3	0.30
Total Mass		509.49

4 Anticipated Flight Performance

4.1 OpenRocket Designs

The team designed the rocket in OpenRocket to ensure that the designs created were feasible and would reach the necessary goals. OpenRocket allows adjustments to be made to the original design and changes to be observed such as the theoretical apogee, stability constant, and various velocities. OpenRocket also calculates the rocket's center of pressure and center of gravity.

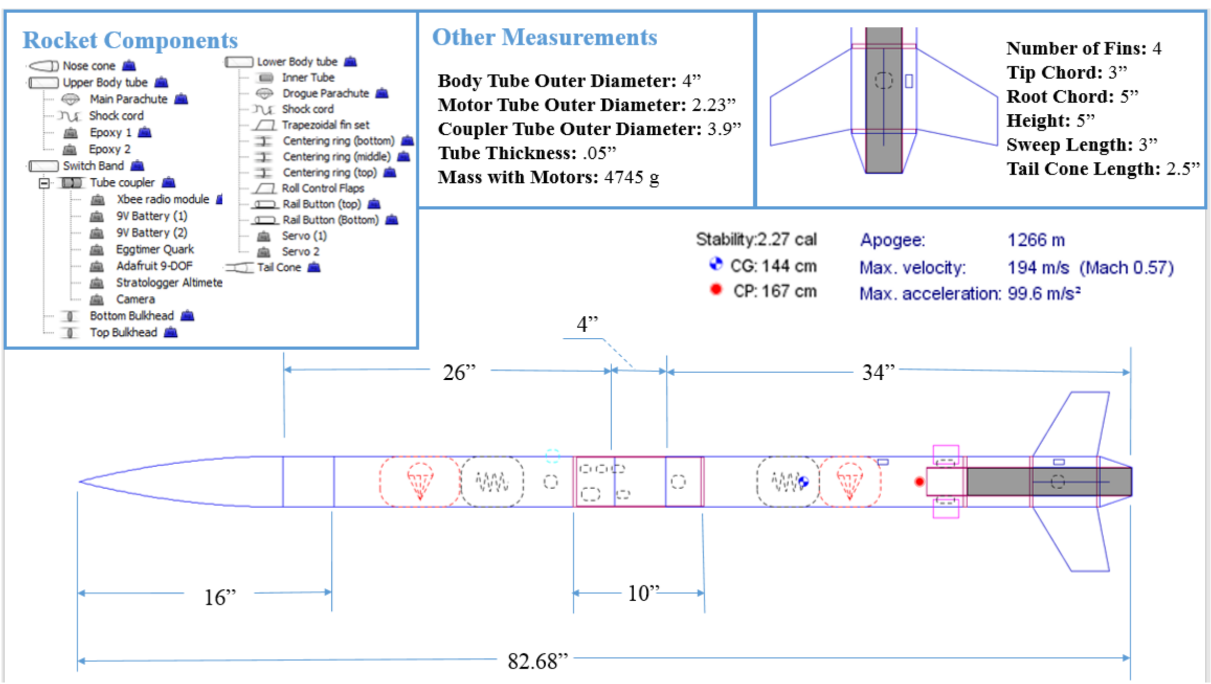

Figure 11: OpenRocket 2D Design

The final design, in a 2D format, is pictured in Figure 11with its components in the upper left hand corner. The rocket consists of a nose cone, an upper body tube, a coupler and switchband section, and a lower body tube. Each of these sections was represented as accurately as possible within OpenRocket by choosing the proper material and masses. The resulting velocities proved to be safe for both the ascent and descent phases of the launch. The calculated center of gravity also allowed the team to place the roll control apparatus in a way that it would be below the center of gravity on the rocket. Within the major components of the rocket are several smaller pieces that affect the design of the rocket. This includes the parachutes, shock chords, avionics bay, camera, fins, roll-control flaps, and epoxy. All of these features were modeled and accounted for as accurately as possible within OpenRocket so that the constructed rocket would perform closely to the predictions of the software.

4.2 Fin Sim Simulations

FinSim is a military software used to analyze the strength and safety of fins at high velocities. Based on the material, size, and adhesive of the fins entered into the software, a divergence velocity and flutter velocity are outputted to reveal when the fin will begin to diverge and when the fin will actually begin to flutter.

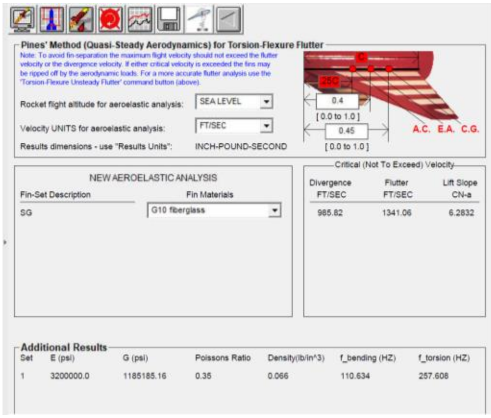

Figure 12: FinSim Divergence Analysis

The team used the dimensions of the fins in the OpenRocket design and entered them into the FinSim software along with the correct material and adhesive to correctly simulate the divergence and flutter velocities. With these values, the software outputted a divergence velocity of 985.82 ft/sec and a flutter velocity of 1341.06 ft/sec as shown in Figure 12. The max vertical velocity that the rocket attains is around 633 ft/sec. This value is obtained from the OpenRocket Simulation in Figure 14. Since the maximum velocity is significantly lower than both the divergence and flutter velocities, the fins will be safe.

4.3 Stability Analysis

During the simulation process, the structures sub-team varied multiple factors in OpenRocket to test which impacted stability most. While mass distribution was heavily weighted, fin size and shape produced the most dramatic difference in the aforementioned ratio. After discussing typical protocol with faculty mentors, members modified the main fins to obtain a range of stability coefficients for testing.

During this process, iterations circulated around three stability coefficient targets – 2.00, 2.5, and 2.25. The 2.14 cal fin variant attained the lowest apogee of the three. Seen as the final physical rocket typically possesses a higher mass than that of the theoretical models, the team omitted this variant. While the 2.46 cal fin variant achieved a highest apogee in OpenRocket simulations, the long, narrow fins' lack of surface area would hinder the team's roll-control measures, possibly raising the risk of the rocket failure during flight. Seen as such characteristics would most directly affect the competition's objectives, the team gravitated more towards a 2.25 stability coefficient. With this target, the structures sub-team underwent numerous fin designs and now considers manufacturing practicality. After conducting OpenRocket simulations for each fin variant, the team decided upon a 2.26 cal variant, the farthest right fin in Figure 13, for optimal stability and fin design.

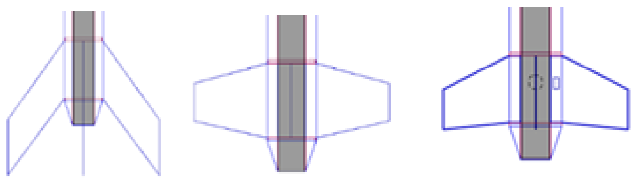

Figure 13: 2.46 Fin (Left), 2.14 Fin (Center), 2.26 Fin (Right)

4.4 Flight Predictions

4.4.1 Basic Flight Performance

The OpenRocket software allows simulations to be ran once a rocket is designed within their program and will output a series of variables based on different environmental conditions entered. The team chose to run their simulation at a 4 mph wind speed since it is the average wind speed during this time of the year. For the results of the simulation, the team chose to focus on the outputs of acceleration, velocity, and altitude to ensure that the rocket reached its goal height safely.

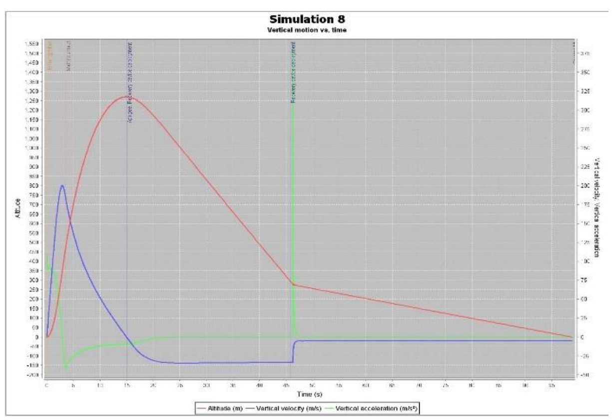

Figure 14: OpenRocket Simulation

The simulations provided by OpenRocket help the team guarantee that the rocket will meet the competition's criteria. Three critical items that are outlined in the competition handbook are descent velocity, apogee, and safe flight and recovery. The simulation shown in Figure 14 reveals that the rocket designed has an apogee of 4121 ft and a descent velocity of about 16.37 ft/sec. These values both satisfy the constraints laid out in the handbook. The thrust to weight ratio can be obtained by taking the thrust of the J415 AeroTech motor represented in Figure 1 and dividing it by the theoretical mass provided by OpenRocket. Using these values, the ratio is theoretically greater than 8 for both of the flights. This allows for the flights to be safer and for the rocket to fit the outlined criteria. The low descent rate also allows for a safe landing and recovery as it is significantly lower than the given limit of 24 ft/sec.

4.5 Environmental Conditions

In order to launch the vehicle, a few criteria concerning the environment must be met. In order to minimize the likelihood that the rocket will land in an irretrievable area, no launches will take place in areas where tall trees, power lines, and buildings pose a hazard. These objects are hazardous if within one-half of the apogee of the rocket, or roughly 2,000 ft. The team will not launch the rocket within 1,500 ft of a public highway. These precautions reduce the likelihood of losing the rocket or damaging property. The team will also not launch the rocket within one-half apogee of any people not involved with the launch. The potential of grass fires to occur at the launch pad when the engine ignites is also a concern. However, it can be mitigated by checking that there is no dry grass and that the area is not prone to grass fires. Wind conditions must also be taken into account before deciding to launch. The upper bound wind speed cannot be greater than 20 mph. This is to reduce the likelihood of the rocket being blown off course or, in the worst case scenario, flipping during flight and plunging into the ground at high speed. Launching when the wind is calm also helps to ensure that the rocket travels into a region with no hazards. Precipitation at the launch site is another important factor to consider when deciding whether to launch the rocket. Continuous or heavy precipitation or lightning within a 10 mile radius qualifies as reason to cancel launch. Cloud cover also poses a threat to the rocket. In order to eradicate this risk, the team will check what altitudes the clouds will be at when preparing to launch the rocket. If there are clouds below the predicted apogee of the rocket (4,121 ft), the team will not launch the rocket and wait for the cloud cover to clear out of that zone. In order to further decrease the chance that the rocket crashes and leaves debris in the environment, the team will take extreme care in preparing the drogue parachute and the main parachute to maximize the likelihood of nominal deployments. This includes making sure the parachutes are properly folded in a way that prevents the shock cords or the shroud lines from tangling, which could affect deployment.

5 Construction Progress and Execution Plan

5.1 Structure of Meetings and General Timeline

The team lead structured meetings to meet on a weekly basis. Mondays would include two-hour research and writing sessions, while Sunday would be dedicated to three to four hour building sessions. The first five months revolved around researching possible solutions and perfecting the plan as well as learning the fundamentals of high power rocketry through the HPR tutorials (elaborated upon in Section 5.3.1).

Second semester, the team lead and sub-team leads set up a calendar detailing internal deadlines involving the written reports and test flights. A general summary can be found below.

Table 5: Execution Timeline for Second Semester

Month	Number of Build Sessions	Number of Writing Sessions	Significant Due Dates
January	2	1 (PDR)	-Receive first set of parts
February	4	4 (PDR)	-Send and receive second set of parts -Start constructing physical body -Test Arduino and XBEE systems

March	1	5 (PDR and FRR)	-Submission of PDR (3/9/18)
April	3	4 (FRR)	-Test Launch (4/14/2018) -Run Through of Launch Procedures
May	2	2 (Oral Presentation and PFR)	-Run Through of Launch Procedures -Competition (5/18-22/18) -Submission of FRR -Oral Presentation -Submission of PFR

5.2 Construction Progress

5.2.1 Structures

The structures sub-team began by laser cutting the centering rings and bulkheads and epoxying two layers of 1/8" aircraft plywood to strengthen the pieces. Members also measured out the blue tube based on the final OpenRocket dimensions and cut out the pieces using a miter saw. Next, the team epoxied the switch band onto the coupler tube and the bottom centering ring into place.

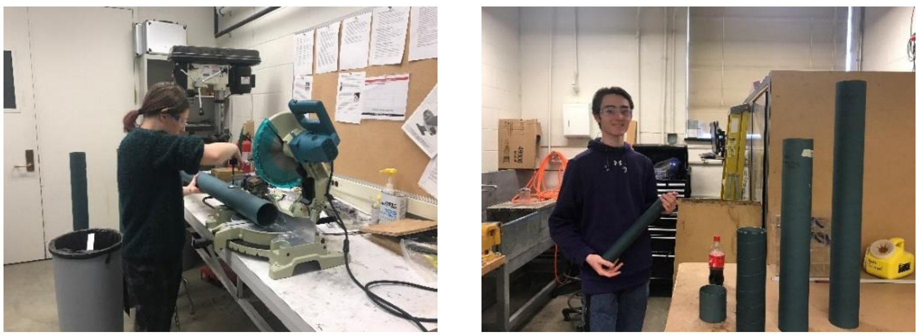

Figure 15: Cutting Blue Tube (Left), Final Pieces of Rocket Body (Right)

Due to using fiberglass, the team used the university's composites lab and, more specifically, their diamond saw. After receiving proper training from the lab manager, the structures team cut two out of four fins and both necessary flaps. The team plans to return within the week to complete this task and draft the fin jigs in NX in order to assemble the motor mount tube.

Figure 16: Motor Mount Tube (Left), Coupler Tube with Switchband (Middle), Completed Fins (Right)

5.2.2 Payload

Upon receiving the needed electronics, the payload sub-team has been testing their code with the Arduino Uno, the Stratologger, the breakout board, and batteries. Members began soldering the aforementioned breakout board as seen in Figure 17. Within the next month, the team will construct the avionics bay.

Figure 17: Soldering the 9-DoF (Left), Team Member testing XBEE Communications

5.3 Safety

5.3.1 High Power Rocketry Tutorial

The ISS Space Grant Team had their first exposure to high-power rocketry through a tutorial series led by ISS. This program aims to introduce many of the most important concepts of high-power rocketry to beginners. This program is headed by the technical director and team advisor Connor Latham.

The tutorial starts with a presentation on the fundamentals of high-power rockets. It goes over basic structures and usual arrangements, payloads, motors, stability, recovery, and construction techniques. The next part in the series is going over OpenRocket and guiding the members through designing an example rocket. This rocket is intended to capture the same elements the presentation covers in the frame of the OpenRocket software. It is often utilized by the team for flight modelling, so having the members of ISS becoming comfortable with it is important for designing safe and successful rockets. The third installation explains the rockets that they end up flying in the second half. The group is split into five teams, and each designs a mid-power rocket (G motor) to fly at a local organized flight. The rockets are around four feet tall, 3 lbs, and reach an altitude of 1000 ft, which makes them flyable without a waiver. The teams focus on changing the lengths of each body section and the fin shape to reach the desired altitude.

The teams then assemble their rockets while making use of the learned construction techniques. They get exposure to working with high strength epoxy, using a table saw to cut body tubes, and using the laser cutter to cut out other parts such as fins and centering rings. Understanding how to use all of these tools is important for being safe and having a productive building session. Pictures of the build process can be seen below. After construction, the rockets were painted and then it was a waiting game with the weather. After many failed attempts, the rockets were finally launched on March 4. All rockets were successfully assembled, launched, and recovered in back to back flights. The teams were exposed to using the Stratologger altimeters, wrapping parachutes, and properly securing the altimeter in the avionics bay. Pictured below is a graph of the altitude and velocity along with group photos.

Figure 18: Construction Photos (Left), Team Members with HPR Rockets (Middle), Altimeter Data from Perfectflite Software (Right)

5.3.2 Activity Risk Mitigation

Table 6: Failure Modes and Mitigation Strategies

Hazard	Likeliness (1-5 Scale)	Severity (1-5 Scale)	Impact	Mitigation
Ejection charge fails leading to parachute deployment failure	2	5	Rocket does not get slowed down and comes in ballistic	Test ejection charge amounts and wiring to ensure it works
Ejection charge causes other components of rocket to fail	2	5	Possible destruction of rocket or failure to execute tasks	Protect all electrical components from the blast
XBEE fails to make connection with team on ground	3	2	Team cannot complete bonus test or receive real time flight data	Test connection with radio before launch
Rocket fins detach	1	5	Instability of rocket and inability to fly again	Securely attach fins and test before launch
Failure of active roll system	2	2	Rocket will attain a higher apogee than originally assumed	Test electrical equipment before flight and test in wind tunnel
Parachute fails to open	2	5	Destruction of rocket	Fold parachute neatly and keep internal components out of way
Shock cord fails	2	5	Rocket completely separates causing damage upon landing	Securely attach the shock cord

Table 7: Personnel Hazards and Mitigation Strategies

Hazard	Likeliness (1-5 Scale)	Severity (1-5 Scale)	Impact	Mitigation
Epoxy	3	2	Irritation to skin and possible allergic reaction	Wear gloves when working with epoxy
Wind tunnel	2	2	Possible injury to hair and fingers	Tie long hair back and be cautious when placing items in wind tunnel

Electrical equipment	**1**	**3**	Electrocution	Turn off all power sources before handling equipment
Rocket launch and flight hazards	**2**	**5**	Rocket components hitting team members or bystanders	Team members and audience will stand a safe distance away and be alert while the rocket is in the air
Laser cutter	**1**	**3**	Skin irritation and damage	Team members trained to operate with cover is down
Dremel/Drill	**2**	**2**	Getting cut, skin irritation, or particles getting in eyes	Wear protective googles and use caution when operating tools
Diamond saw	**1**	**3**	Irritation and skin damage	Team will be given an instructional class on how to operate the diamond saw
Motor innards becoming exposed	**2**	**2**	Explosion of motor or irritation to skin	The team members will handle the motors with care

5.3.3 Launch Procedures

In order to conduct a safe launch during the test flight and the competition runs, the team formulated a flight checklist to be printed, reviewed, and completed before, during, and after any performance.

Table 8: Launch Procedures Checklist

Phase of Flight	Actual Task	Completion
Pre-Flight 1	Connect all electronic systems	
	Attach, fold, and pack drogue and main parachute	
	Assemble rocket airframe	
	Turn on all electronic systems, including camera and GPS	
	Run through last checks with team mentors	
	Insert motor into lower airframe	
	Set rocket on launch pad	
	Initiate flight 1 code sequence	
Post-Flight 1	Check for signs of damage	
	Remove motor from lower airframe	
	Decide on pursuit of flight 2 (dependent of outcome of flight 1)	
	Implement repair measures (if needed)	
	Download camera and sensor data, submit to judges	
Pre-Flight 2	Reset all electronic systems, including camera and GPS	
	Attach, fold, and pack drogue and main parachute	
	Assemble rocket airframe	
	Turn on all electronic systems, including camera and GPS	
	Insert motor into lower airframe	
	Set rocket on launch pad	
	Initiate flight 2 code sequence	
Post-Flight 2	Check for signs of damage	
	Dispose of hazardous, broken material	
	Remove motor from lower airframe	
	Download camera and sensor data, submit to judges	
	Turn off all electronic systems, including camera and GPS	
	Detach drogue and main parachute	
	Disassemble rocket airframe	

5.4 Budget

The ISS Space Grant team has a general budget of $1,000 to encompass all technical expenses needed for the full-scale rocket. The intended distribution is detailed in Table 9. 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.

Table 9: Overall Budget and Parts List

Item	Per unit cost	Quantity	Total Cost	Item	Per unit cost	Quantity	Total Cost
Full Scale Rocket							
(12-Pcs) STMicroelectronics 3.3V 950mA, LD1117V33 Voltage Regulator, LD33V	$8.99	1	$8.99	Mobius Mini Shroud	$34.50	1	$34.50
1/8" G10 garolite sheet, 12in by 12in	$19.36	2	$38.72	Motor Adapter	Owned	1	$0.00
1/8" G10 garolite sheet, 6in by 6in	$10.59	1	$10.59	Motor Casing (54-2560)	Owned	1	$0.00
54 mm Seal Disk	Owned	1	$0.00	Mounting Brackets for Flaps	Owned	2	$0.00
54mm Blue Tube	$23.95	1	$23.95	Mounting Screws for Flaps	Owned	-	$0.00
6V NimH	Owned	1	$0.00	Nose Cone	$21.95	1	$21.95
98 mm Blue Tube	$38.95	1	$77.90	Nuts and Threaded Rods	Owned	1	$0.00
98 mm Coupler Blue Tube	$39.95	1	$39.95	Parachute	Owned	1	$0.00
Adafruit 9-DOF Accel/Mag/Gyro+Temp Breakout Board - LSM9DS0	$24.95	1	$24.95	Parachute Protector	Owned	1	$0.00
Aero Pack 54L/3.9" Tailcone Retainer	$57.78	1	$57.78	Quicklinks	Owned	1	$0.00
Aircraft Plywood	Owned	1	$0.00	Rail Buttons	$3.22	1	$3.22
Arduino UNO	$22.00	1	$22.00	Resistors	$0.14	3	$0.42
Bulkheads	To be cut	3	$25.00	RocketPoxy	$38.25	1	$38.25
Centering Rings	To be cut	3	$0.00	Rotary Switches	$9.93	3	$29.79
Connections Hardware	$25.00	1	$25.00	SD Card	$11.89	1	$11.89
Copper Wire	Owned	1	$0.00	Servo Extension Wires	Owned	1	$0.00
Drogue Parachute	Owned	1	$0.00	Shear Pins	$3.10	1	$3.10
Duracell Procell 9V (x6)	$10.59	1	$10.59	Shock Cord	Owned	2	$0.00
Eggtimer Quark Backup Altimeter	$20.00	1	$20.00	Stratologger Altimeters	Owned	1	$0.00
Gikfun Bluetooth XBee Shield V03 Module For Arduino EK1185_	$9.58	1	$9.58	U-Bolts	$4.96	3	$14.88
Heat Shrink Tubing	Owned	2	$0.00	USB Cable Standard A-B	$3.95	1	$3.95
HobbyKing Servo	$20.45	4	$81.80	USB Data Transfer Kit	$22.46	1	$22.46
J Motor (J415W-L)	$79.04	1	$79.04	XBee Pro Module - Series 1 - 60mW with Wire Antenna - XBP24-AWI-001	$37.95	2	$75.90
MicroSD Breakout Board	$7.50	1	$7.50	XBee USB Adapter TTL Adapter	$11.95	1	$11.95
Mobius Mini Camera	$86.25	1	$86.25			TOTAL:	$921.85

5.5 Educational Outreach

In addition to fulfilling the technical requirements of the competition, the ISS Space Grant team involved themselves in a number of ISS community outreach programs. Early in the 2017-18 school year, ISS hosted the annual Illinois Space Day, drawing in over 150 elementary and middle school level students from local communities. The team also plans to participate in Engineering Open House, where their rocket will be on display to the hundreds of students who go to get an understanding of what goes on at the university.

5.5.1 Illinois Space Day

Illinois Space Day (ISD) is an annual non-profit educational outreach event that occurred in the fall semester of this academic year on Saturday, October 7th 2017. Organized by the Illinois Space Society (ISS) and run by its Education Outreach Director, ISD is an all-day event which occurs in the morning and lasts into the afternoon and includes a provided lunch to attendees. The exhibits and presentations at ISD are intended for late elementary to early high school students and their parents. This year, the attendance reached approximately 200 participants, including 150 kids and 50 adults, which is the largest number of attendees for ISD in society history due to an increase in school interaction. Other outreach events and advertising allowed members of the team to connect with approximately three new schools.

In addition to the various science exhibits at ISD, each year a professional in the aerospace industry is also asked to speak at the event. Professionals with experience teaching or working with children are preferred due to their increased understanding of working with younger groups. This year, Dr. Erik Kroeker, a finalist in the Canadian Space Agency Astronaut trials, spoke about his experiences from training to be an astronaut and how to get involved with STEM as a kid. Dr. Kroeker is a University of Illinois Aerospace alumni and previous faculty member. His relationship with the school and ISS showed throughout his talk, as he knew exactly how to focus his experiences towards the younger kids.

By speaking with college-aged participants, children can be exposed to ideas not only involving space exploration, but also how they can make a difference as students. The children and families that attend often return in subsequent years to expand their understanding of space and see the newest exhibits. Illinois Space Day is ISS's premier annual educational outreach event, and attendance has continued to grow over the last several years.

Beyond simply educating children, all of the ISS Space Grant team members were involved with the setup, takedown, and execution of ISD. This ensures all the team members have experience in the area and can make an impact within the community.